

## SUMMARY

Forest soil scientists and resource managers are being called upon to develop criterion and indicators to assess productivity losses and sustainability of forestry practices. Single criteria as well as integrated approaches are being evaluated for their potential to determine if current forest management practices are damaging the land base and potential productivity. Researchers have developed several good conceptual models, but testing these models is still in the early stages.

Our study measured compaction effects on four different soils and tree species. The interactive effects of soil texture, organic matter content, mineralogy, particle size distribution and other physical properties determined the degree of compaction on each of the four soils examined in this study. Furthermore those differences, in turn, affected properties such as soil strength, porosity and air water balance. Multiple regression growth models described root length density as a function of bulk density and water content, but the general model was only applicable to two of our soils. At high bulk densities, aeration was limiting at the wettest water contents, while strength was limiting at the driest water contents for three of our soils. However, the response varied with soil type and species.

The varied response to compaction and the subsequent affects on root growth that were both soil and species dependent showed that site-specific indicators and criteria are needed to accurately assess potential productivity declines. The actual value of our models will depend on their applicability to field conditions. The LLWR, in conjunction with soil and species specific data, will enhance our ability to determine overall potential loss of productivity due to compaction.

## LITERATURE CITED

- Alexander, E.B. 1980. Bulk densities of California soils in relation to other soil properties. *Soil Sci. Soc. Am. J.* 44:689-692.
- Alexander, E.B. and J.C. McLaughlin. 1990. Soil porosity an an indicator of forest and rangeland soil condition (compaction) and relative productivity. p 52-61. In *Proceedings of the soil quality standards symposium, San Antonio, Texas, October 23. USDA-FS, Washington DC, WO-WSA-2.*
- ASTM. 1972. Soil particle size analysis. Soil and Rock, Section x:Dxxx. In *Annual Book of ASTM Standards, Volume 04.08. Philadelphia, PA.*
- ASTM. 1996. Test method for laboratory compaction characteristics of soil using standard effort (600 kN-m m<sup>3</sup>). Soil and Rock, Section 4:D698. *In Annual Book of ASTM Standards, Volume 04.08. Philadelphia, PA.*
- Atwell, B.J. 1993. Response of roots to mechanical impedance. *Environ. Exp. Bot.* 33:1:27-40.
- Aust , W.M., J.A. Burger, E.A. Carter, D.P. Preston and S.C. Patterson. 1998. Visually determined soil disturbance classes used as indices of forest harvesting disturbance. *South. J. Appl. For.* 22:245-250.
- Ball, B.C, D.J. Campbell and E.A. Hunter. 2000. Soil compactibility in relation to physical and organic properties at 156 sites in the UK. *Soil Tillage Res.* 57:83-91.
- Barley, K.P. 1962. The effects of mechanical stress on the growth of roots. *J. Exp. Bot.* 13:95-110.
- Bengough, A.G. and C.E. Mullins. 1990. Mechanical impedance to root growth: A review of experimental techniques and root growth responses. *J. Soil Sci.* 41:341-358.
- Betz, C.L., R.R. Allmaras, S.M. Copeland, G.W. Randall. 1998. Least limiting water range: Traffic and long-term tillage influences in a Webster soil. *Soil Sci. Soc. Am. J.* 62: 1384-1393.
- Black, C.A. 1968. *Soil-Plant Relationships.* John Wiley and Sons, Inc., New York.
- Bodman, G.B. and G.K. Constantin. 1965. Influence of particle size distribution in soil compaction. *Hilgardia* 36:567-591.
- Brais, S. 2001. Persistence of soil compaction and effects on seedling growth in Northwestern Quebec. *Soil Sci. Soc. Am. J.* 65:1263-1271.

- Burger, J.A. and D.L. Kelting. 1998. Soil quality monitoring for assessing sustainable forest management. *In* The contribution of soil science to the development of and implementation of criteria and indicators of sustainable forest management. Soil. Sci. Soc. Am. Spec. Pub. no. 53.
- Burger, M. 1994. A wetland trafficability hazard index based on soil physical properties and site hydrology evaluations. M.S. Thesis. Dept. of Forestry, Virginia Polytechnic Inst. and State Univ., Blacksburg.
- Busscher, W.J. 1990. Adjustment of flat-tipped penetrometer resistance data to a common water content. *Trans. ASAE.* 33 (2): 519-524.
- Childs, S.W., S.P. Shade, D.W. Miles, E. Shepard, and H.A. Froehlich. 1989. Management of soil physical properties limiting forest productivity. In D.A. Perry et al. (eds.) *Maintaining the long-term productivity of Pacific Northwest forest ecosystems.* Timber Press, Portland, OR, USA.
- Cochran, P.H. and T. Brock. 1985. Soil compaction and initial height growth of planted ponderosa pine. *USDA-For. Serv. Res. Note PNW-434.*
- Conlin, T.S. and R. ven den Driessche. 1996. Short-term effects of soil compaction on growth of *Pinus contorta* seedlings. *Can. J. For. Res.* 26:727-739.
- 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.
- Cruse, R.M., D.K. Cassell and F.G. Averette. 1980. Effect of particle surface roughness on densification of coarse-textured soil. *Soil Sci. Soc. Am. J.* 44:692-697.
- Daddow, R.L. and G.E. Warrington. 1983. Growth-limiting soil bulk densities as influenced by soil texture. *Watershed Systems Development Group Rep. WSDG-TN-00005, USDA Forest Service, Ft. Collins, CO, 17p.*
- da Silva, A.P., B.D. Kay and E. Perfect. 1994. Characterization of the least limiting water range of soils. *Soil Sci. Soc. Am. J.* 58: 1775-1781.
- da Silva, A.P. and B.D. Kay. 1996. The sensitivity of shoot growth of corn to the least limiting water range of soils. *Plant and Soil* 184:323-329.
- da Silva, A.P. and B.D. Kay. 1997a. Estimating the least limiting water range of soils from properties and management. *Soil Sci. Soc. Am. J.* 61: 877-883.
- da Silva, A.P. and B.D. Kay. 1997b. Effect of soil water content variation on the least limiting water range. *Soil Sci. Soc. Am. J.* 61: 884-888.

- Davis, S. 1990. Effectiveness of a winged subsoiler in ameliorating a compacted clayey forest soil. *W. J. Appl. For.* 5(4):138-139.
- Donnelly, J.R. and J.B. Shane. 1986. Forest ecosystem responses to artificially induced soil compaction. I. Soil physical properties and tree diameter growth. *Can. J. For. Res.* 16:750-754.
- Eavis, B.W. 1972. Soil physical conditions affecting seedling root growth. I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam soil. *Plant Soil* 36:613-622.
- Foil, R.R. and C.W. Ralston. 1960. The establishment and growth of loblolly pine seedlings on compacted soils. *Soil Sci. Soc. Am. Proc.* 31:565-568.
- Fritton, D.D. 1990. A standard for interpreting soil penetrometer measurements. *Soil Sci.* 150: 542- 551.
- Froehlich, H.A. 1976. The effect of soil compaction by logging on forest productivity, part 1. USDI Bureau of Land Management. Final Report, Contract No. 53500-CT4-5(N).
- Froehlich, H.A. 1979. Soil compaction from logging equipment. Effects on growth of young ponderosa pine. *J. Soil Water Conserv.* 34:276-278.
- Froehlich, H.A. and D.H. McNabb. 1984. Minimizing soil compaction in Pacific Northwest forests. p. 159-192. *In* E.L. Stone (ed.) *Forest soils and treatment impacts*, Proc. N. Am. For. Soils Conf. 6<sup>th</sup>, Knoxville. June 1983. Univ. of Tennessee, Knoxville.
- Froehlich, H.A., D.W. Miles and R.W. Robbins. 1985. Soil bulk density recovery on compacted skid trails in Central Idaho. *Soil Sci. Soc. Am. J.* 49:1015-1017.
- Gale, M.R. and D.F. Grigal. 1987. Vertical root distributions of northern tree species in relation to successional status. *Can. J. For. Res.* 17:829-834.
- Gale, M.R., D.F. Grigal and R.B. Harding. 1991. Soil productivity index: Predictions of site quality for white spruce plantations. *Soil Sci. Soc. Am. J.* 55:1701-1708.
- Gee, G.W. and J.W. Bauder. 1986. Particle-size analysis. p. 383-410. *In* A. Klute (ed.) *Methods of Soil Analysis, Part I, Physical and Mineralogical Methods*. Soil Sci. Soc. Am. Pub. No. 9. Part 1.
- Gill and Miller. 1956. A method for study of the influence of mechanical impedance and aeration on seedling roots. *Soil Sci. Soc. Am. Proc.* 20:154-157.

- Gomez, G.A., R.F. Powers, M.J. Singer, and W.R. Horwath. 2002. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. *Soil Sci. Soc. Am. J.* 66:1334-1343.
- Goss, M.J. 1977. Effects of mechanical impedance on root growth in barley (*Hordeum vulgare* L.). I. Effects on elongation and branching of seminal root axes. *J. Exp. Bot.* 28:96-111.
- Gott, J. 1975. Soil survey of the Mark Twain National Forest Area. Missouri (Parts of Carter, Oregon, Ripley, and Shannon Counties). USDA For. Serv., Rolla, MO.
- Gowing, D.J., W.J. Davies and H.G. Jones. 1990. A positive root-sourced signal as an indicator of soil drying in apple. *J. Exp. Bot.* 41: 1535-1540.
- Grable, A.R. and E.G. Siemer. 1968. Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potentials, and elongation of corn roots. *Soil Sci. Soc. Am. Proc.* 32:180-186.
- Greacen, E.L. and R. Sands. 1980. Compaction of Forest Soils: A Review. *Aust. J. Soil Res.* 18:163-189.
- Halverson, H.G. and R.P. Zisa. 1982. Measuring the response of conifer seedlings to soil compaction stress. USDA For. Serv. Res. Pap. NE-509.
- Hatchell, G.E., C.W. Ralston and R.R. Foil. 1970. Soil disturbances in logging. *J. For* 68:772-775.
- Hatchell, G.E. and C.W. Ralston. 1971. Natural recovery of surface soils disturbed in logging. *Tree Planters Notes* 22(2):5-9.
- Heilman, P. 1981. Root penetration of Douglas-fir seedlings into compacted soil. *For. Sci.* 27:660-666.
- Hemsath, D. and A.P. Mazurak. 1974. Seedling growth of sorghum in clay-sand mixtures at various compactions and water contents. *Soil Sci. Soc. Am. Proc.* 38:387-390.
- Heninger, R., W. Scott, A. Dobkowski, R. Miller, H. Anderson, and S. Duke. 2002. Soil disturbance and 10-year growth response of coast Douglas-fir on nontilled and tilled skid roads in the Oregon Cascades. *Can. J. For. Res.* 32:233-246.
- Howard, R.F., M.J. Singer and G.A. Frantz. 1981. Effects of soil properties, water content, and compactive effort on the compaction of selected California forest and range soils. *Soil Sci. Soc. Am. J.* 45(2):231-236.

- Horn, R. 1988. Compressibility of arable land. p.53-71. In J. Drescher et al. (eds.) Impact of water and external forces on soil structure. Catena suppl. 11, Catena Verlag, Germany.
- Kelting, D. L. 1999. Timber harvesting and site preparation effects on soil quality for loblolly pine growing on the lower coastal plain of South Carolina. Ph.D. diss. Virginia Polytechnic Inst. and State Univ., Blacksburg (Diss. etd-041399-112354).
- Kiniry, L.N., C.L. Scrivner and M.E. Keener. 1983. A soil productivity index based upon predicted water depletion and root growth. Missouri Agric. Exp. Stn. Res. Bull. 1051. Univ. of Missouri Coop. Ext., Columbia.
- Kleiner, K.W., M.D. Abrams and J.C. Schultz. 1992. The impact of water and nutrient deficiencies on the growth, gas exchange and water relations of red oak and chestnut oak. Tree Phys. 11: 271-287.
- Klute, A. 1986. Water relations:Laboratory methods. In A. Klute (ed.) Methods of Soils Analysis. 2nd ed. ASA, SSSA, Madison, WI.
- Kozlowski, T.T. 1999. Soil compaction and growth of woody plants. Scand. J. For. Res. 14:596-619.
- Kramer, P.J. and J.S. Boyer. 1995. Water relations of plants and soils. Academic Press, London.
- Larson, W.E., S.C. Gupta, and R.A. Useche. 1980. Compression of agricultural soils from eight soil orders. Soil Sci. Soc. Am. J. 44:450-457.
- Letey, J. 1985. Relationship between soil physical properties and crop production. Adv. Soil Sci. 1: 277-294.
- Marshall, T.J. 1959. Relations between water and soil. Commonwealth Bur. Soils, Commonwealth Agr. Bur., Farnham Royal, Tech Comun. 50:70-74.
- McKelvin, M.R., D.D. Hook, and W.H. McKee. 1987. Loblolly pine seedling root anatomy and iron accumulation as affected by soil waterlogging. Can. J. For. Res. 17:1257-1264.
- McMillin, J.D. and M.R. Wagner. 1995. Effects of water stress on biomass partitioning of Ponderosa pine seedlings during primary root growth and shoot growth periods. For. Sci. 41(3): 594-610.
- McNabb, D.H. and L. Boersma. 1993. Evaluation of the relationship between compressibility and shear strength of Andisols. Soil Sci. Soc. Am. J. 57:923-929.

- McNabb, D.H., A.D. Startsev, and H. Nguyen. 2001. Soil wetness and traffic level effects on bulk density and air-filled porosity of compacted Boreal forest soils. *Soil Sci. Soc. Am. J.* 65:1238-1247.
- Miller, R.E., W. Scott and J.W. Hazard. 1996. Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. *Can. J. For. Res.* 26:225-236.
- Mirreh, H.F. and J.W. Ketcheson. 1972. Influence of soil bulk density and matric pressure on soil resistance to penetration. *Can. J. Soil Sci.* 52:477-483.
- Mitchell, J.K. 1993. *Fundamentals of soil behavior*. John Wiley and Sons, Inc., N.Y.
- Mitchell, M.L., A.E. Hassan, C.B. Davey and J.D. Gregory. 1982. Loblolly pine growth in compacted greenhouse soils. *Trans. ASAE* 25:304-307,312.
- Munns, E.N. 1947. Logging can damage soil. *J.For* 45:513.
- Nambiar, E.K. and R. Sands. 1992. Effects of compaction and simulated root channels in the subsoil on root development, water uptake and growth of radiata pine. *Tree Physiol.* 10:297-306.
- Nelson, D.W. and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 573-579. *In* A.L. Page et al. (eds.) *Methods of Soil Analysis, Part II, Chemical and Microbiological Properties*, 2<sup>nd</sup> ed. ASA, SSSA, Madison, WI.
- Page-Dumerose, D.S., A.E. Harvey, M.F. Jurgensen and M.P. Amaranthus. 1998. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. *Can. J. Soil Sci.* 78:29-34.
- Paz, L.W. 2001. Soil-water characteristics and hydrologic implications following forest soil disturbance: The relative influence of organic residue and soil compaction on permeability and moisture capacity. Ph.D. Dissertation, Univ. of California, Berkeley.
- Pfeffer, W. 1893. Druck and Arbeitsleistung durch Wachsende Pflanzen. *Abh. Sachs Akad. Wiss. Leipzig, Math, Naturwiss. Kl.* 33:235-474.
- Powers, R.F., D.H. Alban, R.E. Miller, A.E. Tiarks, C.G. Wells, P.E. Avers, R.G. Cline, R.D. Fitzgerald, and N.S. Loftus Jr. 1990. Sustaining site productivity in North American forests: problems and prospects. P. 49-79. *In* S.P. Gessel et al., (eds.), *Sustained Productivity of Forest Soils*. Proc. 7<sup>th</sup> North Amer. For. Soils Conf. Univ. British Columbia, Vancouver, B.C.

- Powers, R.F., A.E. Tiarks and J.R. Boyle. 1998. Assessing soil quality: Practicable standards for sustainable forest productivity in the United States. p. 53-79. *In* The contribution of soil science to the development of and implementation of criteria and indicators of sustainable forest management. Soil. Sci. Soc. Am. Spec. Pub. no. 53.
- Ramakrishna, K. and E.A. Davidson. 1998. Soil quality monitoring for assessing sustainable forest management. *In* The contribution of soil science to the development of and implementation of criteria and indicators of sustainable forest management. Soil. Sci. Soc. Am. Spec. Pub. no. 53.
- Rawls, W.J. 1983. Estimating soil bulk density from particle size analysis and organic matter content. *Soil Sci.* 135(2): 123-125.
- Reicosky, D.C., W.B. Voorhees and J.K. Radke. 1981. Unsaturated water flow through a simulated wheel track. *Soil Sci. Soc. Am. J.* 45:3-8.
- Richards, L.A. 1959. Availability of water to crops on saline soil. USDA Agric. Info. Bull. 210.
- Russell, R. S. 1977. Mechanical impedance of root growth. p98-111. *In* Plant Root Systems: Their function and interaction with soil. McGraw-Hill Book Company, UK.
- Sands, R. and G.D. Bowen. 1978. Compaction of sandy soils in Radiata pine forests. II. Effects of compaction on root configuration and growth of radiata pine seedlings. *Aust. J. of For. Res.* 8:163-170.
- Sands, R., E.L. Graecen and C.J. Gerard. 1979. Compaction of sandy soils in Radiata pine forests. I. A penetrometer study. *Aust. J. Soil Res.* 17:101-113
- Schultz, R.P. 1997. The Ecology and Culture of loblolly pine (*Pinus taeda* L.). USDA, Forest Service, Agric. Handbook 713, Washington, D.C.
- Simmons, G.L. and W. Ezell. 1982. Root development of loblolly pine seedlings in compacted soils. p 26-29. in Proc. Second Bienn. South. Silv. Res. Conf.
- Simmons, G.L. and P.E. Pope. 1987. Influence of soil compaction and vesicular-arbuscular mycorrhizae on root growth of yellow poplar and sweetgum seedlings. *Can. J. For. Res.* 17(8):970-975.
- Singer, M.J. 1981. Soil compaction – seedling growth study. Final report to USDA Forest Service, Pacific Southwest Region. Coop. Agree. USDA-7USC-2202. Suppl. 43.



- Smith, C.T. and R.J. Raison. 1998. Soil quality monitoring for assessing sustainable forest management. *In* The contribution of soil science to the development of and implementation of criteria and indicators of sustainable forest management. Soil. Sci. Soc. Am. Spec. Pub. no. 53.
- Soane, B.D. 1990. The role of organic matter in soil compactibility: A review of some practical aspects. *Soil Tillage Res.* 16:179-201.
- Soil Survey Division, NRCS, USDA. 2001. Official soil series descriptions [online www]. Available URL: <http://www.statlab.iastate.edu/soils/osd> [accessed 23 Mar 2001].
- Startsev, A.D. and D.H. McNabb. 2001. Skidder traffic effects of water retention, pore-size distribution, and van Genuchten parameters of Boreal forest soils. *Soil Sci. Soc. Am. J.* 65:224-231.
- Steinbrenner, E.C. 1959. A portable air permeameter for forest soils. *Soil Sci. Soc. Am. Proc.* 23(6):478-481.
- Steinbrenner, E.C. and S.P. Gessel. 1955a. The effect of tractor logging on physical properties of forest soils in southwestern Washington. *Soil Sci. Soc. Am. Proc.* 19:372-376
- Steinbrenner, E.C. and S.P. Gessel. 1955b. The effect of tractor logging on soils and regeneration in the Douglas-fir region of southwestern Washington. *Soc. Amer. Foresters Proc.* 77-80.
- Sword, M.A. 1995. Root-zone temperature and water availability affect early root growth of planted longleaf pine. USDA, FS, Southern Res. Stn. GTR.SRS-1. 343-353.
- Tardieu, F., T. Zhang, N. Katerji, S. Bethenod, S. Palmer and W.J. Davies. 1992. Xylem ABA controls the stomatal conductance of field-grown maize subjected to soil compaction or soil drying. *Plant, Cell and Environ.* 15:193-197.
- Taylor, H.M. 1966. Root behavior as affected by soil structure and strength. *In* Soil Structure and Strength.
- Taylor, H.M. and L.F. Ratliff. 1969. Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. *Soil Sci.* 108(2):113-119.
- Teskey, R.O. and T.M. Hinckley. 1981. Influence of temperature and water potential on root growth of white oak. *Physiol. Plant.* 52: 363-369.
- Tippett, M.D. 1992. Impacts of wetland harvesting on soil physical properties. M.S. thesis. Dept. of Forestry, Virginia Polytechnic Inst. and State Univ., Blacksburg.

- Topa, M.A. and K.W. McCleod. 1986. Aerenchyma and lenticel formation in pine seedlings: A possible avoidance mechanism to anaerobic growth conditions. *Phys. Plant.* 68(3):540-550.
- Torreano, S.J. and L.A. Morris. 1998. Loblolly pine root growth and distribution under water stress. *Soil Soc. Am. J.* 62:818-827.
- Tormena, C.A, A.P. da Silva and P.L. Libardi. 1999. Soil physical quality of a Brazilian Oxisol under two tillage systems using the least limiting water range approach. *Soil Till. Res.* 52: 223-232.
- Tuttle, C.L., M.S. Golden and R.S. Meldahl. 1988. Soil compaction effects on *Pinus taeda* establishment from seed and early growth. *Can. J. For. Res.* 18(5):628-632.
- Twoorkoski, T.J., and J.A. Burger, and D.W. Smith. 1983. Soil texture and bulk density affect early growth of white oak seedlings. *Tree Plant Notes.* 34(2):22-25.
- Veihmeyer, F.J. and A.H. Hendrickson. 1948. Soil density and root penetration. *Soil Sci.* 65:487-493.
- Voorhees, W.B., D.A. Farrell and W.E. Larson. 1975. Soil Strength and aeration effects on root elongation. *Soil Sci. Soc. Am. Proc.* 39:948-953.
- Wasterlund, I. 1985. Compaction of till soils and growth tests with Norway spruce and Scots pine. *For. Ecol. Manage.* 11:171-189.
- Zhang, H., K.H. Hartge, and H. Ringe. 1997. Effectiveness of organic matter incorporation in reducing soil compactibility. *Soil Sci. Soc. Am. J.* 61:239-245.
- Zou, C., R. Sands, G. Buchan, and I. Hudson. 2000. Least limiting water range: a potential indicator of physical quality of forest soils. *Aust. J. Soil. Res.* 38:947-958.
- Zur, B. 1967. Osmotic control of the matric soil-water potential: II. Soil-Plant system. *Soil Sci.* 103(1): 30-38.

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