Mechanical thinning impacts on runoff, infiltration, and sediment yield following fuel reduction treatments in a southwestern dry mixed conifer forest

D.S. Cram, T.T. Baker, A.G. Fernald, A. Madrid, and B. Rummer

Abstract: Increasing densities of small diameter trees have changed ecological processes and negatively impacted conservation of soil and water resources in western forests. Thinning treatments are commonplace to reduce stem density and potential fire hazard. We evaluated the impacts of using a specialized heavy piece of equipment to reduce fuel loads on intermediate and steep slopes on surface disturbance, runoff, infiltration, and sediment yield in mixed conifer forests in central New Mexico. Surface disturbance following thinning was similar between slopes, but steep slopes were potentially susceptible to heavy surface disturbance (e.g., deep tire ruts). Rainfall simulations indicated disturbance resulting in exposed bare soil, particularly on steep slopes, increased runoff and sedimentation. However, when surface disturbance was minimized, for example when litter was disturbed but not displaced, regardless of slope, runoff and sedimentation did not exceed non-disturbed sites. Advances in mechanical equipment such as forwarding beds may help reduce surface disturbance. We recommend forest managers focus on minimizing surface disturbance when preparing timber prescription guidelines and on-site priorities.

Key words: erosion—mechanical thinning—rainfall simulation—wildfire risk

Increasing tree densities experienced since the early 1900s throughout forests in the western United States are associated with numerous ecological problems (Dieterich 1983; Covington and Moore 1994a; Covington and Moore 1994b; Kolb et al. 1994). These problems include, but are not limited to conversion from high-frequency, low-intensity fire regimes to low-frequency, high-intensity fire regimes (Swetnam 1990; Sackett et al. 1993; Swetnam and Baisan 1996); reduced water quantity (Trimble and Weirich 1987; Stednick 1996; MacDonald and Stednick 2003; Meixner and Wohlgemuth 2004); and reduced understory vegetation production and diversity (Cooper 1960). Changes in these forest ecosystem processes and characteristics have combined in recent decades to negatively impact the conservation of soil and water resources (Madrid et al. 2006).

The changing vegetation structures and ecological processes in western forests described above place a significant burden on natural resource managers. Dense forests represent increased hazards in the form of severe wildfire to firefighters, property owners and communities, and threatened and endangered species (US General Accounting Office 1999). Opportunities to increase water yield from watersheds has been the subject of numerous research reports and investigations and is of great interest to many western communities (Bosch and Hewlett 1982; Trimble and Weirich 1987; Ffolliot and Brooks 1988; Stednick 1996; Ffolliot and Brooks 2002; MacDonald and Stednick 2003). Adjusting to the negative impacts of increasing forest densities represents a significant cost to local, state, and federal entities and agencies.

Since many natural resource problems can be traced to the overgrown conditions of many western forests, forest managers have been exploring strategies to reduce small-diameter tree densities and increase forest canopy openings. Forest thinning may serve the broader goal of restoring ecosystem processes to historic or prehistoric conditions including fire regimes, hydrologic cycles, understory diversity and production, and wildlife population dynamics. Several states have passed forest restoration acts to address this growing challenge (e.g., New Mexico and Arizona). At the federal level, the 2003 Healthy Forest Restoration Act is designed to reduce barriers to effective forest restoration efforts and make resources available for new approaches to reducing fuel buildups in the US national forest system.

Many of the problems caused by increased forest density can be traced to fire suppression and efforts to prevent all fires (Cram et al. 2006). An important component of forest restoration is effective and safe reintroduction of fire regimes endemic to specific forest ecosystems. Prescribed burning alone may be an economical and effective restoration tool in some areas. However, tree densities in many forests exceed the threshold where fire is a practical or safe silvicultural treatment option. In high-density stands, removal of volatile ladder fuels is a necessary precursor to the use of prescribed burning as a safe and effective maintenance tool (Cram et al. 2006). To reduce forest density, thinning treatments have become more commonplace in recent years across the western United States (USDA Forest Service 2005).

There are many techniques for thinning small-diameter or undesirable trees, and individual approaches are usually selected depending upon site-specific conditions. Hand crews with chainsaws are effective on steep slopes, inaccessible areas, or where labor is not a limiting factor. However, thinning with hand crews is labor intensive, expensive, and has significant safety issues (Rummer and Klepac 2002). In forests with large areas to be thinned or where labor is limited, mechanical thinning techniques may be more appro-

Douglas S. Cram is a research specialist for the Cooperative Extension Service at New Mexico State University in Las Cruces, New Mexico. **Terrell T. Baker** is a professor and extension riparian management specialist and **Alexander G. Fernald** is a professor of watershed management at New Mexico State University in Las Cruces, New Mexico. **Anthony Madrid** is a rangeland management specialist for the USDA Forest Service in Cloudcroft, New Mexico. **Bob Rummer** is project leader at the Forest Operations Research Unit, Southern Research Station, USDA Forest Service, in Auburn, Alabama.

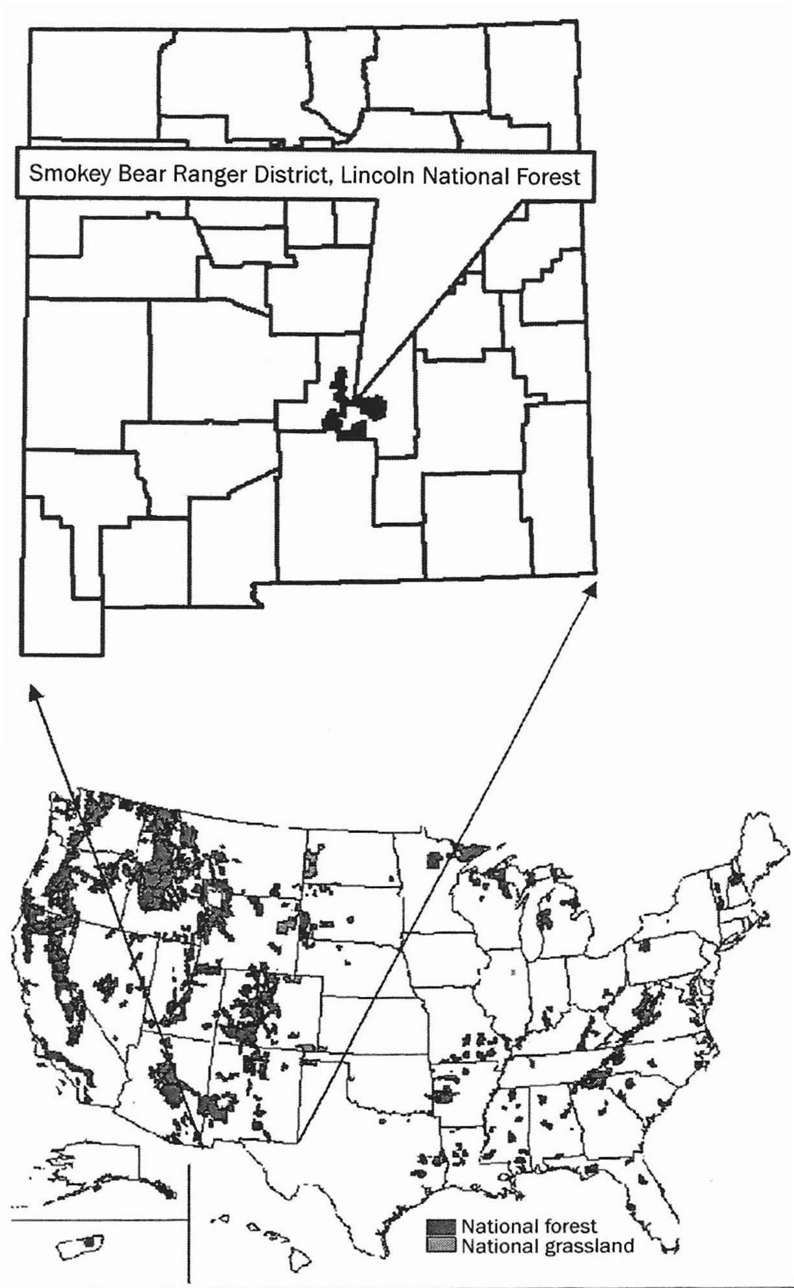
priate. Technological developments have expanded the equipment options available to natural resource managers for harvesting in recent decades. Specially designed harvesting equipment is an alternative with advantages over manual operations approaches including, but not limited to, the harvest and removal of large quantities of timber in a short period of time, the low number of entries into a stand required to harvest, collect, and remove the timber, and the small number of operators required to complete the operation (Klepac and Rummer 2005; Klepac et al. 2006). These new machines, for example, employ large inflatable tires which effectively reduce impacts (e.g., compaction) to the forest floor compared to small-wheeled vehicles (Stenzel et al. 1985). They also carry or forward logs from the site as compared to the dragging or skidding approach used by older equipment (Klepac and Rummer 2005).

With large areas of western forests needing thinning treatments, it is important that a wide range of thinning alternatives be available to forest managers to match specific conditions or situations (USDA Forest Service 2005). In particular, evaluation of new specialized thinning equipment is warranted. In this study, we examined impacts of using a specialized heavy piece of equipment for thinning small-diameter timber. Specifically, our objectives were to (1) quantify soil disturbance on steep and intermediate slopes f[illegible]ving use of a mechanized harvester forwarder or "harwarder" and (2) estimate runoff and erosion on steep and inte[illegible]s at the plot scale following [illegible].

Methods and Materials

Our 19 ha (50 ac) study area (approximately 33°41′N, 105°71′W) was part of the larger 89 ha (220 ac) Eagle Creek Timber Sale just outside of Ruidoso, New Mexico, in the central Sacramento Mountains on the Smokey Bear Ranger District in the Lincoln National Forest, Lincoln County, New Mexico (figure 1). The north-south running Sacramento Mountains cover approximately 5,200 km^2 (2,000 mi^2). The west-facing escarpment rises 2,286 m (7,500 ft) from the Tularosa Basin to the peak of Sierra Blanca 3,650 m (11,973 ft) where the majority of the land area gradually descends east toward the Pecos River. Below the alpine tundra and subalpine coniferous forest lie the two dominant cover types of the Sacramento Mountains: (1) upper montane coniferous forests composed of Douglas fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and ponderosa pine (*Pinus ponderosa*) and (2) lower montane coniferous forests composed of ponderosa pine, piñon pine (*Pinus edulis*), juniper (*Juniperus* spp.) and oak (*Quercus* spp.) (Dick-Peddie 1993). The study area was within the upper montane coniferous forest, also known as mixed conifer, at an elevation of 2,600 m (8,530 ft). Absent disturbance, understory vegetation in mixed conifer stands is suppressed by conifer needle litter produced by the productive overstory (Dieterich 1983). Mean annual precipitation (rainfall only) for the study site region is 74 cm (29 in) (WRCC 2006). Most precipitation occurs in winter as snow (annual mean = 178 cm [70 in]) and summer as rain (June, July, August, and September) (annual mean for 4 months = 40 cm [16 in]) (WRCC 2006). During the summer months, precipi-

Figure 1
The study site was part of the Eagle Creek timber sale in the Smokey Bear Ranger District, Lincoln National Forest, central Sacramento Mountains, New Mexico.



tation in the form of high-intensity, short duration afternoon thundershowers (10.2 cm [4.00 in] per hour) (National Oceanic and Atmospheric Administration 2006) is common to the study area. A dry and windy spring season dries out forest fuels (WRCC 2006). Soils at the study site were classified as Lithic Argiborolls (Bob Danker, US Forest Service, personal communication, 2007).

The Eagle Creek Timber Sale was harvested with a single-machine cut-to-length TimberPro TF 820-E equipped with a LogMax 7000 head during the late summer and fall of 2004. This machine weighs about 23,000 kg (51,000 lb) and exerts a static ground pressure of about 75 kPa (11 psi). The harwarder operator systematically harvested, de-limbed and cut logs within a given area before exiting the immediate stand in order to exchange the processing head for a grapple. With the grapple attached, the harwarder would re-enter the stand and forward logs to a deck. The silvicultural prescription was a thin-from-below cut (removes small diameter trees from midstory and overstory leaving predominately larger diameter trees) based on slope. The intermediate slope (10% to 25%) prescription was marked to 18 to 23 m^2 ha^{-1} (80 to 100 ft^2 ac^{-1}) of basal area with 7.6 m (25 ft) spacing for 30 to 35 cm (12 to 14 in) trees, and the steep slope (26% to 43%) prescription was marked to 23 to 28 m^2 ha^{-1} (100 to 120 ft^2 ac^{-1}) basal area with 6 m (20 ft) spacing for 30 to 35 cm (12 to 14 in) trees. Cut trees were marked and there was no diameter cap. The slash treatment required scattering and cutting residual limbs to within 60 cm (24 in) of the ground surface. Study stand boundaries, other than the controls, were defined entirely by the silvicultural prescription. Fuel reduction and small diameter timber utilization were the primary objectives behind the treatment.

Following harvesting activities, runoff, infiltration, and sediment yield response variables were measured within three distinct surface disturbance classes: no disturbance control (outside of treatment boundary); light-moderate soil disturbance (soil cover $< 50\%$); and heavy soil disturbance (soil cover $\geq 50\%$). Disturbance classes were measured on intermediate slopes (10% to 25%) and on "steep" slopes (26% to 43%). Field work was conducted during the last two weeks of May 2005.

Surface disturbance within the treatment boundary was quantified using the step-point method (Evans and Love 1957). Origin of surface disturbance was characterized in three classes: undisturbed, disturbed by unknown source (e.g., falling tree, slash from delimbing process, grapple hook, etc.), or disturbed by harwarder tire. Within the latter class, disturbance was further characterized as follows: litter in place, mix of soil and litter cover, or soil only. Five hundred forty points were sampled along seven transect lines running perpendicular to the contour. Points were 3.5 m (11.5 ft) apart. Step-points were recorded as intermediate slope (10% to 25%) or steep slope (26% to 43%) accordingly.

We used a completely randomized design with eight replications of six treatments for a total of $n = 48$. Eight rainfall simulations per slope and disturbance class were used to compare and characterize runoff, infiltration, and sediment yield properties. Locations of rainfall simulation plots were randomly selected and conducted first at antecedent moisture conditions (hereafter referred to as "dry run") and 24 hours later at field capacity (hereafter referred to as "wet run"). Partitioning of plots into a particular disturbance class (e.g., light-moderate vs. heavy) was facilitated by the homogeneous litter cover across the stand (82% ± 2.7 se), (D. Cram, unpublished data) prior to harvesting. Rainfall simulation test runs were conducted to (1) determine consistent precipitation rates capable of producing runoff in one hour, (2) ensure equal precipitation rates among simulators, and (3) determine adequate intervals between dry and wet rainfall simulations to achieve field capacity. Although rainfall simulation studies are subject to some limitations, they are helpful tools for investigating hydrologic processes, particularly in arid regions (Wilcox et al. 1986). See Wilcox et al. (1986) for greater discussion of assumptions inherent with rainfall simulation. Portable rainfall simulators were modified after Wilcox et al. (1986). Four rainfall simulators were operated simultaneously. Light weight aluminum tri-pods were used to support jet nozzles (1/4 G10 Full Jet Nozzle from Spraying Systems Co., Wheaton, Illinois). Jets were leveled, centered above plot center, and positioned 175 cm (68.9 in) above the soil surface. Pressure gauges and valves were located adjacent to jets to allow precipitation rates to be adjusted as necessary. One m^2 (10.8 ft^2) steel rings (plots) with runoff trays flush with mineral surface and parallel to slope were pounded into the soil with as little disturbance as possible. Runoff trays funneled runoff and sediment yield into a down slope catchment bucket. Rainfall simulations lasted one hour. Precipitation and runoff were measured every five minutes from time zero (beginning of rainfall simulation) using two rain gauges per simulator and a graduated cylinder, respectively. Infiltration was calculated as the difference between precipitation and runoff. Following each rainfall simulation, the catchment bucket was vigorously agitated and a 1 l (1.1 qt) sediment sample was collected. Plots were covered with plastic for 24 hrs between dry and wet runs to achieve field capacity.

Plot slope (percent) was measured with a level and a ruler. Plot litter depth (centimeters) was measured at five equally spaced locations within each plot following wet runs. Plot surface cover was estimated in the following categories: grass, forb, litter, bare soil, and slash (live woody cover was estimated but not reported due to lack of noteworthy results). Percent cover for categorical groups was estimated using a cover value scale modified after Daubenmire (1959). To characterize plot soil properties, three 5 cm (2 in) soil cores were extracted adjacent to rainfall simulation plot rings. Soil samples were collected before running rainfall simulations. From these cores we calculated soil gravimetric moisture content (antecedent soil moisture), bulk density (from which to infer soil compaction), and texture using a LS230 (Beckman-Coulter, Fullerton, California) laser diffraction particle size analyzer.

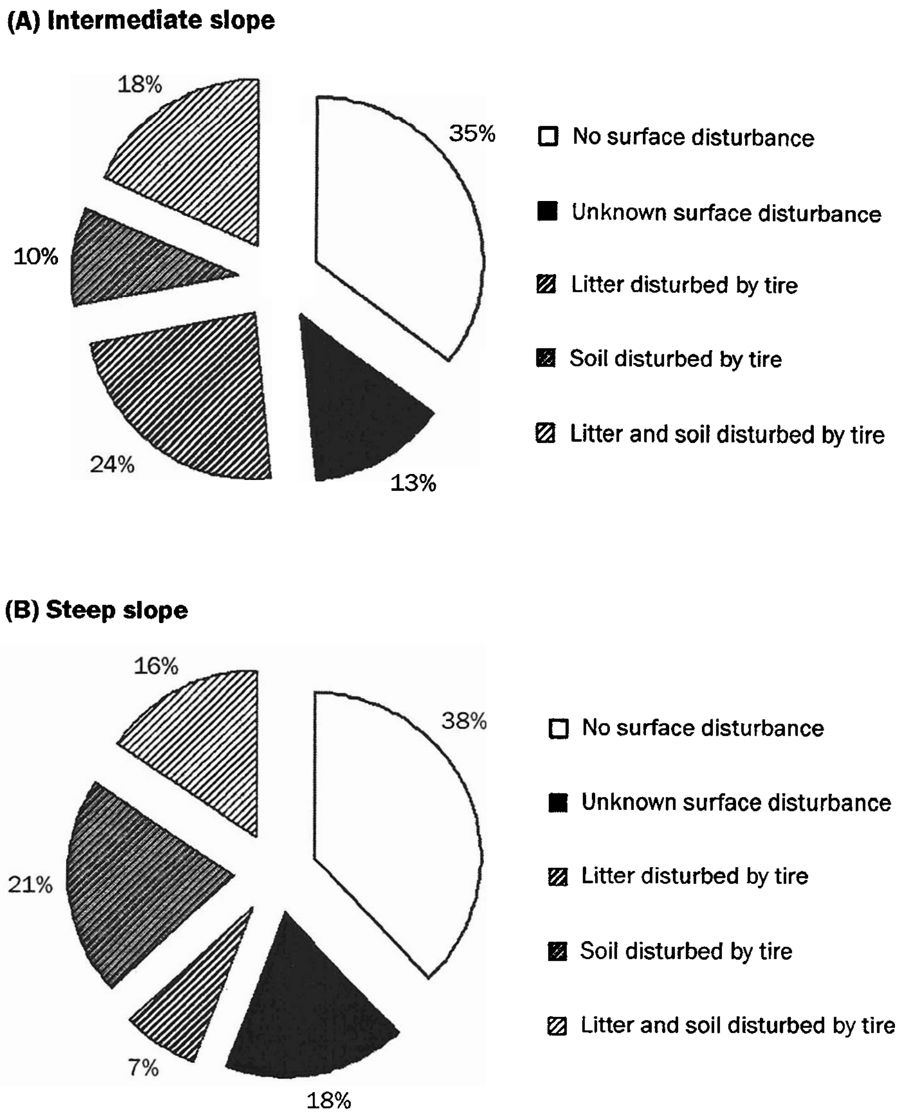
One-way analysis of variance was used to determine treatment differences between rainfall simulation means (Steel el al. 1997). Simulation means were tested for homogeneity of variance among treatments using Levene's test (Snedecor and Cochran 1980). In the presence of significant differences, we used multiple comparisons between means with the least significant difference (LSD) test with $P = 0.05$ (Steel et al. 1997). Repeated measures analyses for differences between dry and wet runs were tested using Proc Mixed. Analyses were conducted using SAS version 9.1 software (SAS Institute Inc. 2003).

Results and Discussion

On intermediate slopes, 35% of the step-points were undisturbed following harwarder activity (figure 2). Fifty-two percent of the step-points on intermediate slopes were disturbed by harwarder tire action (24% litter

Figure 2

Percent surface disturbance for (A) intermediate slope (10% to 25%, n = 310 points) and (B) steep slope (26% to 43%, n = 227).



Note: Slash cover was 27% on moderate slope and 37% on steep slope.

disturbed but not displaced, 10% bare soil exposed, and 18% mix of soil exposed with litter cover still in place). On steep slopes, 38% of the step-points were undisturbed. Of the 40% of step-points on steep slopes disturbed by harwarder tire action, 20% were bare soil. Unknown origin of surface disturbance on steep slopes amounted to 18%.

Results from the step-point method suggested intermediate and steep slopes had similar percent surface disturbances. Visual observation suggested there were differences in the spatial arrangement of surface disturbance types. Steep slopes had areas of heavy disturbance in the form of deep tire ruts. Deep tire ruts were perpendicular to the contour and resulted when the harwarder attempted to travel upslope. In contrast, intermediate slopes had little evidence of contiguous heavy disturbance areas (tire ruts or large patches of bare soil) but considerable evidence of litter disturbed by tire. On intermediate slopes, harwarder travel use appeared uniform across the stand. As slope increased, the harwarder operator was forced to use increased discretion in terms of travel use to minimize surface disturbance (tire ruts) and guard against roll-over (side-slope stability for a loaded forwarder is substantially less than upslope stability; i.e., 10% slope threshold vs. 40% slope threshold, respectively) (Bob Rummer, USDA Forest Service, personal communication, 2007). Harwarder surface disturbance was light-moderate when traveling down steep slopes.

At the rainfall simulation plot level, differences between heavy and light-moderate surface disturbance classes were characterized by comparing litter, bare soil, and slash cover (table 1). Heavy disturbance was characterized by a preponderance of bare soil cover (≥70%) and a scarcity of litter (≤26%) and slash cover (≤1%). Light-moderate disturbance was the opposite (litter cover ≥88%, bare soil cover ≤9%, and slash cover 13% to 44%) (table 1). A fourfold difference in litter depth between heavy and light-moderate disturbance further differentiated disturbance categories (table 1). No disturbance (control) plots and light-moderate disturbance plots were similar in cover and litter depth with the exception of slash cover (table 1).

The majority of surface disturbance was directly related to harwarder tire disturbance as a result of repeated travel, cornering, and use on steep slopes. Disturbance caused by harwarder felling, delimbing, and bucking timber appeared negligible.

Physical soil parameters between disturbance classes and slopes were similar. For example, soil bulk density ranged between 0.8 to 1.2 g cm^{-3} (50.3 to 75.1 lb ft^{-3}), and antecedent soil moisture ranged between 6.3% to 16.9% between disturbance classes (table 1). Field capacity (~30%) was only measured during pre-experimental rainfall simulation tests. Soil texture was also similar among disturbance classes. However, light-moderate and heavy disturbance classes on the steep slopes had less sand and greater clay as compared to the remaining disturbance classes. As a result, soil texture on these steeper slopes was classified as loam (table 1). Although technically classified as loam, soils from light-moderate and heavy disturbance classes on steep slopes fall directly on threshold lines between sandy loam and loam (following USDA system).

With no significant differences between soil parameters, rainfall simulation results between slopes and disturbance classes were comparable. Despite differences in harwarder travel use between control, light-moderate, and heavy disturbance classes, there was no increase in soil compaction (as inferred from

Table 1

Mean and standard error of slope, litter depth, gravimetric soil moisture, soil bulk density, soil texture, and understory cover by disturbance category on rainfall simulation plots in the Eagle Creek study site, Lincoln National Forest, Ruidoso, New Mexico, May 2005.

	Intermediate slope (10% to 25%)						Steep slope (26% to 43%)					
	Control		Light-moderate		Heavy		Control		Light-moderate		Heavy	
	$\bar{\chi}$	se	$\bar{\chi}$	se	$\bar{\chi}$	se	$\bar{\chi}$	se	$\bar{\chi}$	se	$\bar{\chi}$	se
Stand characteristic												
Slope (%)	19.1	0.8	17.8	0.8	17.6	0.9	35.3	1.2	38.9	1.3	35.4	1.5
Litter depth (cm)	3.6	0.5	4.4	0.4	1.0	0.3	3.9	0.4	4.1	0.6	0.1	<0.1
Gravimetric soil moisture (%)	6.3	0.9	12.0	0.9	16.9	3.0	9.9	1.4	9.3	1.4	11.2	2.0
Soil bulk density (g cm^{-3})	0.9	<0.1	1.2	<0.1	1.1	0.1	0.8	0.1	0.8	0.1	0.9	0.1
Soil texture												
Sand (%)	61.3	1.8	62.6	1.4	64.1	1.3	55.8	1.7	48.3	0.8	50.9	1.3
Silt (%)	34.3	1.7	30.8	1.2	29.8	1.3	38.9	1.4	43.4	0.8	39.1	1.3
Clay (%)	4.4	0.3	6.7	0.6	6.2	0.4	5.3	0.4	8.3	0.6	10.0	0.6
Texture	Sandy loam		Sandy loam		Sandy loam		Sandy loam		Loam		Loam	
Understory cover												
Grass (%)	0.2	0.2	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0
Forb (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.3	0.6	0.2	0.4	0.2
Bare soil (%)	1.6	1.0	1.2	0.4	69.7	8.8	1.1	0.6	9.1	7.6	92.8	2.3
Litter (%)	94.4	2.1	95.9	1.6	25.8	4.7	97.5	0.0	88.4	7.4	7.5	1.7
Slash (%)	NA	NA	12.5	4.4	1.1	0.4	NA	NA	44.2	14.9	0.5	0.3

soil bulk density results). Large tires help distribute the weight of heavy machinery on soil surfaces (Stenzel et al. 1985).

Precipitation, intended to be applied at the same rate, showed unexplained variation (table 2). As a result of the inconsistency in rainfall, runoff and infiltration were reported as a ratio to rainfall. Sediment yield was reported as a concentration (grams per liter) for the same reason.

There was no significant difference in runoff ratio between control and light-moderate disturbance plots, regardless of slope (table 2). Runoff ratio was greatest on the heavy disturbance plots for both dry and wet runs, regardless of slope. Runoff ratio between dry and wet runs did not significantly change on control or light-moderate disturbance, regardless of slope. However, runoff ratio on heavy disturbance plots was 7 times greater on wet runs as compared to dry runs.

Infiltration ratio was inversely related to runoff ratio (table 2). Infiltration was lower on heavy disturbance sites as compared to light-moderate and control disturbance sites. There was no difference in infiltration ratio between control and light-moderate disturbance classes, regardless of slope. Infiltration ratio between dry and wet runs did not significantly statistically change on control or light-moderate disturbance, regardless of slope. However, infiltration ratio on heavy disturbance plots decreased on wet run rainfall simulations due to field capacity conditions.

Severity of litter and soil disturbance influenced runoff and infiltration ratios (table 2). This circumstance may be of particular interest to land managers writing forest management prescriptions. For example, concerns about overland flow following mechanical treatment could be proactively mitigated with specific instructions and precautions aimed at reducing surface disturbance. Further, surface remediation immediately following mechanical disturbance such as scattering slash, straw mulching, and erosion control blankets would reduce runoff (Robichaud et al. 2005).

Sediment concentrations for heavy disturbance plots on steep slopes (7.3 g L^{-1} [7,300 ppm] dry run, 3.8 g L^{-1} [3,800 ppm] wet run) were more than one order of magnitude greater than all other disturbance classes (table 2). Sediment concentration for heavy disturbance plots on intermediate slopes was greater (3.8×) than light-moderate disturbance classes, although not as conspicuous as the same comparison on steep slopes (22×). Regardless of slope, there was no difference in sediment concentration between control and light-moderate disturbance classes. There were no statistically significant differences on intermediate slopes between dry and wet runs in terms of sediment concentration. On steep slopes, there was a decrease in sediment concentration between dry and wet runs for control and light-moderate disturbance plots, but as a result of the magnitude in variance there was not a statistically significant difference on heavy disturbance plots.

The significant increase in sediment concentration levels on heavy disturbance plots with steep slopes was salient. However, from a management standpoint, the lack of difference in sediment concentration between control and light-moderate disturbance regardless of slope may be of more interest. Data suggest if surface disturbance is minimized, regardless of slope, sedimentation levels following harwarder disturbance would not exceed background levels. However, there are two caveats: (1) Rainfall simulations did not represent erosion characteristics immediately following harvest operations (5.5 months elapsed). Although precipitation during the interim spring was below long term averages (WRCC 2006), it is likely snowmelt in combination with

Table 2

Mean and standard error of total precipitation, runoff ratio, infiltration ratio, and sediment concentration by disturbance category for dry and wet runs on rainfall simulation plots in the Eagle Creek Study Site, Lincoln National Forest, Ruidoso, New Mexico, May 2005.

	Intermediate slope (10% to 25%)			Steep slope (26% to 43%)			
	Control	Light-moderate	Heavy	Control	Light-moderate	Heavy	
Stand characteristic	$\bar{\chi}$ se	$\bar{\chi}$ se	$\bar{\chi}$ se	$\bar{\chi}$ se	$\bar{\chi}$ se	$\bar{\chi}$ se	*P > F*
Dry run							
Total precipitation (cm)	23 ab 2.6	18 b 1.9	21 ab 1.7	21 ab 1.7	18 b 1.4	26 a 3.0	0.0393
Runoff ratio (cm)	0.02 b <0.1	0.01 b <0.1	0.05 a <0.1	0.01 b <0.1	0.01 b <0.1	0.04 a <0.1	<0.0001
Infiltration ratio (cm)	0.98 a <0.1	0.99 a <0.1	0.95 b <0.1	0.99 a <0.1	0.99 a <0.1	0.96 b <0.1	<0.0001
Sediment concentration (g L^{-1})	0.11 b <0.1	0.11 b <0.1	0.42 b 0.1	0.29 b 0.1	0.33 b 0.1	7.29 a 2.7	0.0002
Wet run							
Total precipitation (cm)	23 ab 2.5	18 bc 1.8	20 bc 1.7	20 bc 1.1	17 c 1.3	28 a 2.8	0.0020
Runoff ratio (cm)	0.05 c <0.1	0.06 c <0.1	0.39 a <0.1	0.07 c <0.1	0.05 c <0.1	0.29 b <0.1	<0.0001
Infiltration ratio (cm)	0.95 a <0.1	0.94 a <0.1	0.61 c <0.1	0.93 a <0.1	0.95 a <0.1	0.71 b <0.1	<0.0001
Sediment concentration (g L^{-1})	0.06 b <0.1	0.06 b <0.1	0.97 b 0.4	0.05 b <0.1	0.13 b 0.1	3.77 a 1.2	<0.0001

Note: Row means followed by the same letter (abc) were not different at the 0.05 level (least significant difference test).

interim precipitation had an effect on runoff, infiltration, and sediment yield properties. (2) On steep slopes mechanical equipment can cause heavy disturbance and must be operated with care.

Solutions to minimizing heavy disturbance by mechanical equipment should be considered. For example, the heavy disturbance we observed and recorded on steep slopes appeared to be directly correlated with slopes ≥ 30%. As slope increased above 30% on our study sites, deep tire rutting appeared to be inevitable (given specific equipment and soil type). However, operators of heavy mechanical equipment could perform test runs on slopes and soil types to determine the rutting threshold and subsequently avoid such slopes and soil types.

The occurrence of severe disturbance in the study may also be the result of this particular machine configuration. The TimberPro TF 820-E is a large machine that can also carry a heavy payload. If payload is reduced, this may increase disturbance due to increased stand entry. However, lighter versions of similar equipment may not be as likely to create ruts. Special adaptations such as tracks can be installed over the tires which help reduce rutting on soft soils.

Although avoidance of soil disturbance is frequently a priority in harvest operations, absolute avoidance may not always be possible or desirable. Consider the following arguments: (1) some degree of surface disturbance (excluding deep, compacted ruts) may be beneficial or even necessary for seed bed preparation. In order to promote a subsequent herbaceous response, disturbance or removal of the antecedent litter layer may be required (Cooper 1960). Emergence and establishment of herbaceous cover will promote increased infiltration (Dunne and Leopold 1978), and offset a short term increase in runoff and erosion (Stednick 2000). (2) Although exposed soil is subject to runoff and erosion, the confluence of adjacent litter and slash piles will help slow runoff and promote infiltration. (3) If isolated heavy soil disturbance is deemed necessary depending on circumstance, soil reclamation work can be effective (Robichaud et al. 2005). Scattering slash, straw mulching, and erosion control blankets can cover exposed mineral soil resulting in increased infiltration, and reduced runoff and sedimentation (Robichaud et al. 2005). A 50% cover of Douglas-fir needles reduced interrill erosion by 80% and rill erosion by 20% (Pannkuk and Robichaud 2003).

Where heavy soil disturbance is not acceptable, for example where exotic or invasive plant introductions are of concern, hand crews could be utilized. Hand crews might also be a less invasive method to manipulate and scatter slash fuels in order to satisfy slash prescriptions. Intensive micro-use of heavy machinery in order to evenly spread slash with a grapple hook could potentially decrease efficiency and increase disturbance.

Reduced travel could also result in increased efficiency and savings in terms of wear and tear on equipment and fuel expenses (see Klepac and Rummer 2005 for an efficiency and economic analysis of the TimberPro 820E conducted in the same area as this study). The harwarder in this study was equipped with a telescoping boom that extended the operating reach of the machine. Personal observation of the harwarder in action suggested the extension boom was not utilized to its maximum potential. Ideally, the extension boom could be better utilized to increase the radius of operation, thereby reducing travel distance and tire disturbance.

Timber harvest and fuel reduction treatments have been shown to reduce wildfire severity (Cram et al. 2006). Erosion and sedimentation following severe wildfires can lead to altered or destroyed wildlife habitat, altered soil hydrology, and loss of duff, litter, and vegetation layers exposing soil to rapid erosion events which in turn overwhelm riparian areas, streams, and rivers (Campbell et al. 1977). Using an erosion prediction model by Elliot and Miller (2002) the USDA Forest Service (2005) found sedimentation following wildland fire to be 70 times greater as compared to a thinning treatment. The model predicted a wildfire on an intermediate slope would yield 9.5 MT ha^{-1} (2,729 T mi^{-2}) of sediment. This is 353 times greater than our highest sediment yield. Although the study did not provide quantitative details about the simulation (e.g., % slope, precipitation characteristics), the magnitude of the effect was clear.

Summary and Conclusions

Percent slope affected harwarder travel-use patterns within a forest stand. Although overall percent surface disturbance caused by the harwarder was similar between steep and intermediate slopes, travel use on steep slopes often resulted in heavy disturbance in the form of tire ruts, whereas harwarder use on intermediate slopes often resulted in disturbed litter but no exposure of bare soil. Results indicated increasing levels of surface disturbance, particularly where bare soil was exposed, had the greatest influence on runoff and sedimentation. Steep slopes with exposed mineral soil exhibited a fourfold increase in runoff and a 22 fold increase in sedimentation. However, steep slopes with light-moderate disturbance did not result in increased runoff or sedimentation over non-disturbed sites.

Significantly, the results of this study indicated light to moderate disturbance from mechanical operations did. not significantly increase erosion over undisturbed control areas, even on steeper slopes. These results suggest, given similar vegetation cover types and soils, forest prescription guidelines and on-site priorities be focused on not necessarily avoiding all traffic but rather on minimizing severe surface disturbance particularly on steep slopes. In particular, minimizing disturbance implies reducing large areas of exposed bare soil. Where soil becomes exposed, mulching or spreading slash is recommended. It could be argued when considering sedimentation, minimizing disturbance is the higher priority when establishing management prescriptions as opposed to abandoning stands based only on steep slope concerns. Steep slopes require operator discretion in terms of travel-use patterns. Advances in mechanical equipment such as flotation tires and tracks, as well as modern practices such as forwarding may continue to decrease soil disturbance in mechanically treated stands.

Acknowledgements

This research was supported by the Forest Operations Research Unit, USDA Forest Service, the Rocky Mountain Research Station, and New Mexico State University. The authors wish to thank Nick Ashcroft, Alfonso Islas, Adam Lujan, Jared Lujan, Clay Mason, Glenn Mason, Carlos Ochoa, and Kyle Tator for their invaluable help and assistance. We also thank the Smokey Bear Ranger District for providing water for rainfall simulations. We thank the three anonymous reviewers for helpful comments on an earlier version of the manuscript.

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