Available online at www.sciencedirect.com
SCIENCE DIRECT

Forest Ecology and Management 202 (2004) 313–323

Forest Ecology and Management

www.elsevier.com/locate/foreco

Effects of forest road amelioration techniques on soil bulk density, surface runoff, sediment transport, soil moisture and seedling growth

R.K. Kolka[a,*], M.F. Smidt[b]

[a]USDA Forest Service, North Central Research Station, Grand Rapids, MN 55744, USA
[b]School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL 36849, USA

Received 19 November 2003; received in revised form 30 December 2003; accepted 25 July 2004

Abstract

Although numerous methods have been used to retire roads, new technologies have evolved that can potentially ameliorate soil damage, lessen the generation of nonpoint source pollution and increase tree productivity on forest roads. In this study we investigated the effects of three forest road amelioration techniques, subsoiling, recontouring and traditional retirement (control treatment), on soil bulk density, surface runoff, sediment production, soil moisture and seedling growth. As a point of comparison, surface runoff, sediment production and soil moisture was also measured on relatively undisturbed forested reference sites. The recontoured treatment had significantly lower bulk densities, surface runoff and sediment production than either the subsoiled or control treatments. The relatively undisturbed reference sites had very little runoff and hence, very low sediment production. Reference sites also had generally lower soil moisture at 0–15 and 15–25 cm than above, within and below the treatment road sections. Among treatments, few differences were found in soil moisture among treatment:landscape position combinations. Recontoured and subsoiled treatments had significantly greater white pine diameter growth than control plots. Yellow-poplar diameter and height growth was greatest for recontoured plots followed by the subsoiled plots and the control plots. The combination of data indicates that the use of recontouring techniques on forest roads generally leads to lower bulk densities, less surface runoff and sediment production and greater seedling growth than both traditional and subsoiling road retirement methods, however, the cost of recontouring is greater than subsoiling or traditional retirement and the preliminary analysis indicates that subsoiling may represent the most economically viable retirement method.

Keywords: Subsoil; Recontour; Skid roads; Forest productivity

1. Introduction

Skidding or yarding on steep terrain requires the construction of a relatively dense network of forest roads including skid roads, haul roads and landings.

* Corresponding author. Tel.: +1 218 326 7115; fax: +1 218 326 7123.
E-mail address: rkolka@fs.fed.us (R.K. Kolka).

0378-1127/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2004.07.042

These forest roads are the largest source of sediment in forested systems (Ketcheson et al., 1999; Swift, 1988). Erosion of organic and nutrient rich surface soil and compaction decreases forest productivity (Pritchett and Fisher, 1987) and the transport of sediment to streams and subsequent sedimentation leads to loss of stream habitat and altered steam hydrology (NCASI, 1999a, 1999b). Over the years the post-harvest treatment of disturbed soil has improved through implementation of best management practices (BMPs) to protect water quality. While BMPs have been designed for, and proven to be effective at reducing erosion caused by logging (Arthur et al., 1998), the soil damage caused by forest roads and landings remains. As landowners desire to improve or maintain productivity on managed forest lands, the effect on productivity from soil damage becomes increasingly important (Wronski and Murphy, 1994).

The extent of the severe disturbance from ground-based harvesting systems varies due to slope and terrain, harvesting machines, methods of designating skid roads, and harvesting season. Miller and Sirois (1986) found that a harvest with a ground-based harvesting system and slopes ranging from 10 to 45% resulted in 3.5% of the area occupied by haul roads, 6.4% in landings, and 21.4% in skid roads. Kochenderfer (1977) and Stuart and Carr (1991) estimated that constructed or bladed skid roads occupied about 10% of the harvest area on similar terrain.

Soil damage on forest roads and landings includes the removal of the organic layer and topsoil, soil compaction, and erosion of the exposed soil. The soil damage affects hillslope infiltration and surface and subsurface flows. If significant, the resulting erosion could be a major source of nutrient loss following the harvest (Binkley, 1986). The tree growth effects resulting from soil damage from machine traffic and construction have varied with respect to soil type (Smith and Wass, 1984), tree species (Froehlich et al., 1986; Smith and Wass, 1980), and severity of damage (Moehring and Rawls, 1970; Froehlich, 1979). Predicting long-term loss of productivity is considerably more complex than predicting growth losses in the compacted area since trees adjacent to the compacted area may grow slower (Smith and Wass, 1979) or grow similarly or faster (Wert and Thomas, 1981; Pfister, 1969) than trees in an undisturbed area. Tree volume in skid roads has been estimated to be as much as 80% less than volume in undisturbed areas (Carr, 1987). Over the entire harvest area growth reductions of 11.8% (Wert and Thomas, 1981) and 12–15% (Smith and Wass, 1979) have been estimated.

Natural recovery of soil properties, especially bulk density and infiltration, is usually slow and relies on wetting and drying, frost activity, animal activity, and root growth. Subsoil bulk density in skid roads had not recovered to undisturbed levels in 23 years in central Idaho (Froelich et al., 1985) and 32 years in Oregon (Wert and Thomas, 1981). In the Virginia coastal plain, Hatchell et al. (1970) indicated that bulk density recovered to pre-logging levels after 18 years. Shorter recovery periods have been observed for surface horizons (Froelich et al., 1985; Mace, 1971; Thorud and Frissell, 1976; Wert and Thomas, 1981) and for secondary or lower use skid roads (Hatchell et al., 1970; Mace, 1971; Reisinger et al., 1992).

BMPs for severely disturbed areas include seeding, fertilizing, and liming to ensure establishment of the cover crop, diversion of surface water from exposed mineral soil, and restriction of traffic following the harvest (Stringer et al., 1997). While effective at reducing long-term water pollution, none of these strategies specifically address recovery of soil properties, site productivity, or normal hillslope hydrology.

The combinations of practices designed specifically for amelioration of soil properties and fertility have included tillage, mulching, and fertilization. Although designed for reducing erosion, the establishment of a cover crop and fertilizing may have contributed to faster bulk density recovery (Reisinger et al., 1992, 1988). Reisinger et al. (1988) suggests that the most effective amelioration techniques for seedling growth included a combination of tillage and fertilization, practices commonly used in intensive forest management throughout the world. To increase infiltration in areas with deep compaction, subsoil ripping was shown to be effective (Luce, 1997).

Moll (1996) outlines procedures including different kinds of tillage and partial and complete recontouring for obliteration of low-volume forest roads. Andrus and Froehlich (1983) and Lawrie et al. (1996) estimated that a 200 hp tractor with a winged subsoiler could treat from 0.28 to 0.36 ha h^{-1}, respectively. To justify the cost associated with this practice, the increase in timber production would have to yield an increase in the net present value equal to or greater than the cost of the practice. Using growth simulators (Stewart et al., 1988) projected that changes in harvest planning or amelioration treatments could be justified by increases in long-term timber value. Since post-harvest treatment of severely disturbed areas (skid-roads, landings and haul roads) is already required by BMPs, it may be possible that an amelioration treatment could partially or completely replace current BMPs and reduce the direct cost of tillage.

While current recommendations to minimize the aerial extent of disturbance represents the best available information (Martin, 1988), they are not precise enough for the more sophisticated questions. Weighing total costs and benefits of harvest design, harvesting systems, and amelioration techniques will require more specific information. The objective of this study is to investigate the effects of amelioration techniques on forest roads on steep side slopes (≥30%) to examine effects on soil bulk density, surface runoff, sediment transport, soil water and seedling growth. Based on the seedling growth and cost data collected during treatment installation we also estimate treatment profitability and develop recommendations for forest road retirement.

2. Sites and methods

Three sections of forest roads were chosen that have approximately a 10% grade on hillslopes ranging from 30 to 40%. The three roads are located in northeast Kentucky, two on the Daniel Boone National Forest near Morehead, KY (Road Branch and Moore Branch sites) and a third site located on industry timberland owned by Mead Paper and Pulp Company (now MeadWestvaco Corporation) near Vanceburg, KY (Mead Site). All road sections are on similar north facing aspects and are composed of gravelly to very gravelly silt loam soils. Roads were previously constructed in a typical cut and fill manner and tended to be outsloped. In the spring of 2000, each road section was installed with three randomly selected duplicate treatments. The treatments included (1) cover crops only (traditional retirement method considered in this study as the control treatment), (2) subsoiling and cover crops, and (3) recontouring and cover crops. The first treatment, cover crops only, is the current BMP used to retire forest roads in many states. A relatively undisturbed hillslope site at a similar landscape position as the road section was also instrumented near to each experimental road section and is considered as the reference condition for soil moisture, surface runoff volume and sediment production measurements. Reference sites were located in mature forests that had not been recently disturbed by harvesting or road building. A 200 m long road section was selected at each site and divided into six 25 m treatment plots. Each treatment plot was separated by 5 m buffers. Treatments were replicated twice and randomly assigned to plots. The subsoil treatment was applied using a winged subsoiler developed at Oregon State University for forest road retirement (Andrus and Froehlich, 1983). Recontoured treatments were installed with a tracked backhoe and original contours were recreated. Fill material for the contoured treatment was the fill that was cast downslope from the original road building. No new fill was needed. Time and cost data were also collected during the installation of the treatments (Smidt and Kolka, 2001).

Soil bulk density was measured at nine random points in each plot shortly after installation and again 2 years post-installation. Soil bulk density is a whole soil density from 0 to 10 cm soil depth using the excavation method and expanding foam (Page-Dumroese et al., 1999). Soil moisture was measured with time domain reflectometry probes (TDR) at 0–15 and 15–25 cm soil depths. Sets of TDR probes were installed 3 m above, 3 m below and in the center of one treatment plot of each treatment at each site. TDR probes were installed at a similar location at each reference site. Soil moisture was measured on a monthly basis for 1 year after treatment installation. Surface runoff diversion plots (~8 m^2) were also installed on one duplicate of each road treatment at each site and on each reference site. To ensure that surface runoff was independent of slope, surface runoff diversion plots were constructed and graded to 2–3% slope. Surface runoff was measured for volume and analyzed for sediment concentration. Water was diverted by gardeners edging into 110 l polyvinyl collection bags that were sampled on a monthly basis for 1 year after treatment installation. A single precipitation collector was centrally located at each site.

Twenty 1-0 yellow-poplar (*Liriodendron tulipifera* L.) and 2-0 eastern white pine (*Pinus strobus* L.) bare root seedlings were planted in each treatment during the spring of 2000. Seedling height and diameter at 10 cm was measured at planting and at the end of the second growing season. No seedlings were planted in the reference sites. Soil fertility analysis was completed prior to planting and sites low in fertility (Road and Moore Branch) were fertilized with N, P and K to offset any initial fertility differences among sites.

All measurements were statistically analyzed through analysis of variance for a completed randomized block design. Two-way ANOVAs indicated significant interactions among sites and treatments for many of our comparisons. Tukey's multiple comparison method was used to test for all pairwise combinations with significance assumed to occur at $P < 0.05$.

3. Results

3.1. Soil bulk density

Soil bulk density measured shortly after plot installation indicated variation by site and by treatment (Fig. 1). The Mead site tended to have the lowest whole soil bulk density with the Road Branch and Moore Branch sites having similar densities (data not shown). No sites had significant changes in bulk density from 2000 to 2001. Particle size analysis indicated that the Mead site classified as a gravelly silt loam whereas the other two sites classified

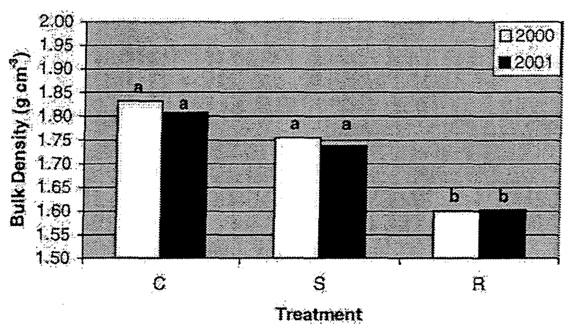

Fig. 1. Soil bulk density results for 2000 and 2001 by treatment. For treatments – C: control, S: subsoil, and R: recontour.

as very gravelly silt loams. The increase rock fragment was likely the cause of higher whole soil bulk densities on the Road and Moore Branch sites. The recontouring treatment had significantly lower bulk densities than either the subsoiling treatment or control, which were similar (Fig. 1).

3.2. Surface runoff volume

Because of variation in incident precipitation among sites (Road Branch 87 cm, Moore Branch 88 cm and Mead 100 cm of total precipitation over the course of the study), runoff volumes were standardized by dividing the runoff volume by the incident precipitation volume, resulting in a runoff percentage (Fig. 2). Like soil bulk density, surface runoff volume varied by site and by treatment. Surface runoff volume was greatest at the Mead site followed by the Moore and Road Branch sites, which were similar (data not shown). The control and subsoil treatment had similar runoff percentages with the recontour treatment having significantly lower runoff than the subsoil treatment. The relatively undisturbed reference sites had significantly lower runoff than any of the treatments (Fig. 2).

3.3. Sediment production

To standardize sediment production among sites because of varying precipitation rates, production was calculated per cm of incident precipitation (Fig. 3). Sediment production also varied by site and by treatment, with relationships following closely with surface runoff volume. The Mead site produced the greatest amount of sediment followed by the Moore and Road Branch sites, which were similar (data not shown). The control and subsoil treatments had similar sediment production with the recontour treatment having significantly lower sediment production (Fig. 3). The reference sites had very little runoff and significantly less sediment production than the treatments.

3.4. Soil moisture

Soil moisture at both 0–15 and 15–25 cm was significantly higher at the Mead and Road Branch sites than at the Moore Branch site (data not shown).

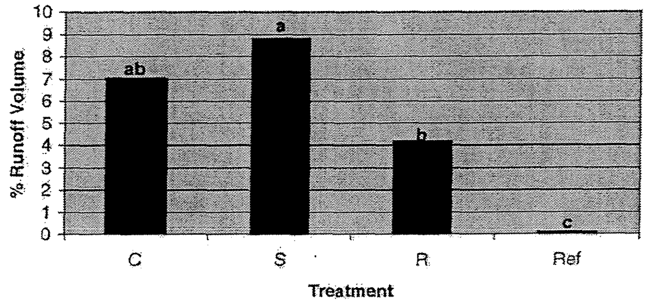

Fig. 2. Runoff volume as a percentage of incident precipitation by treatment. For treatments – C: control, S: subsoil, R: recontour, and Ref.: reference sites.

Reference areas had significantly lower soil moisture than treatments across all sites (data not shown). Soil moisture at 15–25 cm was also significantly higher than soil moisture at 0–15 cm across sites (data not shown). While soil moisture varied by site, treatment, depth and landscape position, few differences were found among treatment:landscape position combinations (Fig. 4). No differences were found at 15–25 cm soil depth when comparing similar positions in relation to the road. At 0–15 cm soil depth, soil moisture below recontoured plots was significantly greater than those on reference plots and above the control plots. Soil moisture at 0–15 cm soil depth tended to be greater within the road on control and subsoiled plots whereas on recontoured plots soil moisture tended to increase from the road to the below road locations.

3.5. Seedling growth

Although survival was 95% or greater on all the treatment plots, deer browsing was a problem for eastern white pine seedlings at the Moore Branch and Road Branch sites. Deer browsing on eastern white pine terminal buds was very evident during both our first and second year diameter and height measurements. As a result, height growth varied by site but not by treatment with negative growth occurring at the Moore Branch site (data not shown). Despite the deer browsing, eastern white pine diameter growth did vary by treatment (Fig. 5). Recontour and subsoil treatments had significantly greater diameter growth than control plots. Yellow-poplar were much less susceptible to deer browsing. Yellow-poplar diameter and height growth varied by site and by treatment. The Mead site had significantly greater growth than both Road Branch and Moore Branch sites (data not shown). Road Branch also had significantly greater growth than the Moore Branch site (data not shown). Yellow-poplar diameter and height growth was greatest for recontoured plots followed by the subsoiled plots and the control plots (Fig. 6). Both height and diameter for yellow-poplar follow similar trends with increases of 130% for recontour versus control, 75% for subsoil versus control and 30% for recontour versus subsoil.

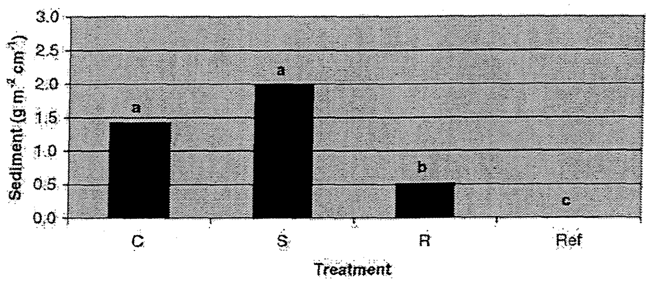

Fig. 3. Sediment production as function of incident precipitation by treatment. The units are amount the amount of sediment produced (g m^{-2}) per cm of incident precipitation. For treatments – C: control, S: subsoil, R: recontour, and Ref.: reference sites.

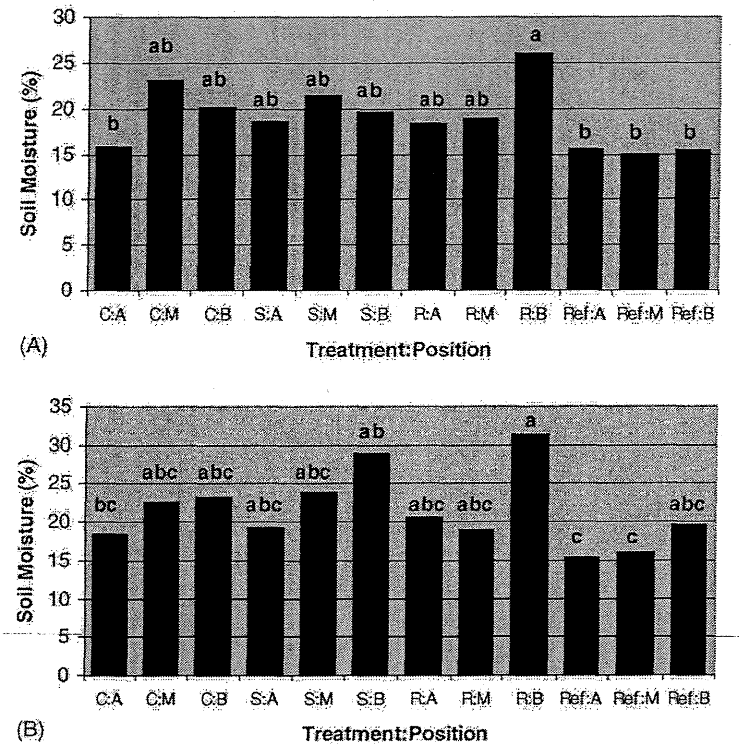

Fig. 4. Volumetric soil moisture comparison among treatments and landscape position at (A) 0–15 cm and (B) 15–25 cm. For treatments – C: control, S: subsoil, R: recontour, and Ref.: reference sites. For landscape position – A: above road, M: middle of road, B: below road.

4. Discussion

Treatment effects indicate that recontouring produces lower density soils that produce less runoff and sediment than subsoiling or traditional retirement methods (control treatment) (Figs. 1–3). Surprisingly we found no differences in soil bulk density, surface runoff and sediment production between subsoiling and the control treatment. During subsoiling it does not appear that the soil surface density or porosity is dramatically affected. However, Heninger et al. (2002) found that subsoiling did significantly decrease bulk density on skid trails at 0–40 cm depth in Oregon. In this study we only measured surface bulk density (0–10 cm), not subsurface soil bulk density and our bulk density was a whole soil density, not fine soil bulk density as in the Heninger et al. (2002) study. We are not surprised by our surface bulk density results because of the way the winged subsoiler tills the soil. The winged subsoiler essentially lifts the soil in place and drops it back down with little surface disturbance. It is quite conceivable that subsoil densities may have decreased without affecting surface densities.

Few studies have reported surface runoff from forest roads. Studies on the lower coastal plain of North Carolina report 6–19% of incident precipitation occurring as surface runoff (Appelboom et al., 2002). Lower runoff percentages are associated with graveled roads with grassed buffer strips along the downslope road edge, whereas higher percentages are associated with no gravel or grassed strip. Studies in tropical rainforests in Indonesia indicate 62–72% of incident precipitation leads to surface runoff on recently constructed skid roads, however, harvested areas only had 0.20–0.35% of incident precipitation occurring as surface runoff (Hartanto et al., 2003). While comparisons are difficult because of the varying climate, slope, soils and treatments in our study, our reference condition led to similar runoff percentages as harvested areas in Indonesia, and our treatment runoff percentages (4–9%; Fig. 2) are near the range of those found in North Carolina (Appelboom et al., 2002).

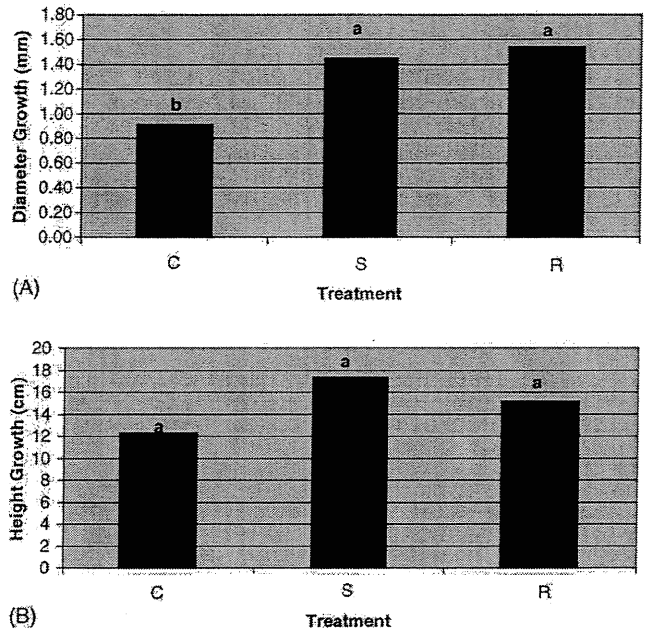

Fig. 5. Two year diameter (A) and height growth (B) for eastern white pine by treatment. For treatments – C: control, S: subsoil, and R: recontour.

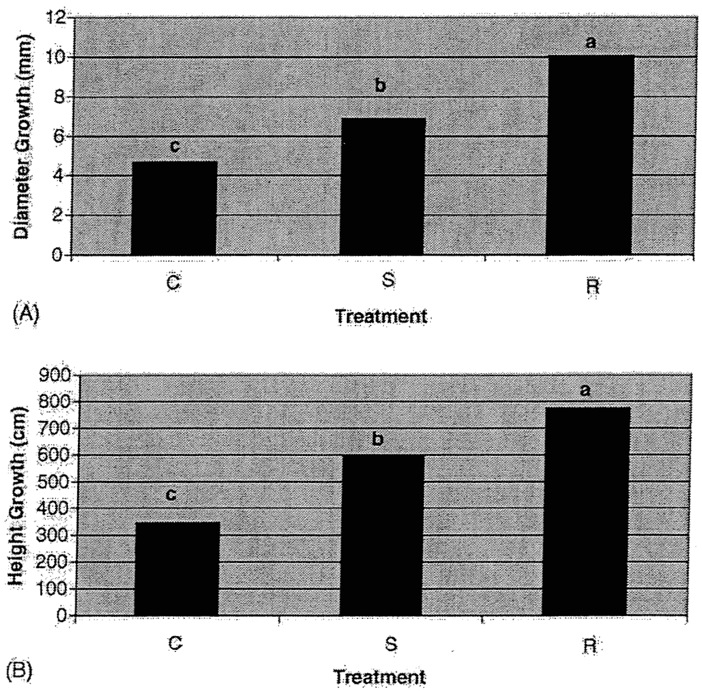

Fig. 6. Two year diameter (A) and height growth (B) for yellow-poplar by treatment. For treatments – C: control, S: subsoil, and R: recontour.

A number of studies have reported sediment production from various types of forest roads and retirement techniques. The North Carolina study cited above reported 0.08–0.8 g m^{-2} cm^{-1} with graveled and grassed stripped roads on the low end of the results and no gravel, no grass strips on the high end of the results (Appelboom et al., 2002). The Indonesian study discussed above reported 21–115 g m^{-2} cm^{-1} on recently developed skid roads, while only 0.004–0.020 g m^{-2} cm^{-1} on harvested plots (Hartanto et al., 2003). Studies in eucalyptus forests in Australia indicate that time since skid road retirement plays and important role in sediment transport. Recently retired skid roads produced 20–96 g m^{-2} cm^{-1} of sediment whereas those retired for 5 years only produced 0.5–8.4 g m^{-2} cm^{-1} (Croke et al., 2001). Other studies in eucalyptus forests in Australia indicate that 31–56 g m^{-2} cm^{-1} of sediment are produced from skid roads depending on the level of use, maintenance, and the amount of gravel used (Grayson et al., 1993). A study in Alabama assessed the influence of revegetating forest roads with native grasses, exotic grasses and the use of erosion mats on sediment production (Grace, 2002). Unvegetated controls produced 27 g m^{-2} cm^{-1}, followed by 11 g m^{-2} cm^{-1} for native species, 8.0 g m^{-2} cm^{-1} for erosion mats and 4.5 g m^{-2} cm^{-1} for exotic species. Earlier research in the southern Appalachian Mountains of North Carolina determined forest roads covered in large stone decreases sediment production when compared to retirement with grass or bare soil (~5 g m^{-2} cm^{-1} versus 65 g m^{-2} cm^{-1} versus 120 g m^{-2} cm^{-1}, respectively; Swift, 1988). As for surface runoff, few of these studies compare well with our study because of variation in climate, landscape and treatment types. Our sediment production averaged from a low of nearly zero on our reference sites to 2 g m^{-2} cm^{-1} on our subsoiled sites. In general our sediment production rates are lower than those found in the literature probably as a result of the seeded grass cover that quickly established on our treatments. Also, at least for the recontoured treatment, the treatment itself led to lower surface runoff and sediment production. No studies that we are aware of have investigated surface runoff or sediment production on forest roads that have been subsoiled or recontoured.

Although there were few differences in soil moisture among treatments, the trends indicate that more soil moisture was held within road sections on the traditional retirement (control) and subsoiled treatments whereas recontoured sites had greater soil moisture below the road than within the road (Fig. 4). Lower soil moisture held in the road section of the recontoured and reference plots also likely led to the lower surface runoff observed when compared to the traditional retirement and subsoiled treatments.

Seedling growth for eastern white pine is difficult to interpret as a result of animal browsing. Yellow-poplar was rarely browsed and provides a better comparison for site and treatment effects. Among treatments, it is clear that recontouring provides the greatest productivity in the first 2 years of seedling growth. Yellow-poplar diameter and height growth in the recontoured treatment are more than double that observed on the traditional retirement treatment. Subsoiling also provides some productivity benefits over the traditional retirement method (control plots) with diameter and height growth about 1.5 times that of the control treatment. Although a number of studies have assessed the productivity of forest roads including using a number of amelioration techniques such as disking, bedding, raking, mulching, fertilization and organic amendments (e.g., Reisinger et al., 1992; Scheerer et al., 1994; Bulmer, 2000), we are only aware of two studies that have assessed productivity gains from subsoiling and only one study that has investigated recontouring the hillslope. Although not conducted on forest roads, subsoiling was used to ameliorate compacted forest soils in Arkansas and Oklahoma with loblolly pine (*Pinus taeda* L.) mean height growth approximately 0.5 m greater in subsoiled areas than control (no tillage) areas 19 years after planting (Fallis and Duzan, 1994). Studies in Oregon grouped two types of tillage into a single analysis (Heninger et al., 2002). Investigators studied eight locations for Douglas-fir (*Pseudotsuga menzieii* (Mirb.) Franco) growth where seven sites were tilled with rock ripping tines while the eighth site was tilled with the winged subsoiler. After 10 years, height was 11% greater and volume was 34% greater on tilled sites than on non-tilled sites. Height and volume of Douglas-fir on tilled sites was similar to logged only sites (Heninger et al., 2002). Dykstra and Curran (2000) studied growth on recontoured hillslopes in southeast British Columbia but had no traditionally retired, compacted treatment. They assessed 3–9 year growth at 10 sites on specific locations across the previous road prism and found that volume and height growth was generally less in the former midroad and inner track sections than on the former berm or in undisturbed forest. Dykstra and Curran (2000) attribute these growth differences to the underlying compacted road that still remains after recontouring and recommend "decompacting" skid trails prior to recontouring.

It is apparent from the combination of data in this study that recontouring to ameliorate forest roads leads to both lower surface runoff and sediment production, initial higher productivity, and different soil moisture gradients than subsoiling or traditional retirement methods. However, previous cost analyses indicate that recontouring (~\$3000 ha^{-1} of treated area) is 4–6 times more expensive than either subsoiling (~\$600–800 ha^{-1}) or traditional retirement methods (~\$550 ha^{-1}) for high gradient slopes in Kentucky (Shouse et al., 2001; Smidt and Kolka, 2001). The results of this study lead to some critical questions regarding the value of the increased productivity and the environmental benefits of recontouring. From a productivity perspective, does the increase in productivity resulting from both subsoiling and recontouring justify the extra costs associated with these amelioration techniques? Using a 4% discount rate (Pelkki and Arthaud, 1998) reported that an increase in site index (base age 50) from 27 to 30 m increased soil expectation value (SEV) of optimal rotations from \$165 to \$235 ha^{-1} over a range in stand quality and product value. The change in SEV resulting from a 22% increase in site index equals or exceeds the difference in cost between subsoiling and traditional retirement. Given the early growth results from the treatments that magnitude difference is possible. On the other hand it is difficult to imagine a scenario where SEVs increase enough to cover the additional cost of recontouring. Even if recontouring leads to a 45% boost in site index, SEV increased less than \$380 ha^{-1} (Pelkki and Arthaud, 1998).

Subsoiling is likely the preferred economic choice since the return is likely to exceed the hurdle rate. The traditional retirement cost is a sunk cost of harvesting paid out of stumpage so no return on investment is applied. The unknown value remains the value of decreased surface runoff, decreased sediment production and the recovery of soil bulk density and hillslope water relations. If those environmental benefits are worth a minimum of \$2200 ha^{-1}, the preferred choice may be recontouring.

5. Conclusions

Since BMPs directly address the potential off-site impacts of forest disturbance, often these practices may have little effect on the land managers primary consideration, stewardship of their forest land. This study begins to address important questions managers must answer to make effective harvest planning and amelioration decisions including "what are the environmental and economic consequences of various forest road amelioration techniques" and, "does the potential long-term loss of productivity justify management and harvesting alternatives that; (a) use harvest planning to minimize extent of severe disturbance while using ground-based harvesting systems, (b) change, if feasible, to aerial harvesting systems with lower road densities, and/or (c) ameliorate soil damage through specific methods that are likely to be cost effective?" Based on the results from this study, it is apparent that only recontouring provides environmental benefits when compared to subsoiling and traditional retirement methods, however, like recontouring, subsoiling also leads to gains in forest productivity and provides the greatest economic return if environmental benefits are not considered.

Acknowledgements

This study was made possible by grants from the USDA Forest Service Southern Research Station, University of Kentucky College of Agriculture, Kentucky Water Resources Institute, and the E.O. Robinson Trust Fund. We would also like to thank Auburn University, the Daniel Boone National Forest, Ed and Susan Fields of Tilth, Inc., Mead Paper and Pulp Complany: Fine Paper Division, University of Kentucky Cooperative Extension Service, Whayne Supply Inc., and Christopher Yeary for their contributions.

References

Andrus, C.W., Froehlich, H.A., 1983. An evaluation of four implements used to till compacted forest soils in the Pacific Northwest. For. Res. Lab., Ore. State Univ., Res. Bull. No. 45.

Appelboom, T.W., Chescheir, G.M., Skaggs, R.W., Hesterberg, D.L., 2002. Management practices for sediment reduction from forest roads in the Coastal Plain. Trans. ASAE 45 (2), 337–344.

Arthur, M.A., Coltharp, G.B., Brown, D.L., 1998. Effects of best management practices on forest streamwater quality in Eastern Kentucky. J. Am. Wat. Resour. Ass. 34 (3), 481–495.

Binkley, D., 1986. Forest Nutrition Management, Wiley, New York.

Bulmer, C., 2000. Reclamation of forest soils with excavator tillage and organic amendments. For. Ecol. Manage. 133, 157–163.

Carr, W.W., 1987. The effect of landing construction on some forest soil properties: a case study. Can. For. Serv. and B.C. Min. For. FRDA Rep. 003.

Croke, J., Hairsine, P., Fogarty, P., 2001. Soil recovery from track construction and harvesting changes in surface infiltration, erosion, and delivery rates with time. For. Ecol. Manage. 143, 3–12.

Dykstra, P.R., Curran, M.P., 2000. Tree growth on rehabilitated skid roads in southeast British Columbia. For. Ecol. Manage. 133, 145–156.

Fallis, F.G., Duzan Jr., H.W., 1994. Effects of ripping (deep subsoiling) on loblolly pine plantation establishment and growth – nineteen years later, Proceedings of the Eighth Biennial Southern Silviculture Conference, Auburn, AL, pp. 525–529.

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

Froehlich, H.A., Miles, D.W.R., Robbins, R.W., 1986. Growth of young *Pinus ponderosa* and *Pinus contorta* on compacted soil in central Washington. For. Ecol. Manage. 15, 285–294.

Froelich, H.A., Miles, D.W.R., Robbins, R.W., 1985. Soil bulk density recovery on compacted skid trails in central Idaho. Soil Sci. Soc. Am. J. 49, 1015–1017.

Grace III, J.M., 2002. Effectiveness of vegetation in erosion control from forest road sideslopes. Trans. ASAE 45 (3), 681–685.

Grayson, R.B., Haydon, S.R., Jayasuriya, M.D.A., Finlayson, B.L., 1993. Water quality in mountain ash forests – separating the impacts of roads from those of logging operations. J. Hydrol. 150, 459–480.

Hartanto, H., Prabhu, R., Widayat, A.S.E., Asdak, C., 2003. Factors affecting runoff and soil erosion: plot level soil loss monitoring for assessing sustainability of forest management. For. Ecol. Manage. 180, 361–374.

Hatchell, G.E., Ralston, C.W., Foil, R.R., 1970. Soil disturbances in logging-effects of soil characteristics and growth of loblolly pine in the Atlantic Coastal Plain. J. For. 68, 772–775.

Heninger, R., Scott, W., Dobkowski, A., Miller, R., Anderson, H., Duke, S., 2002. Soil disturbance and 10-year growth response of coast Douglas-fir on nontilled and tilled skid trails in the Oregon Cascades. Can. J. For. Res. 32, 233–246.

Ketcheson, G.L., Megahan, W.F., King, J.G., 1999. "R1-R4" and "BOISED" sediment prediction model tests using forest roads in granitics. J. Am. Wat. Resour. Ass. 35 (1), 83–98.

Kochenderfer, J.N., 1977. Area in skidroads, truck roads and landings in the central Appalachians. J. For. 75, 507–508.

Lawrie, D., Krag, R.K., Sanborn, P., Bulmer, C., 1996. Reclamation of compacted fine-textured soils on the Aleza Lake research forest using a winged subsoiler and a hydraulic excavator. For. Eng. Res. Inst. of Can. TN-000250, 15 pp.

Luce, C.H., 1997. Effectiveness of road ripping in restoring infiltration capacity of forest roads. Rest. Ecol. 5 (3), 265–270.

Mace, A.C., 1971. Recovery of forest soils from compaction by rubber-tired skidders. Univ. of Minn. Minn. For. Res. Notes No. 226.

Martin, C.W., 1988. Soil disturbance by logging in New England – review and management recommendations. N. J. App. For. 5, 30–34.

Miller, J.H., Sirois, D.L., 1986. Soil disturbance by skyline vs. skidding in a loamy hill forest. Soil Sci. Soc. Am. J. 50, 1579–1583.

Moehring, D.M., Rawls, I.K., 1970. Detrimental effects of wet weather logging. J. For. 68, 166–167.

Moll, J.E., 1996. A guide for road closure and obliteration in the Forest Service. Publ. 9677 1205-SDTDC (Washington, DC). USDA Forest Service Technology and Development Program, 49 pp.

National Council for Air and Stream Improvement, 1999a. Scale considerations and detectability of sedimentary cumulative watershed effects. Technical Bulletin No. 776, Research Triangle Park, NC.

National Council for Air and Stream Improvement, 1999b. Assessing effects of timber harvest on riparian zone features and functions for aquatic and wildlife habitat. Technical Bulletin No. 775, Research Triangle Park, NC.

Page-Dumroese, D.S., Jurgensen, M.F., Brown, R.E., Mroz, G.D., 1999. Comparison of methods of determining bulk density of rocky forest soils. Soil Sci. Soc. Am. J. 63, 379–383.

Pelkki, M.H., Arthaud, G.J., 1998. Evaluating changes in yellow-poplar management in response to new low-end markets. N. J. App. For. 15 (1), 37–42.

Pfister, R.D., 1969. Effects of roads on growth of western white pine plantations in northern Idaho. USDA For. Serv. Res. Pap. INT-65.

Pritchett, W.L., Fisher, R.F., 1987. Properties and Management of Forest Soils, Wiley, New York.

Reisinger, T.W., Pope, P.E., Hammond, S.C., 1992. Natural recovery of compacted soils in an upland hardwood forest in Indiana. N. J. App. For. 9 (4), 138–141.

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

Scheerer, G.A., Aust, W.M., Burger, J.A., McKee Jr., W.H., 1994. Skid trail amelioration following timber harvesting on wet pine flats in South Carolina: two-year results, Proceedings of the Eighth Biennial Southern Silviculture Conference, Auburn, AL, pp. 236–243.

Shouse, S., Stringer, J., Smidt, M., Pelkki, M., Ringe, J., Kolka, R., 2001. Machine and labor times required to implement

Kentucky's skid trail erosion control and revegetation BMPs. In: Wang, J., Wolford, M., McNeel, J., Snowshoe, W.V. (Eds.), Proceedings of the Council on Forest Engineering, Snowshoe, WV, USA.

Smidt, M.F., Kolka, R.K., 2001. Alternative skid trail retirement options for steep terrain logging. In: Wang, J., Wolford, M., McNeel, J. (Eds.), Proceedings of the Council on Forest Engineering, Snowshoe, WV.

Smith R.B., Wass, E.F., 1984. Preliminary assessment of impacts of two stumping operations on site productivity, interior British Columbia. In: Proceedings of the 1983 Soc. Am. For. Nat. Conven., Portland, OR, pp. 247–251.

Smith, R.B., Wass, E.F., 1980.Tree growth on skidroads on steep slopes logged after wildfires in Central and Southestern British Columbia. Can. For. Serv., Pac. For. Res. Cen., Victoria, BC. Inf. Rep. BC-R-6.

Smith, R.B., Wass, E.F., 1979. Tree growth on and adjacent to contour skidroads in the subalpine zone, south-eastern British Columbia, Env. Can., Can. For. Serv. Victoria, B.C.

Stewart, R., Froehlich, H., Olsen, E., 1988. Soil compaction: an economic model. W. J. App. For. 3 (1), 20–22.

Stringer, J., Lowe, L., Smidt, M.F., Perkins, C., 1997. Field guide to best management practices for timber harvesting in Kentucky. Univ. of KY, Coop. Ext. Serv., Dept. of For. FOR-69.

Stuart, W.B., Carr, J.L., 1991. Harvesting impacts on steep slopes in Virginia. In: Proceedings of the Eighth Central Hardwood Conference, March 4–6, 1991. Morgantown, WV, USDA Gen. Tech. Rep. NE-148, pp. 67-81.

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

Thorud, D.B., Frissell, S.S., Jr., 1976. Time changes in soil density following compaction under an oak forest. Univ. of Minn. Minn. For. Res. Notes No. 257.

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

Wronski, E.B., Murphy, G., 1994. Responses of Forest Crops to Soil Compaction, In: Soil Compaction in Crop Production, Elsevier, The Netherlands.