The Effects of Forest Management on Erosion and Soil Productivity

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Introduction

For many years, research has been ongoing to relate soil erosion to productivity. Most research has focused on agricultural or rangeland conditions. Pierce (1991) presents an overview including over 60 references summarizing past research on impacts of erosion on agricultural production. He concluded that exact relationships between erosion and productivity are unclear, and considerable research is necessary over a wide range of soil and plant conditions to define any such relationship. Research on the effects of soil erosion on forest productivity is limited. This paper will provide an overview of current knowledge on the effects of forest management on soil erosion, and related onsite impacts, and the effects of those impacts on forest productivity.

Soil erosion in an undisturbed forest is extremely low, generally under 1 t ha^{-1} yr^{-1}. Disturbances, however, can dramatically increase soil erosion to levels exceeding 100 t ha^{-1} yr^{-1}. These disturbances include natural events such as wild fires and mass movements, and human-induced disturbances such as road construction and timber harvesting. Soil erosion, combined with other impacts from forest disturbance, such as soil compaction, can reduce forest sustainability and soil productivity. Research is ongoing to quantify the effects of disturbance on soil erosion and soil productivity.

Forest Practices

Soil erosion in forests generally follows a disturbance, such as road construction , logging operations, or fire. In undisturbed forests, erosion is generally due to epochal events associated with fire cycles, land slides, and geologic gully incision.

Ground cover by forest litter, duff and organic material is the most important component of the forest environment for protecting the mineral soil from erosion and provides most of the nutrients needed for sustainable forestry. Ground cover amounts can be reduced by the logging operation (harvesting and site preparation) and burning either by wildfire or prescribed fire. For example, skidder traffic on skid trails can reduce ground cover from 100 to 10-65 percent. Burning can reduce ground cover from 100 percent to 10-90 percent depending on the fire severity.

Roads

In most managed forest watersheds, most eroded sediment comes from roads. Roads have no vegetative protection, and tend to have low hydraulic conductivities leading to much greater runoff and erosion rates than in the surrounding forests (Elliot et al., 1994a). Numerous researchers, including Swift (1988) and Bilby et al. (1989), have quantified the major role of roads on sedimentation in forests. In addition to erosion, roads also reduce forest productivity by the land that they occupy. A kilometer of road in 1 km^2 of forest represents a 0.5 percent loss in area and removal from productivity. In some areas, forest roads can occupy up to 10 percent of the forest area if there is a past history of intensive logging. Roads are assumed to be unproductive in forest plans, regardless of any erosion impacts.

Currently, the USDA Forest Service has a major program to close roads. Closure methods can vary from locking a gate to completely removing the road prism in an effort to reduce sedimentation and related hydrologic problems. The productivity of closed or removed roads has not been directly measured, but frequently, additional mitigation measures such as ripping and replanting are included in any closure scenario to encourage maximum regrowth rates (Moll, 1996).

Timber Management

Traditionally, forest management practices focus on fire suppression and clear-cut logging methods. With an increased understanding of forest ecosystems, the USDA Forest Service is applying ecosystem management principles to forest management. These principles include partial cut management systems and increased use of prescribed fires. Such practices, however, require more frequent operations in the forest environment.

Harvesting Effects

Harvesting methods vary in degree of disturbance. On steeper slopes (generally > 35 percent slope) helicopter, skyline, or ground-cable logging systems are common. Trees are felled and removed with full suspension of logs via a helicopter or cable system and carried to landing sites. With a ground cable system, one end of the log is suspended and the other end is slid on the ground to a landing area. On less steep slopes (generally < 35 percent slope), wheeled or tracked forwarders or skidders remove felled trees. A forwarder loads and carries trees to a landing area in one operation, or a skidder drags the logs to the landing generally on designated skid trails. Skid trails cause the most disturbance by displacing the ground cover and compacting the mineral soil. Additional disturbance is caused by skidder tires loosening the soil, especially on slopes of 20-35 percent.

Even though timber harvest operations usually cause less erosion per unit area than roads, the area of timber harvest is usually large relative to roads so that the total erosion from timber harvest operations may approach that from roads (Megahan 1986). Tree cutting by itself does not cause significant erosion, although the resulting decrease in evapotranspiration contributes to increased subsurface flow, streamflow and channel erosion. However, soil disturbance caused by the harvesting operation results in reduced infiltration capacities and increased surface runoff which promotes surface erosion (Yoho 1980). Accelerated erosion caused by timber harvesting activity may result in deterioration of soil physical properties, nutrient loss, and degraded stream water quality from sediment, herbicides and plant nutrient inputs. (Douglas and Goodwin 1980).

Nutrient Impacts

Harvesting trees removes nutrients from a generally nutrient deficient environment (Miller et al., 1989). Table 1 shows the effect of tree harvest on nitrogen availability. Increasing harvest intensity from bole only through whole tree and complete biomass harvesting doubled nitrogen loss on the average quality site, but more than tripled loss at the poor quality site. Leaching losses are also greater on the poorer site. Researchers generally agree that harvesting the bole only will not greatly deplete nutrient reserves, but shorter rotations and whole tree harvesting removes more nutrients than can be replaced in a rotation. Harvesting crowns is undesirable because they contain a large portion of the stand nutrient content.

Fire Effects

The most common method of site preparation in the U.S. is prescribed burning. Although mechanical methods are commonly used in southern forests to physically destroy or remove unwanted vegetation from the site and to facilitate machine planting. Burning is conducted alone, and in combination with other treatments, to dispose of slash, reduce the risk of insects and fire hazards, prepare seedbeds, and suppress plant competition for natural and artificial regeneration. Current research is finding that fire helps maintain forest health. Fire has long been a natural component of forests ecosystems (Agee 1993). The use of prescribed fire will increase as ecosystem management strategies include a greater use of fire, and fewer clearcuts, and more partial cuts.

Erosion following fires can vary from extensive to minimal, depending on the fire severity and areal extent (Robichaud and Waldrop, 1994). Fire severity refers to the effect of the fire on some component of the forest ecosystem, such as nutrient loss or amount of organic material consumed (litter and duff). Erosion from high severity fires can be cover large areas.

and. fires may create hydrophobic or water repellent conditions. Erosion from low severity fires may be minimal to none (Robichaud et al. 1993b; Robichaud and Waldrop 1994).

Erosion Modeling

Since the late 1950s, soil erosion models have provided natural resource managers with tools to predict the impacts of management practices on soil erosion. Earlier models tended to focus on midwest and southeast agricultural conditions where erosion was considered to be a severe problem associated with farming practices. Models for range lands and forest lands have only recently been receiving wide-spread interest as managers have begun to focus as much on off-site sediment impacts as on onsite erosion rates.

Sediment Yield Models

Most of the early models, which culminated in the Universal Soil Loss Equation (USLE), focused on upland soil erosion rates (Wischmeier and Smith, 1978). The USLE was developed to predict soil erosion from small, relatively homogenous plots (Mutchler et al., 1994). Forest environments tend to have much greater spatial variability in vegetation and soils (Elliot et al., 1996), making the application of the USLE difficult. Dissmeyer and Foster (1985) developed a subfactor approach to predict soil erosion from forest conditions for areas where intensive operations such as tillage are carried out, and harvest areas can be considered similar to intensively managed farming systems. The erosion-productivity impact calculator (EPIC) model was developed to apply the USLE prediction technology to long-term productivity impact predictions (Williams et al., 1984). The EPIC model, however, was developed for applications to croplands only.

Forest service specialists have developed watershed models to aid in predicting the cumulative effects of road and harvest area erosion on stream sedimentation (like WATSED, Range, Air, Watershed and Ecology Staff Unit, 1991). The strength of these models is in allowing assessment of cumulative effects on stream sedimentation in a large watershed. WATSED, however, was not developed to predict site-specific effects.

More recent physically-based soil erosion models, including the Chemicals Runoff and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980) and the Water Erosion Prediction Project (WEPP) model (Laflen et al., 1991) have also provided estimates of sedimentation for predicting both onsite and offsite impacts. The WEPP model, in particular, has shown considerable promise as a tool to assist in predicting soil erosion and sediment yields in a forest environment (Elliot et al., 1996).

The physically-based WEPP model allows predicting upland erosion and offsite effects from erosion events influenced by management activities (Laflen et al., 1991). Erodibility values have been measured on forest roads and disturbed harvest areas, and validation activities with the WEPP model for forests have been encouraging (Elliot et al., 1994). The WEPP model not only predicts erosion, but also predicts the textural and organic composition of the eroded sediment.

Productivity Response to Management

A coordinated national research effort is being implemented on a broad spectrum of benchmark sites across the nation (Powers et al., 1990). These sites were relatively undisturbed prior to study installation. An extensive range of pre- and post-harvest measurements are being taken. This study alters site organic matter and total soil porosity over a range of intensities encompassing a range of possible management scenarios and creates a network of comparable experiments producing nil to severe soil disturbance and physiological stress in vegetation over a broad range of soils and climates. Establishing and monitoring this network directly addresses the needs of National Forest Systems, and creates a research opportunity of unusual scope and significance. Early results indicate that immediate post-harvest biomass declines are most likely caused by compaction and not organic matter removal whereas long-term productivity changes will be more dependent on organic matter losses.

Erosion Loss

The close tie between surface organic matter and forest soil productivity is clear (Jurgensen et al., 1996). As a rooting medium for higher plants, soils provide the essentials of water, structural support, nutrients, and soil biota. Mixing and/or short-distance displacement of topsoil and surface organic matter from a site can decrease productivity. Soil disturbance by logging is generally less than 30% of the total harvested area (Rice et al., 1972; Miller and Sirois 1986), but the impact can be severe. Erosion can further damage site productivity. First, erosion reduces crop productivity mainly by decreasing the soil water availability; this is a result of changing the water holding capacity and thickness of the root zone (Swanson et al. 1989). Second, erosion also removes plant available nutrients. Fertilizer applications can partly offset these losses, but they greatly increase costs and are uncommon. Third, erosion reduces productivity by degrading soil structure. Removal of the loose, organic surface materials promotes surface sealing and crusting which decreases infiltration capacity and may increase erosion (Childs et al. 1989). Fourth, erosion results in loss of important soil biota, such as mycorrhizal fungi, which facilitate nutrient uptake by plants (Amaranthus et al., 1989, 1996).

Surface erosion proceeds downward from the O horizons. Because the highest concentrations of nutrients and biota and the maximum water-holding capacity are in the uppermost soil horizons, incremental removals of soil nearer the surface are more damaging than those of subsoils. Productivity may inevitably decline on most shallow forest soils as erosion causes root-restricting layers to be nearer the surface and as organic matter is washed away. Consequently, the largest declines in productivity are most likely to occur in marginal, dry environments.

Assessing the effects of erosion on site productivity is often difficult. Erosion rates are poor indicators of loss in productivity because most soil is redistributed within a watershed and not necessarily lost to production. Soils differ in their tolerance to erosion loss. For instance, Andisols have relatively high water-holding capacity and natural fertility. Erosion may be severe on these sites, but productivity may decline little. In contrast, Spodosols frequently lose productivity because they are commonly highly leached and naturally infertile, they retain fertilizers poorly, and have low water-holding capacity.

Compaction Impacts

Field research has also found that timber harvesting systems tend to compact the soil. Compaction increases soil erosion, and adversely impacts forest productivity. Most erosion comes from skid trails on timber harvested units (Robichaud et al. 1993b). This is due to the low infiltration rates and disturbance to the organic layer.

Compaction of forest soil is a serious concern for managers because of the use of heavy equipment to harvest timber and prepare a site for planting. Usually, the more porous the soil initially, the greater the compaction depth. For example, volcanic ash soils of the western U.S. are highly productive in their undisturbed condition, but are prone to compaction because they have a low volume weight (weight-to-volume ratio) and relatively few coarse fragments (Geist and Cochran 1991). Once these sites have been disturbed through timber harvest activities and site preparation, porosity (Dickerson 1976) and hydraulic conductivity declines (Gent et al., 1984). Compaction depth can exceed 450 mm (Page-Dumroese 1996).

Compaction is a reduction in total porosity. Macro porosity is reduced while micro porosity increases as large pores are compacted into smaller ones. An increase in micro porosity can lead to greater available water-holding capacity throughout a site, but this increase is usually at the expense of aeration and drainage (Incerti et al., 1987).

There is little doubt that compaction reduces productivity (Greacen and Sands 1980; Froehlich and McNabb 1984). Reduction in root growth, height, and timber volume have been observed (Froehlich and McNabb 1984) and may be produced by a single pass of logging equipment across a site (Wronski 1984). Productivity losses have been documented for whole sites (Wert and Thomas 1981) and for individual trees (Froehlich 1979; Helms and Hipkin, 1986). Decreases in important microbial populations have been observed in compacted soils (Amaranthus et al., 1996). In general, however, the environmental degradation observed in the field result from both compaction and disturbance or removal of surface organic horizons (Childs et al., 1989).

Soil compaction may also increase surface runoff because of reduced infiltration (Greacen and Sands 1980). However, because of increased soil strength, compacted soils may have lower erodibility, and consequently suffer less erosion for the same amount of runoff (Liew 1974). A significant amount of erosion after harvest activities has been attributed to compaction, but may be attributable to both compaction and the removal of vegetative cover (Dickerson 1976).

Predicted Erosion Rates and Productivity

A series of WEPP runs were carried out on a productivity study site in central Idaho to allow comparison of a range of management effects on soil erosion. The predicted effects on erosion from wildfires were compared to prescribed fires, partial cuts, and clear cuts to better understand the interactions among natural events, human activities, soil erosion, soil productivity, and ultimately forest ecosystem sustainability.

Harvesting Impacts

For the modeling study, a slope length of 100 m, with a steepness of 61 percent was modeled, typical of the site Soil properties of the site are presented in Table 2. The WEPP management file described a forest in the first year, a disturbance in the second year, and regeneration of forest in eight subsequent years as described by Elliot et al. (1996). The biomass reduction due to harvest effects was described in the residue management and harvest index (harvest index = biomass removed/biomass present) values in the management files. The values assumed are presented in Table 3. The climate for the simulations was stochastically generated with the CLIGEN generator (Flanagan and Livingston, 1995) using the Deadwood Dam, ID climate statistics (mean annual precipitation = 830 mm).

Tables 4 and 5 present the predicted runoff and erosion rates for different treatments. Continuing field research will collect field data from the productivity treatments. The WEPP predictions are generally logical. More compaction leads to greater runoff and greater erosion. The effect of removing greater amounts of vegetation also leads to greater erosion rates. The complete removal of biomass was modeled as removing 100 percent of the surface residue, which resulted in a small increase in runoff, but a doubling of erosion rates. The role of surface residue is critical in controlling erosion in forests just as it is in agriculture.

An additional WEPP run was made with no disturbance. In this scenario, there was no runoff and no erosion. With the amount of residue cover and litter accumulation typical of forests, WEPP seldom predicts erosion. Our field observations generally confirm this, with most sediment from undisturbed watersheds coming from eroding ephemeral channels or landslides.

In order to compare the productivity impacts of soil erosion, an estimation was made of the nitrogen losses associated with the above erosion rates. It was assumed that the typical forest soil contains 4 percent organic matter, and that organic matter is 2 percent nitrogen. The resulting nitrogen losses for 8 years of predicted erosion are presented in Table 6. The values in Table 6 can be compared to Table 1 to see that nutrient losses due to erosion are significant, greater than observed leaching losses, but not as great as losses due to vegetation removal. In a generally nutrient-deficient environment, these nitrogen losses will have a significant impact on future productivity.

Natural Fire Impacts

To model a severe fire, 100 percent of the residue was burned, and half of the remaining biomass was harvested in the autumn. This is generally much more severe than observed in the field, but allows comparison of the extreme events. Generally, even "severe" fires do not remove more than 90 to 95 percent of the residue, and the remaining residue can reduce the predicted erosion rates by more than 90 percent. If the soil hydraulic conductivity remained unchanged, there was little change in either runoff or erosion from the values predicted for the severe compaction, bole removal treatment. If the hydraulic conductivity was reduced to 4 mm/hr to reflect hydrophobic soil conditions that sometimes occurs after severe fires, then the predicted runoff was doubled to 65 mm per year. The predicted erosion was 11.6 t ha^{-1}, greater than the bole and crown removal treatments, but still somewhat less than the predicted rates on sites with complete biomass removal. As the soil hydrologically recovers following a severe fire, the runoff and erosion rates would decline, a characteristic that WEPP is currently not capable of modeling continuously. Such a scenario could be developed with a series of one-year runs with a different conductivity for each year.

Summary/Conclusions

We have presented an overview of the impacts of forest management activities on soil erosion and productivity. Erosion alone is seldom the cause of greatly reduced site productivity. However, erosion in combination with other site factors, work to degrade productivity on the scale of decades and centuries. Extreme disturbances, such as wildfire or tractor logging, cause the loss of nutrients, mycorrhizae, and organic matter. These combined losses reduce long-term site productivity and may lead to sustained periods of extended erosion which could exacerbate degradation.

From a management perspective, we should be concerned with harvesting impacts, site preparation disturbances, amount of tree that is removed, and the accumulation of fuel from fire suppression. On erosion-sensitive sites, we need to carefully evaluate such management factors.

Prescribed fire is generally an excellent tool in preparing sites for regeneration, for reducing fuel loads, and for returning sites to a more natural condition. Burning conducted under correct conditions will reduce the fire hazard, make planting easier, and retain the lower duff material to protect the mineral soil and conserve nutrients to sustain forest productivity.

The WEPP model can describe various impacts due to harvesting, but further work is required to model fire effects and the subsequent temporal and spatial variation in soil hydraulic conductivity and ground cover effects. From field observations and the modeling exercise, it appears that disturbances caused by harvest activities will lead to increases in erosion and runoff rates, much greater than natural conditions, even when extreme wild fire effects are considered.

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Table 1 Comparison of height, diameter, and nitrogen pools after harvest treatments of varying intensities from two sites of differing site quality, Pack Forest, WA[1]

Harvest treatment	Height growth (m)	Diameter growth (cm)	Total N	Harvest loss	3-yr leaching loss	% loss
			- - - - - - - - - - - - kg/ha	- - - - - - - - -		
Average site quality						
Bole only	1.7	2.9	2,935	470	4.4	16
Whole tree	1.9	3.2	2,827	678	0.5	24
Complete[2]	1.8	3.6	2,719	870	0.7	32
Poor site quality						
Bole only	1.4	2.2	984	157	2.1	16
Whole tree	1.1	1.6	903	289	4.7	32
Complete[2]	1.1	1.5	934	486	5.5	53

[1] From Miller et al. 1989.

[2]Complete removal of all above ground biomass.

Table 2. Soil properties assumed for the WEPP model computer simulations

Soil Property	Value	Units
Sand content	40	percent
Silt content	45	percent
Clay content	15	percent
Interrill erodibility	2100	kg s m^{-4}
Rill erodibility	0.008	s m^{-1}
Critical shear	3	Pa
Saturated hydraulic conductivity		
uncompacted	20	mm hr^{-1}
moderate compaction	15	mm hr^{-1}
severe compaction	8	mm hr^{-1}

Table 3. Values describing the effects of timber harvest in the WEPP model computer simulations

Treatment	Residue Management	Harvest Index
Complete biomass removal	100 percent surface residue removed	0.9
Bole and crown removed	No surface residue removed	0.8
Bole only removed	No residue management	0.4

Table 4. Average annual runoff (mm) from rainfall from the WEPP simulations for five simulated forest conditions

	Compaction		
Treatment	None	Moderate	Severe
	- - - - mm - - - -		
Undisturbed	0.0	--	--
Complete biomass removal	12.8	18.8	35.6
Bole & Crown removed	9.2	15.4	32.4
Bole only removed	9.1	16.1	32.7
Severe wild fire	65.0	--	--

Table 5. Average annual soil loss (t ha^{-1}) from the WEPP simulations for five simulated forest conditions

Treatment	Compaction None	 Moderate	 Severe
		- - - - t ha^{-1} - - -	
Undisturbed	0.0	--	--
Complete biomass removal	4.5	7.4	14.4
Bole & crown removed	2.0	3.3	7.2
Bole only removed	2.0	3.5	7.2
Severe wild fire	11.6	--	--

Table 6. Predicted nitrogen loss due to erosion in the first 8 years of regrowth following harvest

Treatment	Compaction None	 Moderate	 Severe
		- - kg ha^{-1} - -	
Undisturbed	0.0	--	--
Complete biomass removal	28.8	47.4	92.2
Bole & crown removed	12.8	21.1	46.1
Bole only removed	12.8	22.4	46.1
Severe wild fire	74.2	--	--

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