RUNOFF AND EROSION FROM HYDROPHOBIC FOREST SOILS DURING SIMULATED RAINFALL

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Soil loss from forest lands involves several complex infiltration and soil particle detachment processes that produce soil materials that are easily transported off-site by surface and rill erosion. Surface soils are exposed to a wide range of external variables that affect erosion, including rainfall, slope, land use, and vegetation. These interact with internal soil properties to determine the amount of soil lost from any particular forest site. *Soil erodibility* is defined as the relative difference in soil loss between soils when all of the external variables are identical (Trott 1982). It is controlled by several internal physical and chemical properties. Physical soil properties that affect erodibility are infiltration capacity, the rate and amount of runoff, the cohesiveness of soil aggregates when subjected to raindrop impact (detachability and aggregate stability), and the transportability of different-sized soil particles during runoff. Chemical factors include the amount and kind of organic matter and absorbed cations.

Another important soil property that affects infiltration into forest soils is *water repellency*, which has been found under a wide range of plant cover, climate, and geological settings worldwide (DeBano 1981; Wallis and Horne 1992; Dekker and Ritsema 1994). Water repellency often occurs at, or near, the soil surface and can be easily detected by placing a water droplet on a dry soil sample. If the water balls up on initial contact with the soil and forms a spherical droplet rather than quickly penetrating, the soil is considered water repellent (DeBano 1981; Dekker and Ritsema 1994). Dry wettable soil usually absorbs water readily because there is a strong attraction between the mineral soil particles and water.

Although it is intuitively obvious that water repellency contributes to runoff and erosion, it has been difficult to quantify this effect using watershed and plot studies because of several factors: a wide variance in the initial degree of severity of the water repellency, the temporal change in initial water repellency after being exposed to water, and the highly irregular distribution of water repellency throughout the soil profile, particularly in forest soils. Organic matter is the source of hydrophobic substances that produce water repellency. Water repellency is produced in unburned environments by microbial processes during the decomposition of organic matter. When organic matter is burned during a fire, hydrophobic substances are volatilized, move downward, and condense on mineral soil particles to produce an "extremely water repellent soil" that in some cases can resist water penetration completely (DeBano 1981). Because water repellency is produced during organic matter decomposition (either slowly by microbial activity or rapidly by fire during combustion), the distribution of water repellency is concentrated under plant canopies, with its spatial distribution throughout the landscape paralleling that of plant cover.

One important technique for gathering information about the hydrologic responses on natural and disturbed lands is using rainfall simulators (Renard 1985; Ward and Bolin 1989). A rotating-boom rainfall simulator has been used widely during the past two to three decades for validating runoff and erosion models developed as part of the Water Erosion Prediction Program (WEPP; USDA 1987). As part of this validation effort and a more general research interest in soil erodibility, study sites on three forested watersheds were subjected to simulated rainfall during a cooperative study between the Rocky Mountain Research Station and the California Division of Forestry. Dry, wet, and very wet simulation trials were applied to soils on these study sites. Soils at all three locations were found to be water repellent. This paper reports data on runoff and sediment responses during the wet rainfall simulation trials, and the cumulative responses over the dry, wet, and very wet rainfall simulator trials. It also pre-

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sents and discusses previous information on the erodibility of these forest soils.

Description of the Study Area

Rotating rainfall simulator trials were conducted on four study sites at three locations in central California: one site on the Tahoe National Forest about 13 km east of the small community of Foresthill (FH) northeast of Auburn, two sites on the Challenge Experimental Forest (CEF) in the Plumas National Forest near the community of Challenge, and a fourth site on the Sierra National Forest (SNF) about 13 km northeast of the community of Oakhurst. Rainfall simulation was applied to 6 plots at each site, for a total of 24 plots.

All four study sites are located in the mixed conifer or transition life zone of the west side of the Sierra Nevada. The general climate at these study areas is typical Mediterranean, having mild, moist winters and hot, dry summers. July and August usually receive less than 25 mm of precipitation per month (USDA 1965). However, because of their elevation (600 to 2400 m), these sites received annual precipitation ranging from 700 to more than 1700 mm, with snow (depending on the elevation) remaining on the ground for several months each winter.

The CEF study is at an elevation of 790 m on the Plumas National Forest. Mean annual precipitation is 1700 mm, of which 98 percent falls between October and May (USDA 1990). The FH site is at 1500 m on the Tahoe National Forest. Annual precipitation is 1320 mm. The experimental site on the SNF is located at an elevation of 1680 m with an annual precipitation range of 760–1000 mm.

Six study plots on each of two CEF sites were located on soils that are presently mapped as Aiken, although they are more similar to the Sites series (Aiken/Sites is used to designate this soil series). The Aiken/Sites soils are deep to very deep, well-drained soils that are formed in material weathered from metasedimentary rocks and have a loam to clay, loam surface texture. The Aiken/Sites soil is classified as a clayey, oxidic, mesic family of Xeric Haplohumults.

An additional six study plots at the FH site were located on the McCarthy soil series, which is widely distributed in the northern Sierra Nevada. McCarthy soils are moderately deep over volcanic mudflow parent materials, have a fine sandy loam texture, and are classified as a medial-skeletal, mesic family of Andic Xerumbrepts.

Six simulation plots on the SNF site were on the Dome soil series. These soils developed from granitic parent materials and exceed 100 cm in depth. Dome soils have a coarse, sandy, loam surface texture and are classified as a coarse loamy, mixed, mesic family of Dystric Xerochrepts.

Methods

A rotating-boom rainfall simulator with 30 spray nozzles (Swanson 1965) was used to simulate rainfall on two 3 X 10 m paired plots simultaneously. The nozzles sprayed downward from an average height of 2.4 m, with rainfall intensities of about 60 or 125 mm/hr, which produced drop-sized distributions and energies similar to natural rainfall (Simanton et al. 1985). Three separate rainfall simulator trials (dry, wet, and very wet) were made on a pair of plots following the procedure described by Simanton et al. (1989). The plots were pre-wetted to field capacity soil moisture conditions using a 60-minute rainfall simulation (60 mm/hr), designated as a dry run. This dry run was used to assure uniform soil water contents prior to the wet run, which was applied 24 hours later and consisted of a 30-minute rainfall application (60 mm/hr). A very wet run was made 30 minutes after the wet run using nominal rainfall intensities of both 60 and 125 mm/hr. The very wet run was used to stress the systems and to provide information on how the important hydrologic processes in saturated soils responded to different rain intensities. Only the runoff and sediment response during the wet simulator trials and the cumulative response over all three trials are reported in this paper. During each simulator trial, runoff and sediment delivery were measured continuously at the bottom of the plots.

All plots on the forest sites had been disturbed extensively by prior logging and site preparation required for reforestation. Site preparation included slash removal by hand, soil ripping, and slash burning. Slash was removed from the CEF sites (Aiken/Sites soil series) with minimal disturbance to the mineral soil. Soil ripping at the FH site (McCarthy soil series) was done by running a 0.6 m tooth attached to a crawler tractor through the soil to reduce compaction and improve infiltration. Slash at the SNF site (Dome soil series) was removed by using prescribed fire. Runoff and soil loss from simulated rainfall could not be determined on the natural or undisturbed forest floor because the standing trees prevented use of the simulator.

Water repellency was determined on five to seven samples of the field soil collected at each site using the water drop penetration time (WDPT).

The average WDPT was 126 seconds for the Aiken/Sites series, 95 seconds for Dome soil, and 2220 seconds for the McCarthy series. The water repellency of the McCarthy series measured during these tests was several times greater than reported earlier (Trott 1982). Although the source of the water repellency is not known, it likely occurred because of large amounts of soil organic matter, from previous wildfires, or from the use of prescribed burning for slash treatment on the Dome site.

Hydrologic response parameters analyzed were total runoff (mm) and total sediment loss (kg/ha/mm). Treatment effects on the runoff and sediment production were analyzed using standard analysis of variance techniques. Multiple comparisons of means were made by the Welch test at the .10 level of significance using Dunnett's T3 procedure (Dunnett 1980).

Results and Discussion

There were differences in hydrologic responses among the three soils. Water repellency, soil erodibility, cultural treatments, and soil type affected the different hydrologic responses discussed below, but the responses were confounded among these four factors.

Runoff

The amount of runoff (mm) was significantly less during the wet simulator trials from plots having the Aiken/Sites soil compared to those plots having either the Dome or the McCarthy soils (Table 1). The runoff responses during the wet simulator trials for the McCarthy and Dome soils were consistent with runoff patterns expected on sites having a water-repellent soil condition (i.e. infiltration was relatively slow and runoff was initiated soon after the beginning of each rainfall simulator trial).

Table 1. Mean comparisons of runoff (mm) and soil loss (kg/ha/mm) during a wet rainfall simulator trial for three forest soils in California.

Soil Series	Runoff (mm)	Soil Loss (kg/ha/mm)
Aiken/Sites (Logged and slash removed)	7a[1]	405a
Dome (Logged and slash burned)	15b	712a
McCarthy (Logged and ripped)	16b	336a

[1]Any two means in the same column with different letters are significantly different at the 0.10 level of probability as determined by the Welch test.

The runoff rates from plots having Dome and McCarthy soils during the wet simulator trials were related to cultural treatment. The cultural treatments that disturbed the soil surface most (burning and ripping) produced more than twice as much runoff as the plots where logging slash was carefully removed from the site (Table 1). The McCarthy soil had been ripped with heavy equipment, which would be expected to disrupt any hydrophobic condition present, thereby increasing infiltration and reducing surface runoff. Although the ripping may have decreased the continuity of the water-repellent layer in the McCarthy soil, this soil still had large amounts of runoff during the wet simulator trials (Table 1). The Dome soil also produced significantly more runoff than the wettable Aiken/Sites soil. This most likely occurred because prescribed fire was used to treat the slash remaining after timber harvesting. Burning could potentially not only destroy surface soil structure (aggregation) but also intensify any pre-fire water repellency present in the underlying soil.

The differences in runoff present during the wet simulator trials were not present when the cumulative runoffs for the dry, wet, and very wet trials were compared (Table 2). The differences in total runoff from the three soils during the three runs were not significant.

Soil Losses

Soil losses (kg/ha/mm) during rainfall simulation varied among the three soil series, but were not significantly different during the wet simulator trials (Table 1). When the total erosion from the three soils during the dry, wet, and very wet trials were compared, however, the Dome soil series was clearly the most erodible of the three soils, and it was statistically different from the other two soils (Table 2).

The increased hydrophobicity in the Dome soil produced during the prescribed burning of slash, along with the destruction of surface soil structure, could explain the higher rates of erosion from this soil. Large soil losses from the Dome soil were attributed to the extensive rill erosion that was observed during the rainfall simulation trials. Rill formation is an important component in the erosion of water repellent soils formed during fire

Table 2. Average total runoff and soil loss from forested soils after two days of rainfall simulation (combined dry, wet, and very wet trials).

Soil	Plots	Treatment	Runoff (mm)	Soil Loss (kg/ha/mm)
Aiken/ Sites	6	Logged and slash cleared	37a	498a[1]
Dome	6	Logged and burned	48a	832b
McCarthy	5	Logged and ripped	63a	432a

[1]Any two means in the same column with different letters are significantly different at the 0.10 level of probability as determined by the Welch test.

(Wells 1987). Rills began to form within 15 minutes of rainfall initiation during the dry run on the Dome soil plots, and quickly became uniformly distributed from top to bottom over most of the plots. Some of the rills were as much as 10 cm deep and wide. Rills also formed on the McCarthy soil plots. However, the rills were less extensive and not as deep or wide as on the Dome soil. Little rilling occurred on the Aiken/Sites soil.

Soil Detachability and Erodibility

These results agree with the current understanding of soil detachment and erosion. The initiation of soil loss by erosion during rainfall involves soil particle detachment and the subsequent entrainment and transport of these detached particles by overland flow. Soil detachability is dependent on soil constituents that promote cohesiveness, the same properties that contribute to aggregation, structural stability, and water repellency. In general, soils having a coarse texture, or having a large amount of relatively undecomposed organic matter, are most easily detached by raindrop splash (Trott 1982) because they possess little structural (aggregate) stability.

Soil particles that are not readily detached are also not easily transported until they are first detached by raindrop splash. Furthermore, if soil particles are not readily transported in runoff, their detachability is unimportant, except to the extent that soil particles or aggregates are moved downhill by raindrop splash. An examination of the runoff and erosion responses of the Dome and the McCarthy soils (Tables 1 and 2) shows that particle detachment and subsequent transport are more important in the Dome soil.

Erodibility of the McCarthy soil appears to be influenced by its transportability, as indicated by its moderately high runoff concentration in Trott's study (1982) and the high runoff production measured during this study. Because the McCarthy soil has a sandy loam texture, the larger sand particles would resist transport, although particle detachment during raindrop splash would occur. However, this soil contains more than 20 percent relatively undecomposed organic material of low density, which is highly transportable, and the soil is also derived from volcanic ash, a material of relatively low particle density (2.20 g/cm^3; Trott 1982). The initial low infiltration capacity and low particle density seem to be major factors contributing to soil detachment and sediment transport in the McCarthy soil.

The Dome soil is classified as a coarse, sandy loam, which should make it more sensitive to particle detachment by raindrop splash, particularly on the areas where burning could have destroyed the structure of the soil surface. The decreased infiltration resulting from water repellency probably contributed to surface runoff and the initiation of an extensive rill network, which transported large amounts of sediment off the plot during all three rainfall simulator trials (dry, wet, and very wet).

The surface texture of the Aiken/Sites soil was classified as a loam to clay loam, which was the finest surface texture of the three soils studied. The finer texture apparently enhanced particle stability to raindrop splash. Because of its finer particle content, this soil was not considered "transport limited" in a separate laboratory experiment (Trott 1982). However, it was considered "detachment limited" because of the cohesiveness and aggregation imparted by the presence of clay and iron oxide binding agents. As a result, erosion by rilling played only a relatively minor role in the erosion processes affecting this soil, as was previously reported (Savabi and Gifford 1989). The careful removal of slash, and the absence of burning, left a relatively undisturbed soil surface having a higher infiltration capacity that was less susceptible to raindrop splash. Although this soil was water repellent, a relatively high infiltration capacity and stable surface aggregates mitigated its resistance to wetting.

Trott (1982) determined the relative erodibility for 20 California soils using laboratory rainfall simulation. Many of the soils placed in his lower erodibility groups are either coarse, sandy loams or loamy sands, or contain high levels of organic matter; this is in agreement with the findings of Wischmeier and Mannering (1969). The Dome and

McCarthy soils fit into this category. Other soils included in this low erodibility group are soils high in iron and aluminum, such as the Aiken/ Sites soil.

A comprehensive analysis of soil erosion must include evaluations of rill erosion. Particle movement by rill erosion becomes important when surface runoff has been initiated and concentrated overland flow begins. This occurred most notably in the Dome soil, although soil rilling also influenced the erodibility of the McCarthy soil to a lesser extent. Soil loss has been shown to increase three to five times when rills develop (Meyer et al. 1975) and significant differences can occur depending on the type of rill formation (Govindaraju and Kavvas 1992).

Conclusions

The runoff and erosion from three forest soils subjected to rainfall simulation trials were influenced by the interactions among soil erodibility properties, water repellency, cultural treatment (prescribed fire or mechanical treatment), and soil type. The following conclusions were made:

- Forest soils subjected to substantial surface disturbance during slash disposal (soil ripping and slash burning) following logging yielded greater amounts of runoff than soils where slash was carefully removed and disturbance to the soil surface was minimized. These differences occurred only during wet rainfall simulator trials, but disappeared when total runoff during the dry, wet, and very wet trials were compared.
- Higher rates of accelerated surface erosion occurred, particularly when surface rilling developed. Extensive surface rilling on the Dome soil produced significantly greater soil loss than from Aiken/Sites or McCarthy soils during the combined dry, wet, and very wet rainfall simulator trials.
- The detachability and transportability of soil particles during runoff and erosion depended on particle size, aggregate stability, and cultural treatment.

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