The Effects of Forest Management on Erosion and Soil Productivity

William J. Elliot — Project Leader
Deborah Page-Dumroese — Research Soil Scientist
Peter R. Robichaud — Research Engineer
Intermountain Research Station, USDA Forest Service, Moscow, Idaho 83843
Tel 208 882 3557 Fax 208 883 2318

An invited paper presented at the Symposium
on Soil Quality and Erosion Interaction
sponsored by
The Soil and Water Conservation Society of America
held at
Keystone, Colorado

July 7th, 1996

Abstract

In forest conditions, surface runoff and soil erosion are generally low because of the surface litter cover. Hydraulic conductivities are in excess of 15 mm/hr, and erosion rates are generally less than 0.1 Mg ha^{-1}. If the litter layer is disturbed, then runoff and erosion rates can increase by several magnitudes. Disturbances can be natural, such as wild fire, or human-induced, such as harvesting or prescription-burning for ecosystem management, where conductivities can drop to under 5 mm/hr, and erosion rates can exceed 20 Mg ha^{-1}. Roads adversely impact forest soil productivity by directly reducing the productive area, and by causing the greatest amount of soil erosion. Conductivities of roads have been measured to be less than 1 mm/hr, and erosion can be in excess of 100 Mg ha^{-1}. Harvesting activities reduce surface cover, and compact the soil, leading to increased runoff and erosion. Erosion generally decreases productivity of forests by decreasing the available soil water for forest growth, and through loss of nutrients in eroded sediment. The Water Erosion Prediction Project (WEPP) model is shown to be a useful tool in predicting the erosion impacts of different levels of vegetation removal at harvest, and different levels of compaction. WEPP predicted that the nutrients lost through the organic matter in sediments are significant, but less than nutrient loss through tree removal. Work is ongoing to collect long-term site productivity data from numerous sites to aid in the analysis of forest management on soil erosion and site productivity.

Key Words: Soil Quality, Soil Erosion Prediction, WEPP

Introduction

For many years research has related soil erosion to productivity with most activities focusing on agricultural or rangeland conditions. The Pierce (1991) overview includes over 60 references to research on impacts of erosion on agricultural production. He concluded that exact relationships between erosion and productivity are unclear, and that to define any such relationship, considerable research is necessary over a wide range of soil and plant conditions.

Research is ongoing into the effects of management practices on forest soil productivity. Table 1 summarizes some of this research. Relationships between disturbance and productivity are not simple, but rather they are extraordinarily complex, reflecting interactions among disturbance levels, soil water-holding capacities, nutrient cycling properties, and climate. Therefore, the effect of a given disturbance is highly dependent on site-specific soil properties and microclimate, and may also be influenced by year to year variation in climate. Table 1 shows that generally disturbances reduce long-term productivity, but there are cases where short-term productivity has increased following disturbances (for example, Harvey et al., 1996; Corns, 1988). Research on the impacts of soil erosion on forest productivity is limited. This paper provides an overview of current knowledge on the influence of forest management activities on soil erosion and related onsite impacts, and the subsequent effects of those impacts on forest productivity.

Soil erosion in an undisturbed forest is extremely low, generally under 1 Mg ha^{-1} yr^{-1} (0.5 ton/acre/yr). Disturbances, however, can dramatically increase soil erosion to levels exceeding 100 Mg ha^{-1} yr^{-1} (50 tons/acre/yr). 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

Forest Practices

Soil erosion in forests generally follows a disturbance such as road construction, a logging operation, or fire. In undisturbed forests, erosion is most often 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. Forest litter 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 which have no vegetative protection and tend to have low hydraulic conductivities leading to runoff and erosion rates that are greater 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 reduce forest productivity by the land that they occupy. A kilometer (0.6 mi) of road in 1 km^2 (250 acres) of forest represents a 0.5 percent loss in area and removal from productivity. Forest roads can occupy up to 10 percent of the forest area if there is a 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 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 focused 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 may be 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. 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 over 20 percent.

Tree cutting by itself does not cause significant erosion, and timber harvest operations usually cause less erosion per unit area than roads, but 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). However, the decrease in the number of trees results in a decrease in evapotranspiration which contributes to increased subsurface flow, streamflow, and channel erosion. Field research has found that timber harvesting tends to compact the soil. Compaction increases soil erosion and adversely impacts forest productivity (Yoho 1980). Most erosion comes from skid trails on timber harvest units because of the reduced infiltration rates and disturbance to the organic layer (Robichaud et al. 1993b). Therefore, the accelerated erosion caused by timber harvesting may result in deterioration of soil physical properties, nutrient loss, and degraded stream water quality from sediment, herbicides, and plant nutrients. (Douglas and Goodwin 1980).

Nutrient Impacts

Harvesting trees removes nutrients from a generally nutrient-deficient environment (Miller et al. 1989). Table 2 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 only the bole 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 United States is prescribed burning. Mechanical site preparation methods, however, are common 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. Fire has long been a natural component of forests ecosystems (Agee 1993), and current research is finding that fire helps maintain forest health. The use of prescribed fire will increase with the current emphasis on ecosystem management.

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 cover large areas, and fires may create hydrophobic or water repellent soil conditions. Erosion from low severity fires may be minimal to none (Robichaud et al. 1993a; 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 a severe problem associated with farming practices. Models for range and forest lands have only recently received widespread interest as managers focus on off-site sediment impacts as well as on onsite erosion rates.

Sediment Yield Models

Most of the early models, which culminated in the empirically-base 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 (such as WATSED, Range, Air, Watershed and Ecology Staff Unit 1991). The strength of these models is in 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)–provide estimates of sedimentation for predicting both onsite and offsite impacts. The WEPP model, in particular, shows considerable promise to assist in predicting soil erosion and sediment yields in a forest environment (Elliot et al. 1996).

The WEPP model predicts 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. 1994b). The WEPP model predicts both erosion and the textural and organic composition of the eroded sediment.

Productivity Response to Management

A coordinated national research effort was implemented on a broad spectrum of benchmark sites across the nation to separate impacts of soil organic matter reduction from soil compaction resulting from management activities (Powers et al. 1990). These sites were relatively undisturbed prior to study installation. An extensive range of pre- and postharvest measurements are being taken. This study alters site organic matter and total soil porosity over a range of intensities encompassing a number of possible management scenarios. It 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 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 clearly exists between surface organic matter and forest soil productivity (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. Logging generally disturbs less than 30 percent of the total harvested area (Rice et al. 1972; Miller and Sirois 1986), but the impact can be severe.

Erosion reduces forest 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). Erosion removes plant available nutrients. Fertilizer applications can partly offset these losses, but they greatly increase costs and are uncommon. Another impact of erosion on productivity is degraded soil structure. Removal of the loose, organic surface materials promotes surface sealing and crusting that decreases infiltration capacity and may increase erosion (Childs et al. 1989). Erosion also 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 surface soil horizons. Because the highest concentrations of nutrients and biota and the maximum water-holding capacity are in the uppermost horizons, incremental removal of soil nearer the surface is more damaging than subsoil losses. 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 how erosion affects 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, Lithosols are shallow and generally less productive, so a small rate of erosion can lead to a significant decline in waterholding capacity and productivity.

Compaction Impacts

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).

Compaction of forest soil is a serious concern for managers because of the use of heavy equipment to harvest timber and to 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 United States are highly productive in their undisturbed condition but are prone to compaction because they have a low volume bulk density and relatively few coarse fragments (Geist and Cochran 1991). Once sensitive sites have been disturbed through timber harvest activities and site preparation, porosity (Dickerson 1976) and hydraulic conductivity decline (Gent et al. 1984). Compaction depth can exceed 450 mm (Page-Dumroese 1996).

Compaction reduces productivity through reduction in root growth, height, and timber volume (Greacen and Sands 1980; 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 results 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

We carried out a series of WEPP runs for a productivity study site in central Idaho to allow comparison of a range of management effects on soil erosion. We compared the predicted effects on erosion from wildfires to different levels of harvest and compaction, 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, we modeled a slope length of 100 m (328 ft), with a steepness of 61 percent, typical of the site. Soil properties of the site are presented in Table 3. 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 4. The climate for the simulations was stochastically generated with the CLIGEN generator (Flanagan and Livingston 1995) from the Deadwood Dam, ID, climate statistics (mean annual precipitation = 830 mm (33 in.)).

An initial 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.

Tables 5 and 6 present the predicted runoff and erosion rates for different 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.

To compare the productivity impacts of soil erosion, we estimated the nitrogen losses associated with the above erosion rates. We 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 7. The values in Table 7 can be compared to Table 2 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, such 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 difference 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 occur after severe fires, then the predicted runoff was doubled to 65 mm per year. The predicted erosion was 11.6 Mg 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 decline, a characteristic that WEPP is currently not capable of modeling continuously. Such a scenario could be developed with a series of 1-year runs with a different conductivity for each year.

Conclusions

In our overview of the impacts of forest management activities on soil erosion and productivity, we show that erosion alone is seldom the cause of greatly reduced site productivity. However, erosion, in combination with other site factors, works 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 that could exacerbate degradation.

Managers 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.

References

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Washington D.C.: Island Press. 493 p.

Amaranthus, M. P., D.S. Page-Dumroese, A. Harvey, E. Cazares, and L. F. Bednar. 1996. Soil compaction and organic matter affect conifer seedling nonmycorrhizal and ectomycorrhizal root tip abundance and diversity. Portland, Or: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Research Paper PNW-RP-494. 12 p.

Amaranthus, M. P., J. M. Trappe, and R. J. Molina. 1989. Long-term forest productivity and the living soil. In: Gessel, S. P., D. S. Lacate, G. F. Weetman, and R. F. Powers (eds). Sustained productivity of forest soils. Proceedings, 7th North American Forest Soils Conference. Vancouver, B.C: University of B.C., Faculty of Forestry Pub. 36-52.

Bilby, R. E., K. Sullivan, and S. H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. Jour. of Forest Sci. 35(2):453-468.

Childs, S. W., S. P Shade, D. W. R. Miles, E. Shepard, and H. A. Froehlich. 1989. Soil physical properties: Importance to long-term productivity. In: Gessel, S. P., D. S Lacate, G. F. Weetman, and R. F. Powers (eds.). Sustained productivity of forest soils. Proceedings, 7th North American Forest Soils Conference. Vancouver, B.C.: University of B.C., Faculty of Forestry Pub. 53-67.

Corns, I. G. W. 1988. Compaction by forestry equipment and effects on coniferous seedling growth on four soils in the Alberta foothills. Can. J. For. Res. 18:75-84.

Dickerson, B. P. 1976. Soil compaction after tree-length skidding in northern Mississippi. Soil Sci. Soc. Am. J. 40: 965-966.

Dissmeyer, G. E., and G. R. Foster. 1985. Modifying the universal soil loss equation for forest land. In Soil Erosion and Conservation. Ankeny Iowa: Soil and Water Conserv Soc. 480-495.

Douglas, J. E., and O. C. Goodwin. 1980. Runoff and soil erosion from forest site preparation practices. In: U.S. forestry and water quality: what course in the 80's?: Proceedings; Richmond, VA: The Water Pollution Control Federation and Virginia Water Pollution Control Association: 50-74.

Elliot, W. J., C. H. Luce, and P. R. Robichaud. 1996. Predicting sedimentation from Timber Harvest areas with the WEPP model. In: Proceedings, Sixth Federal Interagency Sedimentation Conference, Mar. 10-14, Las Vegas, NV. IX:46-53.

Elliot, W. J., R. B. Foltz and M. D. Remboldt. 1994a. Predicting sedimentation from roads at stream crossings with the WEPP model. Presented at the 1994 ASAE International Winter Meeting, Dec 13-16. Paper No. 947511. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659.

Elliot, W. J., R. B. Foltz, and P. R. Robichaud. 1994b. A tool for estimating disturbed forest site sediment production. Proceedings of Interior Cedar-Hemlock-White

Pine Forests: Ecology and Management Mar. 2-4, 1993, Spokane, WA. Pullman, WA: Dept. of Natural Resource Science, Washington State Univ. 233-236.

Flanagan, D. C., and S. J. Livingston (eds.). 1995. WEPP User Summary USDA-Water Erosion Prediction Project. West Lafayette, In: National Soil Erosion Laboratory Report No. 11.

Froehlich, H. A. 1978. The effect of soil compaction by logging on forest productivity. Portland, OR: Bureau of Land Management, Final Report, Contract No. 53500-CT4-5-5(N). 19 p.

Froehlich, H. A. 1979. Soil compaction from logging equipment: effects on growth of young ponderosa pine. J. Soil and Water Conserv. 34: 276-278.

Froehlich, H. A., and D. H. McNabb. 1984. Minimizing soil compaction in Pacific Northwest forests. In: Stone, E. L. (ed.). Forest soils and treatment impacts. Proceedings of the 6th American Forest Soils Conference, Knoxville, TN. 159-192.

Geist, J. M., and P. H. Cochran. 1991. Influences of volcanic ash and pumice deposition on productivity of western interior forest soils. In: Harvey, A. E. and L. F. Neuenschwander, (comps.). Proceedings-management and productivity of western-montane forest soils. Gen. Tech. Rep. INT-GTR-280. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 82-89.

Gent, J. A., Jr., R. Ballard, A. E. Hassan, and D. K. Cassel. 1984. Impact of harvesting and site preparation on physical properties of Piedmont forest soils. Soil Sci. Soc. Am. J. 48: 173-177.

Greacen, E. L., and R. Sands. 1980. Compaction of forest soils - a review. Aust. J. Soil Res. 18: 163-189.

Harvey, A. E., D. S. Page-Dumroese, M. P. Amaranthus, and G. I. McDonald. 1996. The effects of stump removal and simulated harvest-related disturbances on soil properties, ectomycorrhizal development, growth and nutrition of planted western white pine and Douglas-fir in Northern Idaho. Ogden, UT: USDA Forest Service, Intermountain Research Station, Research Paper in Press.

Harvey, A. E., M. F. Jurgensen, and M. J. Larsen. 1979. Role of forest fuels in the biology and management of soil. Ogden UT: USDA Forest Service, Intermountain Research Station, General Technical Report INT-65. 8 p.

Helms, J. A., and C. Hipkin. 1986. Effects of soil compaction on tree volume in a California ponderosa pine plantation. West. J. Appl. For. 1:121-124.

Incerti, M., P. F. Clinnick, and S. T. Willett. 1987. Changes in the physical properties of a forest soil following logging. Aust. For. Res. 17: 91-98.

Jurgensen, M. F., A. E. Harvey, R. T. Graham, D. S. Page-Dumroese, J. R. Tonn, M. J. Larsen, and T. B. Jain. 1996. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of Inland Northwest forests. For. Sci. in press.

Knisel, W. G. 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. Washington D.C.: USDA, Conservation Research Report no. 26. 643 pp.

Laflen, J. M., L. J. Lane, and G. R. Foster. 1991. WEPP a new generation of erosion prediction technology. Jour. of Soil and Water Conserv. 46(1):34-38.

Liew, T. C. 1974. A note on soil erosion study at Tawau Hills Forest Reserve, Malay. Nat. J. 27: 20-26.

Megahan, W. F. 1986. Recent studies on erosion and its control on forest lands in the United States. In: Richard, F. (ed.). Range basin sediment delivery: Proceedings; 1986 August; Albuquerque, NM. IAHS Pub. 159, Wallingford, Oxon, United Kingdom: 178-189.

Megahan, W. F., and W. J. Kidd. 1972. Effect of logging roads on sediment production rates in the Idaho Batholith. Ogden, UT: USDA Forest Service, Intermountain Research Station Research Paper INT-123. 14 p.

Miller, J. H., and D. L. Sirois. 1986. Soil disturbance by skyline yarding vs. skidding in a loamy hill forest. Soil Sci. Soc. Am. J. 50:462-464.

Miller, R. E., W. J. Stein, R. L. Heninger, W. Scott, S. M. Little, and D. J Goheen. 1989. Maintaining and improving site productivity in the Douglas-fir region. In: Perry, D. A., R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C. R. Perry, and R. F. Powers (eds.). Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Timber Press. 98-136.

Moll, J. E. 1996. A guide for road closure and obliteration in the Forest Service. Washington D.C.: USDA Forest Service Technology and Development Program. 49 p.

Mutchler, C. K., C. E. Murphree, and K. C. McGregor. 1994. Laboratory and field plots for erosion research. In: Lal, R. (ed.). Soil Erosion Research Methods, Second Edition. Ankeny, Iowa: Soil and Water Conserv Soc. 11-37.

Page-Dumroese, D. S. 1996. Evaluating management impacts on long-term soil productivity: a research and national forest systems cooperative study - local results. In: Proceedings-western regional cooperative soil survey conference. In press.

Pierce, F. J. 1991. Erosion productivity impact prediction. In: Lal, R., and F. J. Pierce (Eds.), Soil Management for Sustainability. Ankeny, Iowa: Soil and Water Conserv Soc. 35-52.

Powers, R. F., D. H. Alban, R. E. Miller, A. E. Tiarks, C. G. Wells, P. E. Avers, R. G. Cline, R. O. Fitzgerald, and N. S. Loftus. 1990. Sustaining site productivity in North American forests: problems and perspectives. In: Gessel, S. P., D. S. Lacate, G. F. Weetman, and R. F. Powers (eds.). Sustained productivity of forest soils. Proceedings, 7th North American Forest Soils Conference. Vancouver, B.C.: University of B.C., Faculty of Forestry Pub. 49-79.

Range, Air, Watershed and Ecology Staff Unit and Montana Cumulative Watershed Effects Cooperative. 1991. WATSED Water and sediment yields. Region 1, USDA Forest Service, Missoula, MT.

Reisinger, T. W., G. L. Simmons, and P. E. Pope. 1988. The impact of timber harvesting on soil properties and seedling growth in the South. South. J. of Appl. For. 12(1):58-67.

Rice, R. M., J. S. Rothacher, and W. F. Megahan. 1972. Erosional consequences of timber harvesting: An appraisal. In: Watersheds in transition, Urbana, Ill: American Water Resources Association Proceedings Series 14. 321-329.

Robichaud, P. R., R. T. Graham, and R. D. Hungerford. 1993a. Onsite sediment production and nutrient losses from a low-severity burn in the interior Northwest. In: Baumgartner, D. M., J. E. Lotan, J. R. Tonn (compilers). Interior cedar-hemlock-whitepine forests: ecology and management: Proceedings; 1993 March; Spokane, WA: 227-232.

Robichaud, P. R., C. H. Luce, and R. E. Brown. 1993b. Variation among different surface conditions in timber harvest sites in the Southern Appalachians. In: International workshop on soil erosion: Proceedings; September, 1993; Moscow, Russia. West Lafayette, IN: The Center of Technology Transfer and Pollution Prevention, Purdue University: 231-241.

Robichaud, P. R.; and T. A. Waldrop. 1994. A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. Water Resources Bulletin 30(1): 27-36.

Swanson, F. J., J. L. Clayton, W. F. Megahan, and G. Bush. 1989. Erosional processes and long-term site productivity. In: Perry, D. A., R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C. R. Perry, and R. F. Powers (eds.). Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Timber Press. 67-82.

Swift, L. W., Jr. 1988. Forest access roads: design, maintenance, and soil loss. In: Swank, W. T., and D. A. Crossley, Jr. (eds.). Ecological Studies, 66: Forest Hydrology and Ecology at Coweeta. New York: Springer-Verlag. 313-324.

Wert, S., and B. R. Thomas. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Sci. Soc. Am. J. 45: 629-632.

Williams, J. R., C. A. Jones, and P. T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Transactions of the ASAE 27:129-144.

Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion losses-a guide to conservation planning. USDA Agricultural Handbook No. 537.

Wronski, E. B. 1984. Impact of tractor thinning operations on soils and tree roots in a Karri forest, Western Australia. Aust. For. Res. 14: 319-332.

Yoho, N. S. 1980. Forest management and sediment production in the South-a review. Southern Journal of Applied Forestry 4: 27-36.

Table 1 Typical effects of forest disturbances on productivity

Practice	Impact	Productivity Response
Roads	Area removed from production	Up to 30% of forest area lost[1]
Fire	Organic matter loss Disease reduction	Long-term effects not measured. Observed loss of organic matter leading to growth reduction from water and nutrient stress[2]
Compaction	Reduced water availability and increased runoff	Height reduction of 50%[3] or more Volume reduction up to 75%[4]
Tree Harvest	Loss of organic matter and site disturbance	Up to 50% reduction if site is severely compacted[5]

[1] Megahan and Kidd, 1972
[2] Harvey et al., 1979
[3] Reisinger et al., 1988
[4] Froehlich, 1978
[5] Amaranthus et al., 1996

Table 2 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 (mm)	Total N	Harvest loss	3-yr leaching loss	% loss
			- - - - - - - - - - - - kg/ha	- -- - - - - - -		
Average site quality						
Bole only	1.7	29	2,935	470	4.4	16
Whole tree	1.9	32	2,827	678	0.5	24
Complete[2]	1.8	36	2,719	870	0.7	32
Poor site quality						
Bole only	1.4	22	984	157	2.1	16
Whole tree	1.1	16	903	289	4.7	32
Complete[2]	1.1	15	934	486	5.5	53

[1] From Miller et al. 1989.

[2]Complete removal of all above ground biomass.

Table 3. 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}
hydrophobic	4	mm hr^{-1}

Table 4. 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 5. Predicted average annual runoff (mm) from rainfall from the WEPP simulations for five simulated forest conditions

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

Table 6. Predicted average annual soil loss (Mg ha^{-1}) from the WEPP simulations for five simulated forest conditions

Treatment	Compaction None	 Moderate	 Severe
	- - - - Mg 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 7. 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	--	--

Elliot, W.J.; Page-Dumroese, D.; Robichaud, P.R. 1999. *The effects of forest management on erosion and soil productivity.* **Proceedings of the Symposium on Soil Quality and Erosion Interaction,** Keystone, CO, July 7, 1996. Ankeney, IA: Soil and Water Conservation Society. 16 p.
Keywords: Soil Quality, Soil Erosion Prediction, WEPP
1999c

Moscow Forestry Sciences Laboratory
Rocky Mountain Research Station
USDA Forest Service
1221 South Main Street
Moscow, ID 83843

http://forest.moscowfsl.wsu.edu/engr/