

Logging Operations and Soil Compaction

Manisha Parajuli, PhD, Patrick Hiesl, PhD, Donald Hagan, PhD, Puskar Khanal, PhD

Clemson University, College of Agriculture, Forestry and Life Sciences, Forestry and Environmental Conservation Department

Soil is highly sensitive to improper logging activities that can cause long-lasting soil compaction and reduce forest productivity, seedling growth, and survival. All logging operations can cause soil compaction; however, the extent and severity of compaction depend on various factors such as soil type, harvesting equipment, number of machine cycles, time of the year, and slope. Soil compaction during logging operations can be minimized by limiting heavy machinery in the steep slopes, avoiding logging in wet areas, and applying slash and brush mats on the skid trails. Forest landowners, managers, and loggers can use the information in this article to profit from logging and protect and minimize negative impacts on the harvested site.

Introduction

Forest landowners may have multiple forest management objectives such as timber production, forest health, wildlife habitat enhancement, recreation, or aesthetics. Different harvesting systems can be used to meet these objectives. Worldwide, mechanized harvesting systems ranging from site preparation to final harvest is increasing. In South Carolina, less than 2% of respondents of a logging business survey in 2017 reported using a chainsaw harvesting system.¹

In the southeastern United States, the whole-tree harvesting method is most common. With whole-tree harvesting, trees are cut and transported to the landing with the top and branches still attached to the bole. In this method, harvesting equipment includes wheeled feller-buncher (figure 1), grapple skidder (figure 2), loader, and delimber.²



Figure 1. Feller-buncher. Image credit: Manisha Parajuli, Clemson University.



Figure 2. Grapple skidder pulling a pile of trees. Image credit: Patrick Hiesl, Clemson University.

In addition, a delimbing gate (which has a large metal frame with cross beams) is sometimes used to break off many branches before the tree is processed by the loader and pull-through delimber.³ For a brief overview of mechanized harvesting equipment used in South Carolina, see the Land-Grant Press publication, [Timber Harvesting Equipment in South Carolina](https://bit.ly/36hZwRx) (bit.ly/36hZwRx). The use of heavy machinery in logging operations can increase the productivity of the

harvesting system.⁴ However, heavy machinery can cause soil compaction and loss soil productivity, which consequently affects regeneration establishment and tree growth.⁵⁻⁷

Factors Affecting Soil Compaction

Soil compaction occurs when soil particles are pressed together, reducing pore space between them, and increasing bulk density (the weight of soil per volume). As Howard W. Lull said, “whenever you put a foot down on forest or rangeland, you are to a degree compacting the soil.”⁸ The extent and severity of soil compaction are influenced by several factors such as soil texture, soil structure, type of machinery used, the number of machine passes, time of the year of harvest, and slope.^{6,9,10}

Soil Texture and Soil Structure

Soil texture refers to the relative percentage of sand, silt, and clay within a soil layer. A fine-textured soil has a high proportion of finer particles such as silt and clay, while a coarse-textured soil has a high proportion of sand. Clayey soils, sands, and sandy soils are difficult to compress, but moderately textured soils such as loam, silt loam, sandy loam are easily compressed and are most susceptible to compaction. The relationship between soil compaction and soil texture implies particular attention to soil conditions when logging on moderately-textured soils.¹¹ The textures of South Carolina soils range widely from deep sandy soils in the Coastal Plain and clayey ultisols in the Piedmont to steep rocky inceptisols in the mountainous Blue Ridge region.

Soil structure refers to the arrangement of individual soil particles (sand, silt, and clay) in relation to each other and their aggregation into varying sizes and shapes. Soil organic matter causes soil to clump and plays a significant role in forming soil aggregates that improve soil structure. Therefore, an increase in soil particle aggregation enhances the capacity of soil to resist heavy machinery pressure.^{6,12} In the Piedmont region, as soil bulk density increases, porosity decreases, and hydraulic conductivity also decreases to an average depth of 6.7 inches following whole-tree harvesting operations.¹³ Machine-induced soil compaction is strongly affected by soil texture and structure, and the impact can last for decades.¹⁴⁻¹⁶

Harvesting Equipment

Whether for site preparation or timber harvesting operations, equipment used in forestry can have different wheels, tracks, load capacities, and sizes. The pressure on the soil varies with the number of wheels or tracks, size of the wheels or tracks, the machine's weight, the load of the harvested timber, and tire pressure.^{17,18} Most of the machinery used in logging operations ranges from 11,000 to 121,000 pounds.^{6,19,20} As the machine pressure exceeds the internal soil strength, soil particles get pressed together, increasing soil compaction.²¹ On the one hand, compaction helps support the equipment, but on the other hand, it can make the soil impenetrable for plant roots, influencing soil water relations and gas exchange.⁶

In deeper soil layers, machine pressure is less because the mechanical force is spread over a larger soil volume. Therefore, when the pressure per unit soil volume decreases, soil compaction becomes less.^{22,23} The highest degree of soil compaction commonly occurs within the first 12 inches of the soil.²⁴ However, it can also reach up to a depth of 39 inches depending upon the types of equipment used, initial soil density, and soil moisture level.²⁵

Numbers of Machine Cycles

A machine cycle is defined as one empty and one loaded trip. The number of machine cycles necessary for any harvesting operation depends on the machine's capacity and site characteristics. Regardless of the machine type, the soil's bulk density increases up to 50% with the first three passes.^{26,27} After ten passes, the bulk density of the soil increases at a much slower rate.¹³



Time of the Year

The time of the year when logging occurs impacts soil compaction potential as it correlates with soil moisture and rainfall frequency. Soil moisture is the ratio of the volume of water held in the soil relative to dry soil. Soil compaction commonly occurs when the moisture content in the soil is around 30%.²⁸ Soil pore water acts as a lubricant of surrounding soil particles, permitting easier movement.²⁹ Thus, an increase in water content reduces cohesion (togetherness) forces between soil particles, decreasing soil weight-bearing capacity.²¹ Reducing soil weight-bearing capacity, in turn, increases the risk of soil compaction.⁶

Slope

Forest soil compaction is unavoidable in logging operations and the degree and extent of soil compaction increase with the forest slope gradient.^{5,30,31} As the slope increases, the degree of soil compaction by harvesting equipment can increase faster (i.e., after relatively few machines passes), increasing soil bulk density while decreasing soil porosity.³² The strong adverse effect of increasing skid trail slope on soil compaction is likely due to the difficulties in skidding on steep terrain where machine wheels can slip, pushing soil particles closer together.^{32,33} In addition, lower speed on a steep slope increases the topsoil vibration that causes severe soil compaction compared to flat terrain.^{27,34,35} Further, changes in machine weight distribution toward the rear axle when driving uphill in steeper terrain mean that the rear axle carries a greater load, resulting in higher ground pressure for the same load than flat terrain. Bulk density and rut depth increase with the increase of traffic frequency and slope. Therefore, ground-based logging operation is suitable for slopes less than 30%. For slopes greater than 30%, ground-based operations are feasible following some extra precautions to protect soils and prevent erosion. However, in many instances, cable logging operation can be a better alternative.^{30,36}

Effects of Soil Compaction

Soil compaction detrimentally affects soil physio-chemical and biological properties, creating unfavorable plant growth conditions and reducing plant productivity.^{5,6,30} Compacted soil alters the physiological function of plants by affecting the availability of water, minerals, and soil air and increases the potential for runoff and erosion. For example, research conducted in the Coastal Plain region of South Carolina reported that the height of one-year-old loblolly pine seedling on compacted skid trails was 40 to 50% less than height growth on non-compacted soil.³⁷ However, all soil compaction is not harmful to plant growth. In coarse-textured soils, moderate soil compaction can improve the capillary forces that slow the downward movement of water and thus promotes tree growth. Similarly, in finer texture soil, the uptake of nitrogen can be improved by soil compaction and retention of the forest floor.^{38,39}

Increased Bulk Density

Soil with low initial bulk density is the most vulnerable to compaction.⁴⁰ A soil with low bulk density contains many macropores (pore spaces greater than 0.003 inches) that are easy to compact. As the macropores are compressed into micropores (pore spaces less than 0.003 inches), soil bulk density increases, increasing soil resistance to compaction forces.^{23,41,42}

Surface soil compaction and bulk density of the upper eight inches of the soil profile are typically greater at harvested sites than at unharvested sites, regardless of slope position, soil texture, or time of the year of harvest.⁴³ The amount of soil compaction depends on the initial bulk density. For example, research conducted in Mississippi and Louisiana in clay loam and loamy soils shows that when the initial bulk density of soil is 87.4 lb/ft³ or more, it does not cause further compaction because the soil is already dense.⁴⁴ However, forest soils generally have a bulk density lower than 87.4 lb/ft³ due to the high organic matter content and macroporosity. In the Piedmont region of the southeastern United States, soil bulk density increased by 17% after whole-tree harvesting.¹³ An increase in soil bulk density negatively affects forest regeneration by inhibiting seed germination.⁴⁵ Even if seeds germinate in the heavily compacted soil, they may not survive because the emerging radicle will not penetrate the dense soil surface.⁴⁶



Reduced Soil Porosity

When bulk density increases, soil porosity decreases.⁶ Soil porosity is the volume percentage of the total bulk soil not occupied by the solid particles but by air or water. Forest soils are especially susceptible to compaction due to their loose, fragile structure and high porosity.⁵ In South Carolina, sandy subsoils have porosity values greater than 10%, sandy clay loam soil porosity averages 9%, clay loam soil porosity is 7%, and clay soil porosity is 5%.⁴⁷

Harvesting equipment that passes over the soil surface exerts force onto the soil surface, compressing the soil and reducing soil porosity.⁴⁸ When soil porosity declines, previously open spaces are filled with soil solids. Compaction caused by machine traffic can reduce porosity up to 60%.^{6,26,49} Regardless of soil texture, the total porosity of the soil located in the operating machine trail is considerably lower than that of the undisturbed area. Soil porosity also decreases consistently with increasing traffic frequencies.^{6,26,49,50}

Roots rely on pore spaces in the soil to penetrate deeper into the soil profile, but in compacted soil, the pore spaces can be too limited to permit the elongation and penetration of plant roots.^{51,52} As root growth is restricted, plants cannot exploit the soil for nutrients and moisture, leading to stunted growth and seedling mortality.^{21,45}

Decreased Hydraulic Conductivity

Reducing soil porosity through compaction simultaneously reduces water holding capacity, infiltration rate, and hydraulic conductivity.⁴⁵ A decrease in water infiltration rate and hydraulic conductivity in forest soils could benefit plants in sandy soils that would otherwise drain quickly. However, reduced soil porosity may also lead to soil water deficiency, increased waterlogging, standing water on flat terrain, increased surface runoff, and erosion on steeper slopes.^{6,10,53} In waterlogged areas, plant roots are both more stressed and likely to come into contact with *Phytophthora* spp., a water-borne plant pathogen that causes root dieback and eventual plant death.⁵⁴ Similarly, upland plant species may die because their roots are not adapted to permit gas exchange in saturated (low-oxygen) soils.⁵⁵

Decreased Gas Diffusivity

Compacted soil has a higher carbon dioxide to oxygen (CO₂:O₂) concentration ratio relative to undisturbed soils. Higher CO₂:O₂ ratios in compacted soils result from decreased gas diffusivity (gas interchange between soil and atmosphere). When the CO₂:O₂ concentration ratio increases, it impedes root respiration and root growth. When oxygen concentration drops below the 6-10% range, it hinders the uptake of water and nutrients and can inhibit seedling growth affecting the natural regeneration of the forest.⁵⁶

Potential Runoff and Erosion

Logging operations can cause crucial changes in the characteristics of the soil; they can remove the fertile topsoil and herbaceous cover, alter soil characteristics, hinder forest regeneration, and reduce root growth.^{6,48,57,58} Bare and compacted soils resulting from logging operations are potential sites for erosion and surface runoff.⁵⁹ Surface runoff and erosion lead to the loss of mineral nutrients. In disturbed or compacted sites, soil erosion begins with the detachment of the soil particles from the soil mass. If harvesting is improperly implemented on a sloping site, timber extraction with skidders could lead to high soil compaction and later to soil erosion and rutting, especially along skid trails.⁶ Ruts function like a pathway for water runoff on steep slopes, thus causing gully formation and soil erosion.³³ When the slope becomes greater than 25%, runoff risk increases substantially.⁶⁰ If compaction is extensive, increased surface runoff may also increase stream flows after rainfall events, increasing the potential for channel scouring that contributes to water quality issues like sedimentation.^{48,61,62}

Management Strategies

Increased heavy machinery use in logging operations can cause several negative environmental impacts, necessitating the strict application of management strategies. The US Forest Service has a monitoring guideline that more than a 15%



increase in soil bulk density is detrimental to forest sustainability and recommends applying soil compaction prevention strategies during logging operations.⁶³ Strategies for limiting soil compaction include minimizing skid trail gradients, selecting suitable equipment, avoiding waterlogged areas, and applying slash and brush mats during harvesting.

Skid Trail Gradient

Skid trails are temporary trails constructed in the forest to connect the harvested area to the landing. A straightforward technique to minimize soil compaction is to use designated skid trails to limit the extent of soil compaction.^{15,32} It is also necessary to limit the length of logs transported on skid trails. Longer logs are more likely to extend outside the skid trail, causing soil compaction when dragged over the soil.³² Trail gradients exceeding 20% should be avoided when possible.³² If unavoidable, only a few uphill skidding passes should be permitted at steep grades, considering the increased risk of runoff and erosion on these slopes. Implementing best management practices such as installing water bars and soil stabilization on hillsides are also recommended on steep trails. Soil stabilization includes mulching, rocking, seeding with grasses, or using erosion-resistant fabrics. The South Carolina Forestry Commission provides specific recommendations in the [Best Management Practices \(BMPs\) for Forestry manual](https://bit.ly/3CH3BuE) (bit.ly/3CH3BuE). The recommendation in the manual for spacing water bars is 245 feet, 125 feet, and 80 feet when the slope is 2%, 5%, and 10%, respectively.

Selection of Suitable Equipment

Reducing heavy machinery traffic reduces the harmful effects on ground vegetation and forest regeneration. Reduced traffic can be achieved using light equipment, increasing the number of tires, and using wider tires.²¹ Equipment with wider tires or tracks placed around wheels can reduce soil compaction compared to equipment without tracks by displacing machine weight over a greater surface area than tires alone.^{18,64} The effective reduction in compaction comes from limiting the land area where heavy machinery operates, not necessarily by reducing machine cycles on a given skid trail. Similarly, harvesting on a steep slope demands suitable harvesting methods and harvesting equipment. The cable logging method is well-suited for use on steep slope areas because it causes a very low amount of soil disturbance compared to ground-based logging systems.^{65–67} The degree of surface disturbance using cable logging systems is only 1% compared to 5±11% for ground-based logging systems.⁶⁷ In the southern upland hardwood forest, cable logging is suited well on slopes greater than 30%.⁶⁸ However, the cable logging system is more expensive than a ground-based system.⁶⁹ Cable logging systems are rarely used on flat terrain.

Avoid Waterlogged Areas

Swampy areas, bottomland hardwood sites, and other wetland areas have saturated soil for much of the year. Using equipment with wider wheels or tracks provides low ground pressure and reduces soil compaction. Avoiding logging activities in wet soil or allowing water to drain naturally is the best way to minimize soil compaction risk.^{70,71} Logging under dry conditions can eliminate intensive site preparation and skid road rehabilitation costs.

Shovel logging is mainly used in wet bottomland hardwoods in the southern United States. If waterlogged areas, swamps, and other low-lying areas subjected to flooding still need to be harvested, it typically requires the shovel logging method (figure 3).⁷⁰ In this method, cut trees can be placed on the ground to construct a temporary skid trail.⁷² The skidder uses the same skid trail to harvest and skid timber during wet ground conditions. These trails are also known as shovel roads. The primary purpose of the shovel road is to prevent skidders from sinking into the wet ground and reduce ground pressure caused by the movement of skidders.³ The shovel logging method has less impact on the forest soil than other ground-



Figure 3. Shovel logging with cut trees to construct a temporary skid trail. Image credit: Patrick Hiesl, Clemson University.



COOPERATIVE EXTENSION
College of Agriculture, Forestry and Life Sciences

based logging methods.⁷³ Equipment used when shovel logging has a high flotation undercarriage to provide a stable operating base.

Slash and Brush Mats

Soil compaction can be reduced by applying slash and brush mats and limiting the number of machine passes on a skid trail (figure 4).^{20,26,74} The use of mats made from treetops and branches is more effective because the machine's weight is spread over a greater area than the actual area of the machine, which reduces the wheel pressure on the soil.⁷⁴ For instance, brush mats of 3 to 4 lb/ft² along machine operating trails have less soil compaction caused by timber harvesting equipment than the trail segments with no brush mats.⁷⁵ The degree of soil compaction decreases as the amount of logging slash applied increases. Heavy slash (8 lb/ft²) is more effective in reducing soil compaction than light slash (1.5 lb/ft²).²⁸



Figure 4. Application of slash in the forest skid trail. Image credit: Courtesy of Maine Forest Service - Forest Policy and Management.

The protective role of the brush mat is undeniable when compared to timber extraction over bare soil. Yet, using slash and brush mats cannot prevent compaction completely because the soil under the brush mats can experience at least 18 inches of compaction.⁷⁴

Strategies for the Recovery of Compacted Soil

Forest soil compaction during logging operations is unavoidable. The natural soil recovery rate depends on the type of soil and depth of the compacted layer, where coarse-textured soils with a shallow compaction depth typically recover faster.^{6,76} In the southern region, the natural recovery rate of compacted soil is very slow and may take as long as 60 years due to the absence of freezing and thawing cycles.^{77,78} The freezing and thawing cycle, macro and microbial activities, and function of plant roots can naturally improve the compacted topsoil over time but not the subsoils. Site preparation treatments such as bedding and mole-plowing can be used for speeding up the recovery process of the compacted soil.⁷⁹ Topsoil compaction reduces soil productivity for a short period, but subsoil compaction impedes productivity for decades.⁸⁰ If a subsoil is compacted, subsoiling can alleviate compaction and increase soil productivity. This practice is more common in the agriculture fields.

Subsoiling fractures a compacted soil to create larger pores space to allow better water movement, better aeration, and access to minerals and nutrients for plant growth.⁸¹ It should be performed as deep as compaction depth using special equipment called subsoilers.⁸¹ A 3- to 6-inch wide shank (parabolic or straight) subsoiler when pulled through the soil surface and generally cuts the soil surface to a depth of 16 to 24 inches (figure 5).⁸² Subsoiling helps restore an area that is previously compacted and supports the survival and growth of seedlings. Subsoiling activities should be performed when the soil moisture content is neither too wet nor too dry to avoid soil disturbance. In the southeastern United States, the cost of subsoiling for forestry prescriptions ranges between 40\$/acre to 50\$ per acre.⁸²

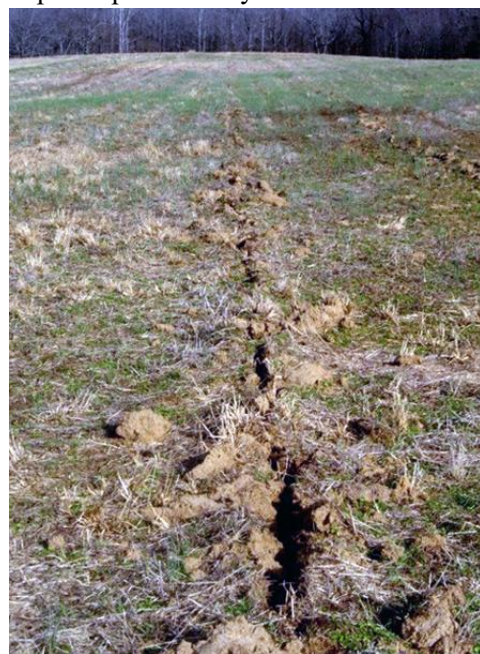


Figure 5. Subsoiling using a parabolic Shank Subsoiler. Image credit: Courtesy of [Randy Rousseau, PhD](#), Mississippi State University, College of Forest Resources. In: [Mechanical Site Preparation for Forestry in Mississippi](#), 2019.

Conclusion

Soil compaction has harmful effects on soil quality coincide with increased use of heavy machinery during logging. Apart from the productivity and cost, landowners, loggers, and foresters should consider the impacts of logging operation on forest soils susceptible to erosion and compaction. Slope, moisture content, and heavy traffic are significant factors causing soil compaction during the logging operation. Soil compaction impedes soil productivity and limits the germination and growth of seedlings and saplings in the forest. It is thus essential to ensure that logging operations do not negatively impact soil productivity for future rotations. Soil compaction is caused by many factors that cannot be avoided entirely but can be mitigated by limiting ground-based logging and adopting cable logging on steep slopes, avoiding traffic in wet areas, and using suitable harvesting equipment. Forest landowners and managers should assess how their harvesting activities might impact the soil conditions and plan to implement site-specific best management practices to minimize and mitigate these impacts.

References Cited

1. Conrad JL, Greene WD, Hiesl P. The evolution of logging businesses in Georgia 1987-2017 and South Carolina 2012-2017. *Forest Science*. 2018 Nov;64(6):671–681.
2. Parajuli M, Hiesl P, Smidt M, Mitchell D. An evaluation of woody biomass and pulpwood market competition within a range of procurement distances. *Forest Products Journal*. 2021 Oct;71(4):407–418. doi:10.13073/FPJ-D-21-00032
3. Hiesl P, Steele J. Timber harvesting equipment in South Carolina. Clemson (SC): Clemson Cooperative Extension, Land-Grant Press by Clemson Extension. 2020. LGP 1056. <https://lgpress.clemson.edu/publication/timber-harvesting-equipment-in-south-carolina/>.
4. Parajuli M, Hiesl P, Smidt M, Mitchell D. Factors influencing productivity and cost the whole-tree harvesting system. In: Clemson (SC): Clemson Cooperative Extension, Land-Grant Press by Clemson Extension. 2020. LGP 1079. <https://lgpress.clemson.edu/publication/factors-influencing-productivity-and-cost-in-the-whole-tree-harvesting-system/>.
5. Crawford LJ. Soil disturbance recovery after timber harvests on the Malheur National Forest, Oregon [master's thesis]. Moscow (ID): University of Idaho; 2020. https://www.lib.uidaho.edu/digital/etd/items/crawford_idaho_0089n_11752.html.
6. Cambi M, Certini G, Neri F, Marchi E. The impact of heavy traffic on forest soils: a review. *Forest Ecology and Management*. 2015 Feb;338:124–138.
7. Kremers J, Boosten M. Soil compaction and deformation in forest exploitation. *American Journal for Alternative Agriculture*. 2018;7(1–2):25–31.
8. Lull HW. Soil compaction on forest and range lands. Washington (DC): Forest Service, US Department of Agriculture; 1959. No. 768.
9. Laffan M, Jordan G, Duhig N. Impacts on soils from cable-logging steep slopes in northeastern Tasmania, Australia. *Forest Ecology and Management*. 2001 Apr;144:91–99.



10. Naghdi R, Solgi A, Labelle ER, Zenner EK. Influence of ground-based skidding on physical and chemical properties of forest soils and their effects on maple seedling growth. *European Journal of Forest Research*. 2016 Oct;135:949–962.
11. Warren J, Taylor R. Managing soil compaction. Stillwater (OK): Oklahoma State University, Oklahoma Cooperative Extension Service; 2014. PSS-2244. https://shareok.org/bitstream/handle/11244/317951/oksa_pss_2244_2014-09.pdf?sequence=1.
12. Lefroy RD, Blair GJ, Craswell ET. Organic matter management for sustainable agriculture. *Soil Organic Matter Management for Sustainable Agriculture*. 1995;(56):24–26. <https://www.aciar.gov.au/publication/technical-publications/soil-organic-matter-management-sustainable-agriculture>
13. Gent J, Ballard R, Hassan A, Cassel D. Impact of harvesting and site preparation on physical properties of Piedmont forest soils. *Soil Science Society of America Journal*. 1984 Jan;48:173–177.
14. Mitchell ML, Hassan AE, Davey CB, Gregory JD. Loblolly Pine Growth in Compacted Greenhouse Soils. *Transactions of the ASAE*. 1982;25:304–312.
15. DeArmond D, Emmert F, Lima AJN, Higuchi N. Impacts of soil compaction persist 30 years after logging operations in the Amazon Basin. *Soil and Tillage Research*. 2019 Jun;189:207–216. doi:10.1016/j.still.2019.01.010.
16. Stewart CC. Harvesting and site preparation effects on soil physical properties 12 years after establishment of a loblolly pine plantation [master's thesis]. Raleigh (NC): North Carolina State University; 1995.
17. Alakukku L, Weisskopf P, Chamen WC., Tijink FG., Van Der Linden JP, Pires S, Sommer C, Spoor G. Prevention strategies for field traffic-induced subsoil compaction: a review part 1. machine/soil interactions. *Soil and Tillage Research*. 2003 Oct;73(1–2):145–160. doi:10.1016/S0167-1987(03)00107-7.
18. Sakai H, Nordfjell T, Suadican K, Talbot B, Bøllehuus E. Soil compaction on forest soils from different kinds of tires and tracks and possibility of accurate estimate. *Croatian Journal of Forest Engineering*. 2008 Jun;29(1):15–27.
19. Eliasson L. Effects of forwarder tyre pressure on rut formation and soil compaction. *Silva Fennica Monographs*. 2005 Sep;39(4):549–557. doi:10.14214/sf.366.
20. Labelle ER, Poltorak BJ, Jaeger D. The role of brush mats in mitigating machine-induced soil disturbances: An assessment using absolute and relative soil bulk density and penetration resistance. *Canadian Journal of Forest Research*. 2019;49(2):164–178. doi:10.1139/cjfr-2018-0324.
21. Ampoorter E, De Schrijver A, Van Nevel L, Hermy M, Verheyen K. Impact of mechanized harvesting on compaction of sandy and clayey forest soils: results of a meta-analysis. *Annals of Forest Science*. 2012;69(5):533–542. doi:10.1007/s13595-012-0199-y.
22. Horn R, Vossbrink J, Peth S, Becker S. Impact of modern forest vehicles on soil physical properties. *Forest Ecology and Management*. 2007 Aug;248(1–2):56–63. doi:10.1016/j.foreco.2007.02.037.
23. Shetron SG, Sturos JA, Padley E, Trettin C. Forest soil compaction: effect of multiple passes and loadings on wheel track surface soil bulk density. *Northern Journal of Applied Forestry*. 1988 Jun;5:120–123.



24. Wingate-Hill R, Jakobsen B. Increased mechanisation and soil damage in forests-A review. *New Zealand Journal of Forestry Science*. 1982 Jan;12(2):380–393.
25. Eriksson J, Haekanson, Danfors B. The effect of soil compaction on soil structure and crop yields. Gothenburg (SE): Swedish Institute of Agricultural Engineering; 1975.
26. Ampoorter E, Goris R, Cornelis WM, Verheyen K. Impact of mechanized logging on compaction status of sandy forest soils. *Forest Ecology and Management*. 2007 Mar;241(1–3):162–174. doi:10.1016/j.foreco.2007.01.019.
27. Naghdi R, Solgi A. Effects of skidder passes and slope on soil disturbance in two soil water contents. *Croatian Journal of Forest Engineering*. 2014 Mar;35(1):73–80.
28. Han S-K, Han H-S, Page-Dumroese, Deborah S Johnson LR. Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest. *Canadian Journal of Forest Research*. 2009 May;39(5):976–989. doi:10.1139/X09-027.
29. Holsonback E, Brewington L. Lynchburg South Carolina state soil. Madison (WI): Soil Science Society of America; 2021. 5 p.
30. Miller RE, Colbert SR, Morris LA. Effects of heavy equipment on physical properties of soils and on long-term productivity: a review of literature and current research. Research Triangle Park (NC): National Council for Air and Stream Improvement, Inc. (NCASI); 2004. Technical Bulletin No. 887.
31. Soghi A, Naghdi R, Nirooy M. Effects of skidder on soil compaction, forest floor removal and rut formation. *Madera y bosques*. 2015;21:147–155.
32. Solgi A, Najafi A, Page-Dumroese DS, Zenner EK. Assessment of topsoil disturbance caused by different skidding machine types beyond the margins of the machine operating trail. *Geoderma*. 2020 May;367:114238. doi:10.1016/j.geoderma.2020.114238.
33. Frey B, Kremer J, Rüdert A, Sciacca S, Matthies D, Lüscher P. Compaction of forest soils with heavy logging machinery affects soil bacterial community structure. *European Journal of Soil Biology*. 2009 Jul;45(4):312–320. doi:10.1016/j.ejsobi.2009.05.006.
34. Majnounian B, Jourgholami M. Effects of rubber-tired cable skidder on soil compaction in Hyrcanian forest. *Croatian Journal of Forest Engineering*. 2013 Jun;34(1):123–135.
35. Williamson JR, Neilson W. The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. *Canadian Journal of Forest Research*. 2000 Aug;30(8):1196–1205. doi:10.1139/x00-041.
36. Berkett H, Visser R. Measuring slope of forestry machines on steep terrain. Rotorua (NZ): Future Forests Research Limited; 2012. Harvesting Technical Note, HTN05-02. 8 p.
37. Hatchell G, Ralston C, Foil R. Soil Disturbances in logging. *Journal of Forestry*. 1970;68(12):772–775.



38. Gomez A, Powers RF, Singer MJ, Horwath WR. N uptake and N status in ponderosa pine as affected by soil compaction and forest floor removal. *Plant and Soil*. 2002 May;242(2):263–275. doi:10.1023/A:1016218316381
39. Gomez A, Powers RF, Singer MJ, Horwath WR. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. *Soil Science Society of America Journal*. 2002 Jul;66(4):1334–1343. doi:10.2136/sssaj2002.1334.
40. Puhlick JJ, Fernandez IJ. Influence of mechanized timber harvesting on soil compaction in northern hardwood forests. *Soil Science Society of America Journal*. 2020 Sep;84(5):1737–50.
41. Berli M, Kirby JM, Springman SM, Schulin R. Modelling compaction of agricultural subsoils by tracked heavy construction machinery under various moisture conditions in Switzerland. *Soil and Tillage Research*. 2003 Oct;73(1–2):57–66. doi:10.1016/S0167-1987(03)00099-
42. Hillel D. *Environmental soil physics: Fundamentals, applications, and environmental considerations*. Elsevier. 1st ed. Amsterdam (NL): Elsevier; 1998.
43. Kolka R, Steber A, Brooks K, Perry CH, Powers M. Relationships between soil compaction and harvest season, soil texture, and landscape position for aspen forests. *Northern Journal of Applied Forestry*. 2012 Mar;29(1):21–25.
44. Powers R, Scott DA, Sanchez FG, Voldseth RA, Page-Dumroese D, Elioff JD, Stone DM. The North American long-term soil productivity experiment: findings from the first decade of research. *Forest Ecology and Management*. 2005;220(1–3):31–50. doi:10.1016/j.foreco.2005.08.003.
45. Kozłowski TT. Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research*. 1999 Dec;14(6):596–619. doi:10.1080/02827589908540825.
46. Foil RR, Ralston CW. The establishment and growth of loblolly pine seedlings on compacted soils. *Soil Science Society of America Journal*. 1967 Jul;31(4):565–568. doi:10.2136/sssaj1967.03615995003100040037x.
47. Williams TM, Amatya DM. Coastal plain soils and geomorphology: a key to understanding forest hydrology. In: Stringer CE, Krauss KW, Latimer JS, editors. 2016. *Headwaters to estuaries: advances in watershed science and management*. Proceedings of the Fifth Interagency Conference on Research in the Watersheds; 2015 Mar 2–5; North Charleston (SC). Asheville (NC): US Department of Agriculture Forest Service, Southern Research Station; 2016. e-General Technical Report SRS-211. p. 14-21.
48. Demir M, Makineci E, Yilmaz E. Investigation of timber harvesting impacts on herbaceous cover, forest floor and surface soil properties on skid road in an oak (*Quercus petraea* L.) stand. *Building and Environment*. 2005;42(3):1194–1199. doi:10.1016/j.buildenv.2005.11.008.
49. Ares A, Terry TA, Miller RE, Anderson HW, Flaming BL. Ground-based forest harvesting effects on soil physical properties and Douglas-fir growth. *Soil Science Society of America Journal*. 2005 Nov;69(6):1822–1832. doi:10.2136/sssaj2004.0331.
50. Naghdi R, Solgi A, Labelle ER, Nikooy M. Combined effects of soil texture and machine operating trail gradient on changes in forest soil physical properties during ground-based skidding. *Pedosphere*. 2020 Aug;30(4):508–516. doi:10.1016/S1002-0160(17)60428-4.



51. Kim H, Anderson SH, Motavalli PP, Gantzer CJ. Compaction effects on soil macropore geometry and related parameters for an arable field. *Geoderma*. 2010 Dec;160(2):244–251. doi:10.1016/j.geoderma.2010.09.030.
52. Kozłowski TT, Pallardy SG. *Physiology of woody plants*. 2nd ed. Amsterdam (NL): Elsevier; 1996.
53. Grace MJ, Skaggs RW, Cassel DK. Soil physical changes associated with forest harvesting operations on an organic soil. *Soil Science Society of America Journal*. 2006 Mar;70(2):503–509. doi:10.2136/sssaj2005.0154.
54. Duniway J, Gordon T. Water relations and pathogen activity in soil. In: Ayres PG, Boddy L, editors. 1986. *Water, fungi and plants: symposium of the British Mycological Society, held at the University of Lancaster, April 1985*. Cambridge (UB); Cambridge University Press; 1986. p. 119–136
55. Visser, Colmer TD, Blom CWPM, Voesenek LACJ. Changes in growth, porosity, and radial oxygen loss from adventitious roots of selected mono- and dicotyledonous wetland species with contrasting types of aerenchyma. *Plant, Cell and Environment*. 2000 Nov;23(11):1237–1245. doi:10.1046/j.1365-3040.2000.00628.x.
56. Ampoorter E, Goris R, Verheyen K. Maatregelen bij houtoogst. In: den Ouden J, Muys B, Mohren F, Verheyen K, editors. *Bosecologie en bosbeheer*. Leuven, België; Den Haag, Nederland: Acco; 2010. p. 477–484.
57. Jacobson S, Kukkola M, Mälkönen E, Tveite B. Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. *Forest Ecology and Management*. 2000 Apr;129(1–3):41–51. doi:10.1016/S0378-1127(99)00159-0.
58. Marshall VG. Impacts of forest harvesting on biological processes in northern forest soils. *Forest Ecology and Management*. 2000 Aug;133(1–2):43–60. doi:10.1016/S0378-1127(99)00297-2.
59. Rice R, Rothacher J, Megahan W. Erosional consequences of timber harvesting: an appraisal. In: Csallany SC, McLaughlin TG, Striffler WD, editors. *Watersheds in transition: proceedings of a symposium on "watersheds in transition" held at Fort Collins, Colorado June 19-22, 1972*. Urbana (IL): American Water Resources Association; 1972. p. 321–329.
60. Naghdi R, Bagheri I, Lotfalian M, Setodeh B. Rutting and soil displacement caused by 450c Timber Jack wheeled skidder (asalem forest northern Iran). *Journal of Forest Science*. 2009 Mar;55(4):177–183. doi:10.17221/102/2008-jfs.
61. Anderson, Lockaby BG. The effectiveness of forestry best management practices for sediment control in the southeastern United States: A literature review. *Southern Journal of Applied Forestry*. 2011 Nov;35(4):170–177. doi:10.1093/sjaf/35.4.170.
62. Stephanie F, West B. Forestry impacts on water quality. In: Wear DN, Greis JG, editors. *Southern forest resource assessment*. Gen. Tech. Rep. SRS-53. Asheville (NC): U.S. Department of Agriculture, Forest Service, Southern Research Station; 2002. p. 501-518.
63. Powers R, Tiarks AE, Boyle JR. Assessing soil quality: practicable standards for sustainable forest productivity in the United States. In: Davidson EA, editor. *Criteria and indicators of soil quality for sustainable forest productivity*. Madison (WA): Soil Science Society of America, Special Publication 53; 1998. p. 53–80.



64. Greene WD, Stuart WB. Skidder and tire size effects on soil compaction. *Southern Journal of Applied Forestry*. 1985 Aug;9(1):154–157.
65. Schweier J, Ludowicy C. Comparison of a cable-based and a ground-based system in flat and soil-sensitive area: A case study from Southern Baden in Germany. *Forests*. 2020 Jun;11(6):1–16. doi:10.3390/F11060611.
66. Visser R, Stampfer K. Expanding ground-based harvesting onto steep terrain: a review. *Croatian Journal of Forest Engineering*. 2015 Oct;36(2):321–331.
67. Williamson JR. Effects of mechanised forest harvesting operations on soil properties and site productivity. Hobart (AU): Tasmanian Forest Research Council; 1990. Jointly published by the National Soil Conservation Programme. p. 193.
68. LeDoux CB, May DM, Johnson T, Widmann RH. Assessing the feasibility and profitability of cable logging in southern upland hardwood forests. *Southern Journal of Applied Forestry*. 1995 Aug;19(3):97–102. doi:10.1093/sjaf/19.3.97.
69. Erber G, Spinelli R. Timber extraction by cable yarding on flat and wet terrain: A survey of cable yarder manufacturer's experience. *Silva Fennica*. 2020;54(2):0–19. doi:10.14214/sf.10211.
70. Mahaffey A, Evans A. Ecological forestry practices for bottomland hardwood forests of the southeastern U.S. Santa Fe (NM): Forest Stewards Guild; 2016. 45 p.
71. Al-kaisi M. How and why to avoid soil compaction. Ames (IA): Iowa State University, Extension and Outreach, Integrated Crop Management News; 2010. p. 9–11.
72. Sessions J, Boston K. Optimization of road spacing for log length shovel logging on gentle terrain. *International Journal of Forest Engineering*. 2006 Jan;17(1):67–75. doi:10.1080/14942119.2006.10702530.
73. Fisher J. Shovel logging: cost effective system gains ground. In: Proceedings of the international mountain logging and 10th Pacific Northwest skyline symposium. 1999 Mar 28-Apr 1; Corvallis (OR). Corvallis (OR): Oregon State University, Forest Engineering Department; 1999. p. 61–67.
74. Hutchings TR, Moffat AJ, French CJ. Soil compaction under timber harvesting machinery: a preliminary report on the role of brush mats in its prevention. *Soil Use and Management*. 2002 Mar;18(1):34–38. doi:10.1111/j.1475-2743.2002.tb00047.x.
75. Poltorak BJ, Labelle ER, Jaeger D. Soil displacement during ground-based mechanized forest operations using mixed-wood brush mats. *Soil and Tillage Research*. 2018 Jun;179:96–104. doi:10.1016/j.still.2018.02.005.
76. Page-Dumroese DS, Jurgensen MF, Tiarks AE, Ponder F, Sanchez FG, Fleming RL, Kranabetter JM, Powers RF, Stone DM, Elioff JD, et al. Soil physical property changes at the North American long-term soil productivity study sites: 1 and 5 years after compaction. *Canadian Journal of Forest Research*. 2006 Mar;36(3):551–564. doi:10.1139/x05-273.



77. Perry TO. Soil compaction and loblolly pine growth. Washington (DC): US Forest Service, Reforestation, Nurseries and Genetic Resources (RNGR) Program, Tree Planters' Notes; 1964. Issue 67.
<file:///Users/dawnw/Downloads/Soil%20Compaction%20and%20Loblolly%20Pine%20Growth.pdf>.
78. Drissi DK. Recovery of abandoned logging road soil in the North Carolina Piedmont [master's thesis]. Raleigh (NC): North Carolina State University; 1975.
79. Lang AJ, Cristan R, Aust WM, Bolding MC, Strahm BD, Vance ED, Roberts ET. Long-term effects of wet and dry site harvesting on soil physical properties mitigated by mechanical site preparation in coastal plain loblolly pine (*Pinus taeda*) plantations. *Forest Ecology and Management*. 2016 Jan;359:162–173.
<http://dx.doi.org/10.1016/j.foreco.2015.09.034>. doi:10.1016/j.foreco.2015.09.034.
80. Duiker SW, Miesky GW. Avoiding and mitigating soil compaction associated with natural gas development. University Park (PA): The Pennsylvania State University, PennState Extension; 2009.
<https://extension.psu.edu/avoiding-and-mitigating-soil-compaction-associated-with-natural-gas-development>.
81. Kees G. Using subsoiling to reduce soil compaction. Missoula (MT): USDA Forest Service Technology and Development Program; 2008 Jul. 5E52F74 Soil Tilth Restorer. <https://www.fs.fed.us/t-d/pubs/pdfpubs/pdf08342828/pdf08342828dpi72.pdf>.
82. Self AB, Kushla JD. Mechanical site preparation for forestry in Mississippi. Mississippi State (MS): Mississippi State University Extension; 2016. Publication 3006 (POD-11-19).
<http://extension.msstate.edu/sites/default/files/publications/publications/P3006.pdf>.

Additional Resources

South Carolina Forestry Commission. Best management practices (BMPs) for forestry. Columbia (SC): SC Forestry Commission; 2021. www.scfc.gov/wp-content/uploads/2021/03/best-management-practices-manual.pdf.

Citation

Parajuli M, Hiesl P, Hagan D, Khanal P. Logging operations and soil compaction. Clemson (SC): Clemson Cooperative Extension, Land-Grant Press by Clemson Extension; 2022. LGP 1135. <http://lgpress.clemson.edu/publication/logging-operations-and-soil-compaction>.

Clemson University Cooperative Extension Service offers its programs to people of all ages, regardless of race, color, gender, religion, national origin, disability, political beliefs, sexual orientation, gender identity, marital or family status and is an equal opportunity employer.

The information in this publication is provided for educational and informational purposes only. The use of any brand names and any mention or listing of commercial products or services in this publication does not imply endorsement by Clemson University nor does it imply discrimination against similar products or services not mentioned. Recommendations for the use of agricultural chemicals may be included in this publication as a convenience to the reader. Individuals who use agricultural chemicals are responsible for ensuring that their intended use of the chemical complies with current regulations and conforms to the product label.

This publication may be reprinted in its entirety for distribution for educational and informational purposes only. Any reference made from this publication must use the provided citation.

