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EFFECTS OF HEAVY EQUIPMENT ON PHYSICAL PROPERTIES OF SOILS AND ON LONG-TERM PRODUCTIVITY: A REVIEW OF LITERATURE AND CURRENT RESEARCH

TECHNICAL BULLETIN NO. 887

OCTOBER 2004

by

Richard E. Miller, Ph.D.
USDA Forest Service
Olympia, Washington

Stephen R. Colbert, Ph.D.
American Forest Management
Raleigh, North Carolina

Larry A. Morris, Ph.D.
University of Georgia
Athens, Georgia

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For more information about this research, contact:

Eric D. Vance, Ph.D.
Project Leader
NCASI
P.O. Box 13318
Research Triangle Park, N.C 27709-3318
(919) 941-6415
evince@ncasi.org

Alan A. Lucier, Ph.D.
Senior Vice President
NCASI
P.O. Box 13318
Research Triangle Park, N.C. 27709-3318
(919) 941-6403
alucier@ncasi.org

For information about NCASI publications, contact:

Publications Coordinator
NCASI
P.O. Box 13318
Research Triangle Park, NC 27709-3318
(919) 941-6400
publications@ncasi.org

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PRESIDENT'S NOTE

Soil physical properties heavily influence the availability of water, nutrients, and oxygen to trees and are strongly related to the ability of a site to sustain productive forest growth. Soil physical properties also influence the susceptibility of soils to erosion, which has implications for both long-term site productivity and water quality. Forest management has the potential to degrade soil physical properties, but degradation can usually be avoided through appropriate management practices. Management can even mitigate poor physical properties inherent to some soil types or that result from past land uses or management practices. Because the physical state of the soil directly influences several indicators of sustainable forest management, it is intrinsically relevant to the goals of forest certification.

Quantifying relationships between soil physical properties and tree growth and the effects of forest management practices on these relationships is difficult. This is due to the close ties between forest growth and other site limiting factors related to climate, topography, and inherent soil fertility. Because of these complexities, traditional agricultural models of soil disturbance and productivity cannot always be used to interpret the effects of forest management practices. Soil disturbance can also indirectly influence tree growth and stand productivity by altering limiting site factors. For example, soil compaction reduces vegetative competition and increases tree seedling growth on some sites. Effects of management practices also depend to a large extent on the time of year the practices take place, the type of equipment used, the expertise of the operator, and whether appropriate guidelines (e.g., Best Management Practices) are followed. Despite evidence of negative effects of soil disturbance, trees have a remarkable ability to adapt. There is also strong evidence that short-term effects of management-induced soil disturbance on tree growth should not be used to derive conclusions about long-term site productivity.

This report provides a comprehensive review of relationships between soil physical properties and long-term site productivity. It contains detailed information on a) mechanistic relationships between soil physical properties and root growth, b) tree growth on disturbed soil, c) soil recovery from compaction and puddling, d) ameliorating soil disturbance, and e) preventive measures. The report is based on data collected from a wide range of forest sites across the United States, western Canada, Australia, and New Zealand, and should serve as a valuable reference on this important topic for years to come.

Ronald A. Yeske

October 2004

MOT DU PRÉSIDENT

Les propriétés physiques des sols jouent un rôle important dans l'approvisionnement des arbres en eau, en éléments nutritifs et en oxygène et sont intimement liées à la capacité du site de soutenir la croissance des arbres d'une façon productive. Les propriétés physiques des sols influencent également leur susceptibilité à l'érosion ce qui a des conséquences à long terme sur la productivité des sites et la qualité de l'eau. Les pratiques d'aménagement forestier peuvent détériorer les propriétés physiques des sols, mais cette dégradation est évitable si on fait appel à des pratiques d'aménagement adéquates. Les gestionnaires peuvent même réduire les faibles propriétés physiques inhérentes de certains types de sols ou de ceux découlant d'une utilisation passée des terres ou de vieilles pratiques d'aménagement. Les conditions physiques des sols sont par nature liées aux objectifs de la certification forestière car elles influencent directement plusieurs indicateurs d'aménagement forestier durable.

Il est difficile de déterminer les relations entre les propriétés physiques des sols et la croissance des arbres et de quantifier l'effet des pratiques d'aménagement forestier sur ces relations en raison des liens étroits qui existent entre la croissance des arbres et les autres facteurs limitatifs du site liés au climat, à la topographie et à la fertilité inhérente du sol. Compte tenu de la complexité du système, il n'est pas toujours possible de faire appel aux modèles agricoles traditionnels sur la productivité et le déséquilibre des sols pour interpréter les effets des pratiques de gestion forestière. Les perturbations du sol peuvent également agir indirectement sur la croissance des arbres et la productivité des peuplements en modifiant les facteurs limitatifs du site. Par exemple, le tassement des sols diminue la concurrence végétale et augmente la croissance des semis d'arbres sur certains sites. Les effets des pratiques d'aménagement dépendent aussi en grande partie de la période dans l'année où s'opèrent ces pratiques, du type d'équipement employé, de la compétence de l'opérateur et de l'utilisation ou non de directives adéquates (c'est-à-dire de bonnes pratiques de gestion). Malgré qu'on puisse démontrer les effets négatifs de la perturbation des sols sur les arbres, ceux-ci ont une capacité remarquable d'adaptation. Il y a aussi de nombreuses évidences que les effets à court terme de la perturbation des sols sur la croissance des arbres causée par un aménagement artificiel ne devraient pas servir à établir des conclusions sur la productivité à long terme du site.

Le présent rapport est une revue complète des relations entre les propriétés physiques des sols et la productivité à long terme d'un site. Il contient de l'information détaillée sur a) les relations mécanistes entre les propriétés physiques des sols et la croissance des racines, b) la croissance des arbres sur des sols perturbés, c) la régénération d'un sol tassé ou transformé en boue, d) les façons de moins perturber les sols et e) les mesures de prévention. Ce rapport repose sur des données recueillies dans de nombreux sites forestiers à travers les États-Unis, l'ouest canadien, l'Australie et la Nouvelle-Zélande. Il devrait être une référence utile pour les prochaines années en ce qui concerne cet important sujet.

Ronald A. Yeske

Octobre 2004

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ABSTRACT

Soil disturbance caused by heavy equipment used for harvesting or site preparation can have negative effects on soil properties and long-term forest site productivity. Soil compaction, churning, rutting, mixing, displacement, and removal are types of disturbance that can reduce tree root growth through their influence on soil physical, chemical, and biological properties. Removal or displacement of surface soil can also expose deeper subsoil, which may be less suitable for root growth due to its greater bulk density and soil strength.

Most information on the effects of soil disturbance on root growth is derived from studies of agricultural crops under carefully controlled laboratory and greenhouse conditions. In contrast, trees are long-lived and have great capacity to adapt to restrictive soil conditions through morphological and distributional changes in their root system. This adaptive capacity limits our ability to predict how trees will respond to soil compaction under field conditions. In most soils, compaction reduces subsequent root growth in direct proportion to the degree of compaction. The long-term significance of observed short-term reductions in growth will depend on whether reduced root growth is associated with a) an overall reduction in rootable soil volume and quality or b) simply a slower exploitation of the pre-disturbance rooting volume.

The likelihood or severity of growth impairment from soil disturbance is difficult to generalize because disturbance influences or interacts with other site-specific, growth-determining factors. In most situations, short-term growth of seedlings or saplings on skid trails is less than on adjacent non-skid trail areas; this may or may not reduce ultimate stand yield. Soil disturbance can also have unanticipated secondary effects on tree growth. A good example of this is enhanced seedling growth found on some disturbed sites due to reductions in competing vegetation.

Some soils are more resilient to physical impact than are other soils, and mitigative measures or corrective treatment are not always needed. Compaction of some coarse-textured soils can actually improve moisture relations for tree growth. Loamy soils are more susceptible to compaction; clayey soils are more susceptible to rutting and churning. The time required for natural recovery from compaction varies with soil physical characteristics, chemical characteristics, climate, and the severity of compaction. Recovery may be faster where soils are subjected to freezing-thawing or wetting-drying cycles. In the absence of site-specific information, the effects of compaction on forest soils may be assumed to persist for several decades.

Rehabilitation of compacted soil can be attempted by mechanical manipulation, such as disk harrowing, bedding or mounding, subsoiling or ripping, and spot cultivation. If properly applied, these tillage practices can favorably alter soil properties and enhance seedling survival and growth. Tillage under non-optimum conditions (e.g., wet soil), however, can cause additional soil compaction and/or puddling, and create further risk to long-term productivity.

This technical bulletin reviews the types of soil disturbances that can occur from common forest management operations and how these disturbances influence soil physical properties, root growth, and ultimately, stand yield. Management practices that can be used to prevent or ameliorate soil disturbance are also described.

KEYWORDS

Best Management Practices, forest certification, harvesting, site preparation, site productivity, soil disturbance, soil physical properties, stand yields, sustainable forest management, tree growth

RELATED NCASI PUBLICATIONS

Technical Bulletin No. 839 (December 2001). *Assessing management effects on Pacific Northwest site productivity: an inventory and evaluation of research and operational sites.*

Technical Bulletin No. 798. (February 2000). *Utilizing paper mill by-products as forest soil amendments: forest responses, recommendations, and industry case studies.*

Technical Bulletin No. 766 (December 1998). *Agricultural site productivity: principles derived from long-term experiments and their implications for managed forests.*

Technical Bulletin No. 628 (March 1992). *Effects of forest management on soil carbon storage.*

LES EFFETS DE L'ÉQUIPEMENT LOURD SUR LES PROPRIÉTÉS PHYSIQUES DES SOLS ET SUR LA PRODUCTIVITÉ À LONG TERME: REVUE DE LA LITTÉRATURE ET DE LA RECHERCHE ACTUELLE

BULLETIN TECHNIQUE NO. 887
OCTOBRE 2004

RÉSUMÉ

La perturbation des sols attribuable à l'utilisation d'équipements lourds pour la récolte ou la préparation d'un site peut avoir des effets négatifs sur les propriétés des sols et sur la productivité à long terme d'un site forestier. Le tassement, le brassage, l'orniérage, le mélange, le déplacement, et l'enlèvement des sols sont des types de perturbations qui peuvent diminuer la croissance des racines des arbres par la modification des propriétés physiques, chimiques et biologiques des sols. L'enlèvement ou le déplacement du sol de surface peut aussi exposer un sous-sol qui peut être moins propice à la croissance des racines en raison de sa plus grande densité apparente et de sa résistance.

La majorité des informations sur les effets de la perturbation des sols sur la croissance des racines proviennent d'études sur les plantes agricoles effectuées dans des conditions soigneusement contrôlées de laboratoire et de serre. Par contraste, les arbres ont une longue durée de vie et s'adaptent plus facilement aux conditions limitatives des sols en modifiant la morphologie et la répartition de leur système racinaire. Ce pouvoir d'adaptation restreint notre capacité à prédire la façon dont les arbres répondent au phénomène de tassement des sols dans des conditions de terrain. Dans la plupart des sols, le tassement réduit la croissance subséquente des racines d'une façon directement proportionnelle au degré de tassement. Les conséquences à long terme des réductions de croissance observées à court terme varieront selon que le ralentissement de la croissance des racines est liée à a) une diminution globale de la qualité et du volume de sol pouvant contenir des racines ou b) simplement une mise à profit plus lente du volume d'enracinement d'avant les perturbations.

Il est difficile de généraliser le risque ou la gravité d'un déficit de croissance causé par un déséquilibre dans le sol car les perturbations agissent sur ou interagissent avec d'autres facteurs décisifs de croissance propres au site. Dans la plupart des cas, la croissance à court terme des semis ou des gaules dans les pistes de débardage est plus lente que celle dans les zones adjacentes aux pistes de débardage ce qui peut réduire ou non le rendement final des gaules. Les perturbations des sols peuvent aussi avoir des effets secondaires imprévus sur la croissance des arbres. Un bon exemple de cette situation est la croissance accélérée des semis observée dans certains sites perturbés en raison d'une concurrence végétale moindre.

Certains sols sont plus résilients aux impacts physiques que d'autres. Les mesures d'atténuation ou de correction ne donc pas toujours nécessaires. Le tassement de certains sols à texture grossière peut améliorer de façon positive les régimes d'humidité liés à la croissance des arbres. Les sols loameux réagissent davantage au tassement tandis que les sols argileux sont plus sensibles à l'orniérage et au brassage. Le temps dont un sol a besoin pour se régénérer de façon naturelle suite à un tassement varie en fonction des caractéristiques physiques du sol, du climat et de l'importance du tassement. La régénération peut être plus rapide lorsque les sols sont l'objet de cycles de gel et de dégel ou d'humidification et de séchage. En l'absence d'informations propres au site, on peut supposer que les effets du tassement sur les sols forestiers subsistent sur plusieurs décennies.

On peut tenter de régénérer un sol tassé à l'aide de moyens mécaniques dont le hersage, le billonnage ou le buttage par disque, le sous-solage ou le ripage, et la culture localisée. Si on les applique adéquatement, ces pratiques de travail peuvent modifier avantageusement les propriétés d'un sol et accroître la croissance et la survie des semis. Toutefois, le travail du sol effectué dans des conditions qui ne sont pas optimales (par exemple, sol humide) peut tasser le sol encore plus ou le transformer davantage en boue et soumettre sa productivité à long terme à de plus grands risques.

Le présent bulletin technique examine les types de perturbations des sols qui peuvent se manifester lors des opérations d'aménagement forestier et la façon dont ces perturbations influencent les propriétés physiques des sols, la croissance des racines et finalement le rendement des peuplements. Il décrit aussi les pratiques d'aménagement qui peuvent servir à prévenir ou à améliorer les perturbations des sols.

MOTS CLÉS

aménagement forestier durable, certification forestière, croissance des arbres, meilleures pratiques de gestion, perturbation des sols, préparation du site, propriétés physiques des sols, productivité du site, récolte, rendements des peuplements

AUTRES PUBLICATIONS DE NCASI DANS CE DOMAINE

Bulletin technique No. 839 (décembre 2001). *Assessing management effects on Pacific Northwest site productivity: an inventory and evaluation of research and operational sites.*

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1.0 INTRODUCTION

Use of heavy rubber-tired or tracked equipment required to harvest and move large trees creates risk of soil disturbance that could reduce productivity of forest soils. Additionally, soil disturbance can contribute to stream sedimentation, and visually suggests poor stewardship. Soil disturbance during harvesting and site preparation can be avoided or minimized by choice of appropriate equipment, scheduling activities to avoid operations on susceptible sites during wet periods, and by careful monitoring and controlling operations. When they occur, the potentially negative effects of soil disturbance on soil properties and processes can be mitigated to varying degrees by remedial actions such as tillage, reestablishing drainage patterns, or erosion control. Both preventive and remedial mitigation increase costs of harvesting and site preparation, but the potential benefits of increased tree growth or reduced erosion could compensate for these increased costs. Hence, both costs and benefits need to be quantified. The choice and benefits of mitigation, however, are site-specific. For example, some soils are more resilient to physical impact than are other soils, and there is no need for corrective treatment. Compaction of some coarse-textured soils can actually improve moisture relations for tree growth, and soil disturbance at some locations can enhance seedling growth by controlling competing vegetation. Moreover, soil and climate can be so favorable for plant growth at some sites that light or moderate soil disturbance has relatively small effects. Finally, both reductions in tree growth from disturbance and increases from corrective treatment are difficult to quantify. Even when statistically significant effects of management operations on soil properties or seedling growth are detected, extrapolation of the effects to the end of the rotation produces questionable results.

1.1 Thesis of This Review

Risk of soil disturbance and site degradation exists whenever ground-based equipment is used in forest operations. The severity and areal extent of this disturbance can be managed. Although negative effects of soil disturbance on soil properties are well documented, effects on tree growth and stand yield are less documented and more variable. It is not warranted to generalize that tree growth will be reduced after soil disturbance. The consequences of soil disturbance or mitigative practices for subsequent tree growth are site-specific and also depend on other growth-determining factors.

1.2 Objectives of This Review

By summarizing and interpreting existing scientific literature, we intend to

1. describe types of soil disturbance and their general effects on soil properties and processes;
2. review relationships between root growth and soil physical properties;
3. document results of investigations of tree growth and yield on disturbed soil;
4. discuss rates of soil recovery through natural processes;
5. evaluate the efficacy of ripping and other techniques for ameliorating soil disturbance and tree growth;
6. discuss means to prevent soil disturbance.

1.3 Scope of This Review

The geographic scope of this review is primarily North America with appropriate principles and findings from worldwide forestry and agriculture.

1.4 Types of Soil Disturbance

Primary soil disturbance differs in severity and extent. Three types of disturbance are generally recognized:

1. Compaction: the process by which the soil grains are rearranged to decrease void space (particularly large pores) and bring them into closer contact with one another, thereby increasing the bulk density (SSSA 1997)
2. Puddling: the destruction of soil structure usually by churning or kneading action of wheeled or tracked equipment
3. Displacement: the act of moving soil laterally from narrow ruts or wider areas.

A soil can be compacted with only minor structural change. In contrast, the destruction of soil structure in puddled soils inevitably results in compaction. Even if soils are puddled without compaction, they will self-compact as they dry (Chancellor 1977). Failure to recognize this distinction has led some researchers to ascribe changes in soil properties and tree performance to compaction, when in fact, other types of disturbance were involved and were probably more influential.

1.5 Effects of Heavy Equipment

Heavy equipment can affect soil properties and subsequent forest productivity a) through its immediate effects on soil physical properties or on residual trees, and b) through its subsequent (longer-term) effects on soil processes. The consequences for forest productivity depend both on the nature of the change and the areal extent of impacted area.

1.5.1 *Immediate Effects on Physical Properties of Surface Soil or Subsoil*

The immediate (direct) effects of heavy equipment on soil properties are to a) increase soil resistance to penetration; b) reduce conductivity of soil to water and gas flow through a reduction in size, continuity, and total volume of pores, especially large pores; and c) reduce the number, size, and/or strength of structural aggregates. The distribution of these effects within the profile is a function of the ground pressure and total load (ground pressure x contact area of the tire or track), soil characteristics (e.g., texture, structure), and moisture conditions at the time of operation. Ground pressure is greatest at the soil surface and decreases with depth (Figure 1.1). Other things being equal, compaction will be greatest where pressure is greatest. Soil texture and moisture are also important. Soils are most subject to compaction at soil moisture contents just drier than field capacity (see Section 6.1). As moisture content decreases, soil strength increases and compaction potential decreases. At moisture contents above field capacity, water-filled pores prevent compaction while lubricating the soil. Consequently, when wet soil is trafficked, “plastic” flow occurs that results in churned and rutted soil.

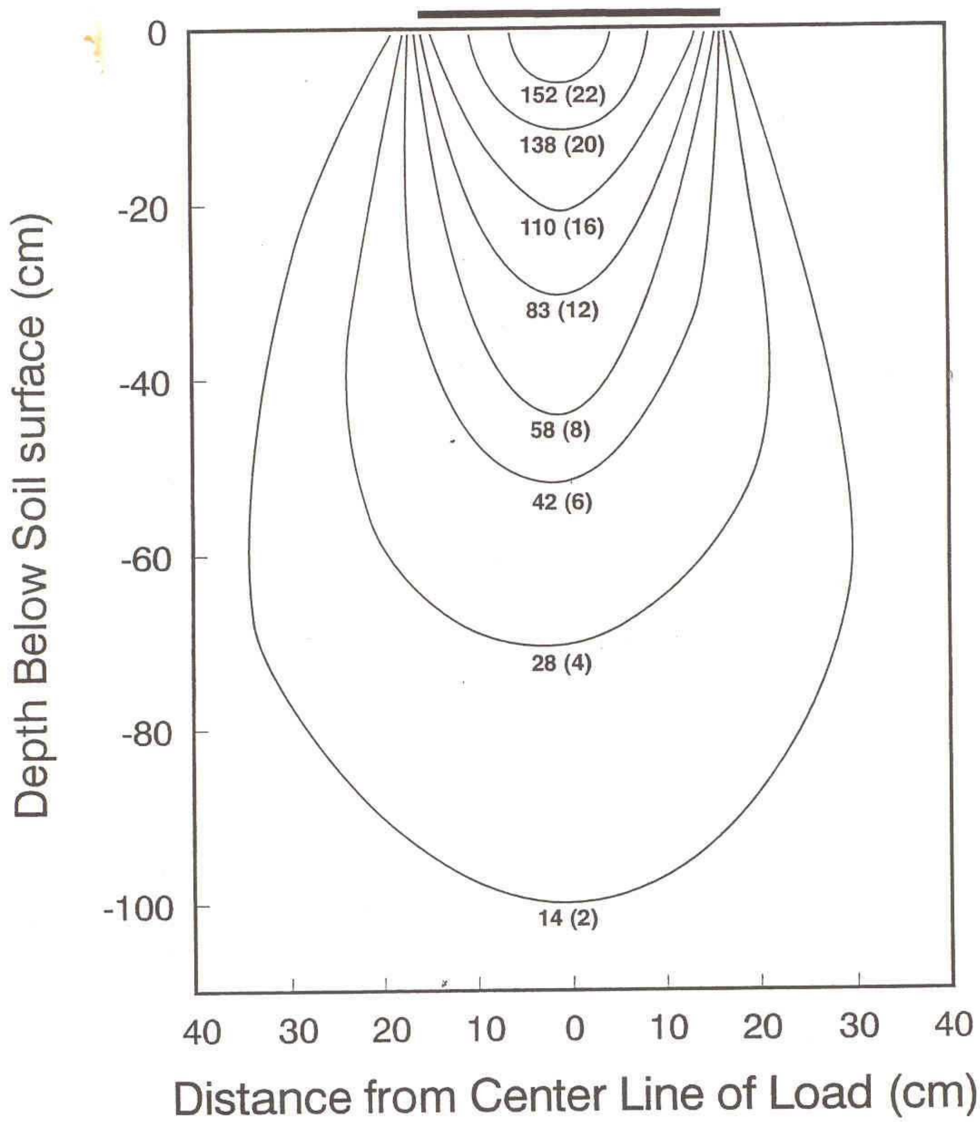

Figure 1.1 Vertical Pressure Distribution beneath a 13-38 Tractor Tire Inflated to 110 kPa (16 lb in^{-2}) and Carrying a 1635 kg (3600 lb) Vertical and 680 kg (1500 lb) Horizontal Load Pressure isobars are in kPa and (lb in^{-2}). [Redrawn from Reaves and Cooper (1960). Reprinted with permission from the American Society for Agricultural Engineers.]

1.5.2 *Direct Effects on Residual Trees*

Roots can be damaged or severed by heavy equipment. This results in reduced uptake of water and nutrients, and provides potential entry points for disease or insects.

1.5.3 *Subsequent (Secondary) Effects on Soil Processes*

Heavy equipment also can have indirect effects on soil properties and functioning. Exposed mineral soil is also more susceptible to subsequent impacts of rain or equipment, and displaced soil particles plug soil pores and further reduce infiltration and gas exchange. Slower infiltration of rainfall into mineral soil can increase water runoff and erosion. Slower movement of moisture and gases can cause moisture saturation above, and moisture deficits below restrictive depths. Such changes in soil moisture and aeration also tend to reduce activity of soil organisms that help cycle nutrients and organic matter.

1.5.4 *Consequences for Trees and Other Vegetation*

Changes in soil properties resulting from disturbance by heavy equipment usually make soil more physically resistant to roots and can reduce root and top growth. These changes also are associated with reduced capacity to provide air, nutrients, and water to plants and soil organisms. Plant growth can decline for a variable period of time. At some locations, soil rutting and displacement can cause saturated soils and/or place roots closer to root-restrictive layers or bedrock, or to chemically unfavorable subsoil (e.g., alkaline, saline). Consequently, the rooting zone is degraded in volume and quality.

1.6 Factors Affecting Severity and Areal Extent of Soil Disturbance Associated with Heavy Equipment

All soils are susceptible to disturbance by tracked and wheeled equipment. Vertical loading may lead to soil compaction and rutting. Wheel slippage causes soil shearing, churning, and mixing. The degree to which disturbance affects a given soil depends on

* physical properties of the specific soil;
* soil wetness when equipment traffics the soil (soil moisture depends on the amount of recent precipitation and on how rapidly moisture drains through the soil);
* depth to which soil is frozen and the depth of accumulated snow, which acts as a protective cover;
* equipment, methods, and harvest layout;
* operator knowledge and skill, which can be increased by training.

Table 1.1 summarizes relations among these factors and the risks of soil disturbance.

Table 1.1 Factors Affecting the Severity and Extent of Soil Disturbance by Heavy Equipment

	Risk of Detrimental Soil Disturbance			
Factor	Low	Moderate	High	Very High
		Fixed factors		
Soil properties:				
• Water tables, depth to	>4 ft	2-4 ft	0.5-2 ft	< 0.5 ft
• Moisture movement	rapid	moderate	slow	very slow
• Depth of A-horiz (E-if present)	very deep	deep	moderate	shallow
• Texture classes[a]	sand to loamy sand	sandy loam to sandy clay loam	clay loam	clay
o Slope %	0-5	6-15	16-30	>30
		Variable factors		
Rainfall:				
Seasonal amount	small	moderate	large	very large
Recent (days since)	10	5	3	0
Depth of snow	very deep	deep	moderate	shallow
Depth of frozen soil	very deep	deep	shallow	non-frozen
Equipment:				
Static weight (psi)	light (<7)	moderate	heavy	very heavy (>25)
Dynamic load	light	--	--	very heavy
Operator:				
Knowledge	high	--	--	low
Skill	high	--	--	low

[a] Loams are more susceptible to compaction than are clays; clays are more susceptible to rutting.

1.7 Severity of Soil Disturbance (Disturbance Classes 1 to 4)

A soil disturbance classification developed and used by Weyerhaeuser Company is based on the observation that disturbance from the movement of heavy machinery and logs can be separated into four classes (Miller et al. 1989):

* compacted surface soil (Disturbance Class 1);
* a compacted or mixed surface soil with destroyed soil structure (puddled), and subsoil that may or may not be compacted (Disturbance Class 2);
* displacement of some surface soil, with the remainder mixed into the subsoil (Disturbance Class 3);
* displacement of all surface soil (Disturbance Class 4).

The original classification was augmented by adding a subclass for the risk of saturation because movement of water on and within the soil has been disrupted (Scott 2000). These disruptions can cause the soil to become too saturated for seedlings of some species to survive. This classification has proven useful for assessing severity of soil disturbance and potential site degradation (Figure 1.2) in the Pacific Northwest. Similar classification systems have been employed in the Southeast and have recently been evaluated by Aust et al. (1998a) at a low-lying, wet pine flat in the lower Coastal Plain of South Carolina. These investigators found that a visual classification of soil as non-disturbed, compressed, rutted, or churned was related to static measures of these disturbed soils (bulk density, saturated hydraulic conductivity, and macropore space), but not related to changes in dynamic soil properties (soil strength, depth to water table, or volumetric moisture content). These poorly drained soils had increased strength (resistance to penetration) on compacted areas that only resulted when harvest occurred on dry soil.

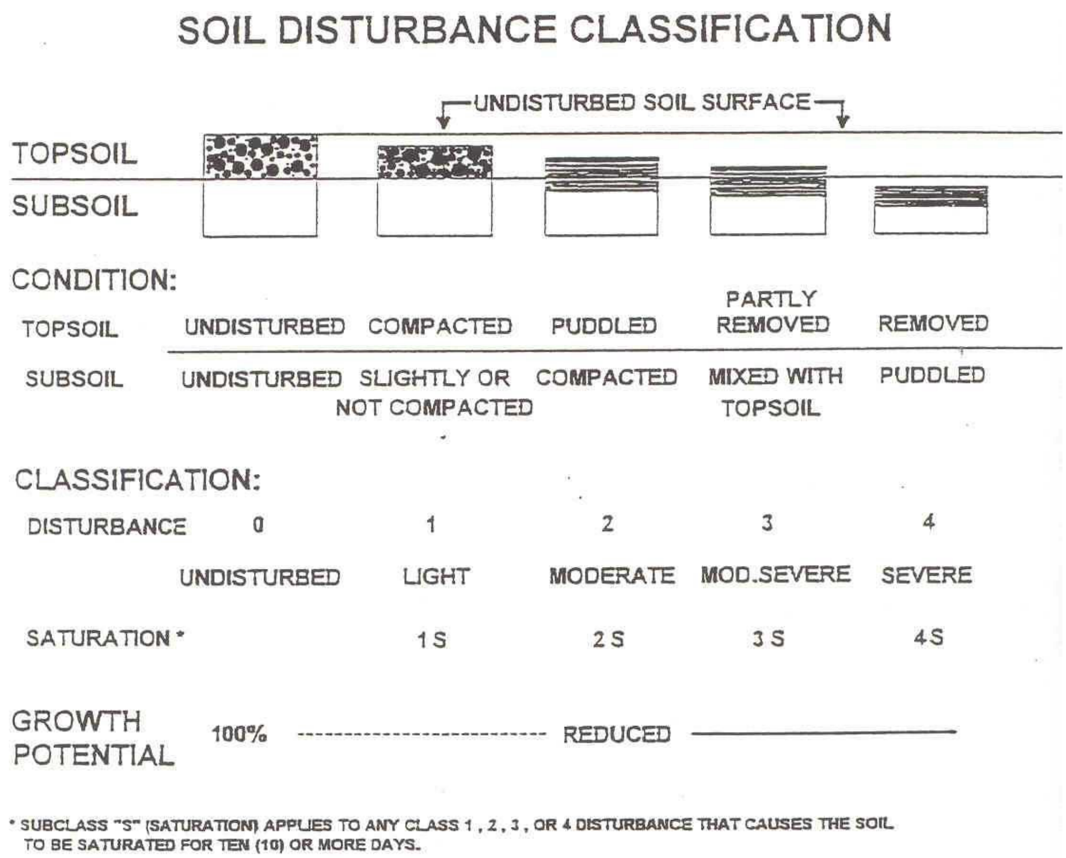

Figure 1. A soil disturbance classification developed and used by Weyerhaeuser Company

Figure 1.2 A Soil Disturbance Classification Developed and Used by Weyerhaeuser Company [Reprinted with permission from Weyerhaeuser Company and NRC Research Press]

1.8 Areal Extent of Soil Disturbance

Ground-based yarding with rubber-tired or tracked shovels, feller-bunchers, or processors is usually restricted to slopes less than about 30%. Soil disturbance varies in severity and extent. Displacement of all surface soil (Disturbance Class 4) is usually restricted to portions with deep ruts or with blading to create a smoother trail. Steeper slopes can also be harvested with skidders, but cross-contour skid roads must be deliberately constructed to maintain equipment stability. This has been a commonly used method in Interior British Columbia (Senyk and Craigdallie 1997). Up to 30% of the harvested area can be in primary (frequently used) skid trails or skid roads (Table 1.2). In the southeastern United States where ground-based skidding is the norm, 17 to 32% of the harvested area is in primary and secondary skid trails (Table 1.2).

Least soil disturbance usually occurs when low volumes per unit area are removed or when yarding systems are used that primarily lift rather than drag logs (e.g., skyline, balloon, or helicopter). Balloon or helicopter logging, for example, compacts or disturbs deeply (to the subsoil) only 4% to 5% of the logged area (Dyrness 1972; Bockheim, Ballard, and Willington 1975). In contrast, where cable systems did not provide full suspension or lift, the area of disturbed soil ranged from 35 to 45% of the logged area; specifically, 7-11% of the logged area was compacted and 6-14% was disturbed to the subsoil (Dyrness 1965). Because full-suspension yarding methods are more costly, skidding logs with tractors, especially rubber-tired tractors, is more common where slopes are less than about 30% and skidding distances less than about 200 m.

Although some methods of ground-based yarding cause more soil disturbance than others, the amount and types of disturbance also differ among sites and operators. Critical variables include size and amount of logging residue, equipment used, irregularity of terrain, moisture content at time of traffic, and inherent resistance of each soil to disturbance.

Table 1.2 Percentage of Total Harvested Area in Skid Trails after Tractor Yarding of Clearcut Douglas Fir or Western Hemlock, by State or Province

Area and Source	Locations (no.)	Skid Trails or Skid Roads: Primary	Secondary	Both
		% of harvested area		
Eastern British Columbia:				
Smith (1988)	6	(17-61)	--	--
Smith and Wass (1976):				
Summer skidding		28	--	--
Winter skidding		13	--	--
Hammond (1983):	77			
<20% slopes		2	--	--
20-40% slopes		(10-14)	--	--
>40% slopes		16	--	--
Smith and Wass (1980)	4	32	--	--
Western Washington:				
Steinbrenner and Gessel (1955)	9	--	--	17-34
Scott et al. (1999)	3	(7-21) [a]	--	--
Western Oregon:				
Aulerich, Johnson, and Froehlich (1974)	2	10	8	16-27
Froehlich (1979a)	2	--	--	12-15
Wert and Thomas (1981)	1	10	--	--
Sidle and Drlica (1981)	1	--	--	14
Scott et al. (1999)	4	(11-30)[a]	--	--
South Carolina and Virginia Coastal Plain:				
Hatchell, Ralston, and Foil (1970)	9	12.4	19.9	32
		(3-23)	(9-42)	--
Mississippi Coastal Plain:				
Miller and Sirois (1986)	4	14.0[b]	13.4	--
Dickerson (1976)	4	--	--	17
Georgia Piedmont:				
Willis (1971)	2	6[c]	15	21

[a] range of weighted means for each location
[b] severely disturbed and compacted areas of skid trails
[c] includes deck areas

2.0 SOIL PHYSICAL PROPERTIES AND ROOT GROWTH

2.1 Introduction

Roots provide water, nutrients, and mechanical stability to trees. Hence, unconstrained root growth is fundamental to optimum tree growth. Roots grow through the soil in one of two ways: a) by growing through pores larger than their own diameter, or b) by enlarging pores smaller than their own diameter. Where root growth is due largely to expansion of smaller pores, which is the norm, three physical factors are directly related to root growth: a) mechanical resistance to penetration, b) soil water potential, and c) gas diffusion rates that control oxygen availability and concentrations of toxic metabolites near roots. Besides affecting these three factors, soil compaction from heavy equipment can also influence root growth indirectly by affecting moisture, temperature, microbial activity, decomposition rate, nutrient transformations, and activity of organisms that promote formation of soil structure and macropores.

2.2 Mechanical Resistance to Root Penetration

Large and continuous macropores provide a path for root growth, even in soils with high mechanical resistance. In the absence of large macropores, root growth depends upon the ability of roots to enter and expand small pores. The forces associated with root extension into small pores currently cannot be measured directly. Penetrometer resistance, measured as the force required to push a metal probe through the soil at a specified rate, provides the most commonly used estimate of mechanical resistance to root penetration. Such resistance only approximates the actual resistive forces on growing roots. Unlike metal rods, roots are flexible, self-lubricating, and easily deformed. Penetrometers overestimate the actual root penetration resistance by two- to eight-fold (Bengough and Mullins 1990). Thus, there is a discrepancy between measures of maximum pressures which roots are capable of exerting and penetrometer-measured soil resistance through which roots can grow (Whitely, Utomo, and Dexter 1981; Atwell 1993). Despite this limitation, penetrometers provide a standard measure of mechanical resistance to plant roots.

In the absence of other limitations, root growth and extension are greatest at minimal resistance, and generally decline linearly with increased mechanical resistance up to a maximum resistance above which growth ceases or is confined to large pores. Similar to agronomic crops, tree root growth slows at resistances as low as 0.5 MPa and stops at resistances between 2.0 MPa and 3.0 MPa (Table 2.1). The relation between root growth for an individual crop species and penetrometer resistance is relatively consistent across a range of soil textures. Root growth of tree seedlings appears to respond to mechanical resistance in a similar manner (Figure 2.1) and, as a consequence, penetrometer resistance has been considered a useful means of evaluating soil compaction under field conditions.

Table 2.1 Mechanical Resistance at Which Tree Root Growth Is Severely Restricted or Stopped

Species	Soil Texture	Study Conditions	Limiting Value	Resistance Measure	Response Observed	Reference
			MPa			
Pinus radiata	sand	Field-plantations, age not specified	2	60^o cone, 1 cm-wide base	No. of roots reduced from 8/100 cm^3 to 4/100·cm^3 soil volume	Sands, Greacen, and Gerard (1979)
Pinus elliottii	sand	Field; mature plantations	3.0	60^o cone, 1 cm-wide base	Root length reduced from 100 cm cm^{-3} to <20 cm cm^{-3}	Van Rees and Comerford (unpublished data)
Pinus radiata	sand and loamy sand	Field; 7-year-old plantation	3.0	Indentation penetrometer	Reduction of roots in soil pit walls to near zero	Mason and Cullen (1986)
Pinus taeda	loamy sand	Greenhouse; root growth into compacted layer after 10 weeks	2.4	30^o cone, 1 cm-wide base	Regression relationship between root mass and resistance	Torreano (1992)
Pinus caribaea	sandy loam	Greenhouse; seeds germinated in repacked cores	3.25	6.5mm-wide blunt tip	Radicle elongation ceased	Costantini, So, and Doley (1996b)
Eucalyptus nitens	clay	Field	4.2	600 cone, 2.15 mm-wide base	71% reduction in primary root growth; 31% reduction in lateral root growth	Misra and Gibbons 1996)

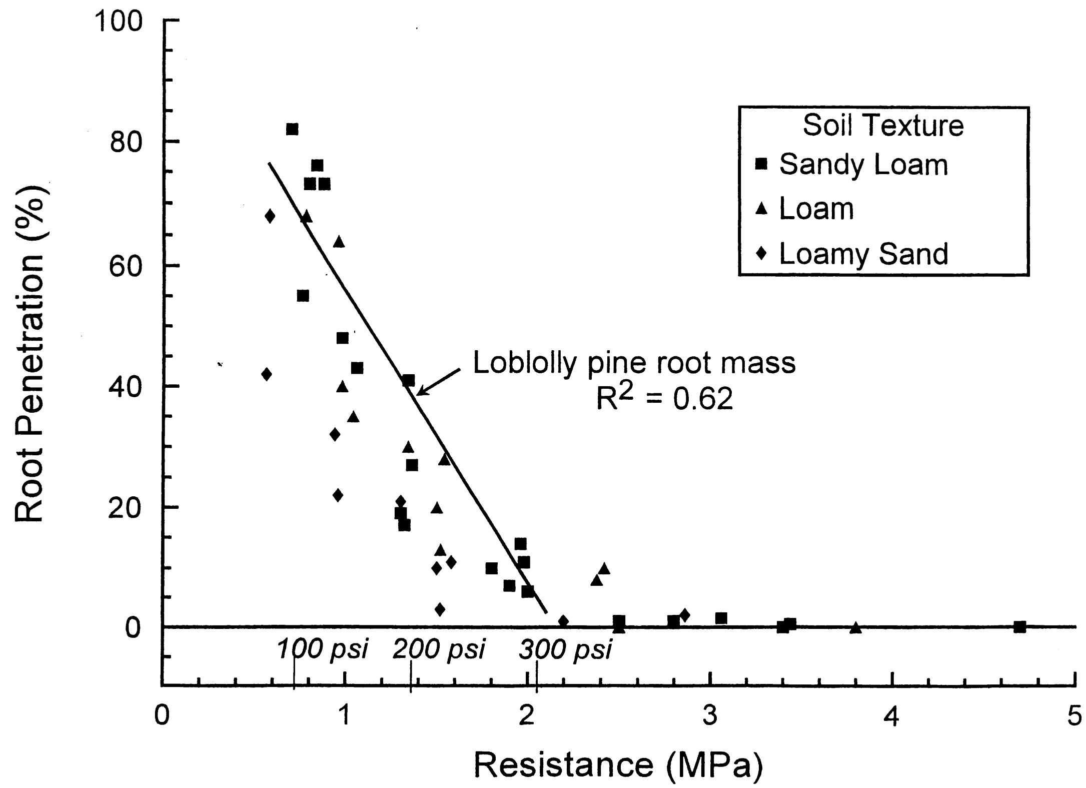

Figure 2.1 Root Penetration of Cotton (*Gossypium hirsutum* L.) on Soils of Three Textures [Redrawn from Taylor, Roberson, and Parker 1966. For comparison, the relationship between root growth of loblolly pine and resistance to penetration in a loamy sand (Torreano 1992) is superimposed.]

2.2.1 *Physiological Basis of Root Response*

Physiological response to strong soil resistance is not completely understood. Even small external pressures have been shown to rapidly reduce root elongation, suggesting that a metabolic pathway is involved. Tardieu (1994) presented three lines of evidence to support this: a) root elongation rates do not correspond to physical models based on relationships among root water potential, root turgor, and root osmotic potential; b) response is not immediate as would be expected for a hydraulic response and lag periods occur between the imposition or removal of resistance and plant response; and c) rapid changes in growth of above-ground portions of the plant occur in response to increased root resistance. See also a review by Glinski and Lipiec (1990). For instance, in a study designed to disentangle the effects of direct resistance from the secondary effects of compaction on water and nutrient availability, Young et al. (1997) evaluated wheat (*Triticum aestivum* L.) and barley (*Hordeum* spp. L) growth in a growth cell that allowed soil strength to be manipulated while other factors were held constant. These investigators found that leaf elongation rates decreased within 10 minutes of increasing root impedance, suggesting the role of a growth hormone signal. Although abscisic acid (AbA) is known to regulate leaf and root growth in non-stressed plants, it appears to be less important in stressed plants, such as those grown in compacted soils (Munns and Cramer 1996). Indolacetic acid (IAA) and ethylene have also been suggested as possible signals for morphological and growth change associated with mechanical resistance. However, it is not yet clear how these signals work or interact to control plant response.

2.2.2 *Morphological Adaptations to Mechanical Resistance*

Roots that encounter mechanical resistance adapt morphologically. Generally, primary root length decreases, root diameters increase, and the number of lateral roots increases (Gilman, Leone, and Flower 1987; Glinski and Lipiec 1990; Bengough, Croser, and Pritchard 1997). The length of lateral roots may either increase or decrease. These changes appear to enable plants to adapt to adverse soil conditions. Plants with larger diameter roots tend to better penetrate soils of high mechanical resistance (Materchera et al. 1992) and increased lateral root number and/or length may make up for reduced primary root growth. For example, Misra and Gibbons (1996) showed that for shining gum (*Eucalyptus nitens* Maiden), an increase in resistance from 0.4 to 4.2 MPa reduced both primary and lateral root length (71% and 31%, respectively), but increased the abundance of root hairs and the abundance of lateral roots. The increased lateral root abundance partially compensated for reduced root length. The degree of this type of a response appears to be specific to both species and genotype. Simmons and Pope (1987) found that lateral root growth of both sweetgum seedlings (*Liquidambar styraciflua* L.) and yellow poplar (*Liriodendron tulipfera* L.) increased in compacted soil conditions but that the relative increase in lateral root growth of sweetgum was greater than yellow poplar. Costantini, So, and Doley (1996b) demonstrated for *Pinus caribbaea* that response of lateral roots to high mechanical resistance is under strong genetic control. Together, these results suggest it should be possible to select both species and genotypes for planting on sites characterized by soils with high mechanical resistance.

2.2.3 *Role of Mycorrhizae in Adaptation to Strong Mechanical Resistance*

Mycorrhizae provide a compensatory mechanism for trees growing in strongly resistant soils; hyphae can grow through small pores that cannot be penetrated and enlarged by larger diameter roots. Mycorrhizae on crop plants can modify the effects of physical resistance on uptake of low-mobility nutrients such as P. For example, Li et al. (1997) evaluated P uptake in mycorrhizal and non-mycorrhizal clover. They found little difference in P absorption when soil bulk densities were low and P-fertilized compartments were accessible to roots; however, when soil was compacted and root accessibility decreased, mycorrhizal plants had much greater uptake of P. Similar benefits of mycorrhizae have also been demonstrated for trees. Simmons and Pope (1988) compared growth of mycorrhizal-inoculated and non-inoculated sweetgum and yellow poplar seedlings in a silt loam soil compacted to provide a range of resistances and maintained at two moisture potentials. Although results varied between the species and inoculates, mycorrhizal seedlings generally grew more and developed greater root length than non-mycorrhizal seedlings in compacted soils.

2.2.4 *Role of Macropores in Root Response*

Compacted soils are seldom uniformly hard and resistant to root penetration. Rather, they include portions of low resistance to penetration and large pores that provide access through less favorable areas into more favorable areas. Several authors have demonstrated how the use of a few large pores can provide access to favorable soil environments. For instance, radiata pine (*P. radiata* D. Don) grown on soils with restrictive subsoils utilized simulated root channels through a compacted layer to reach less restrictive layers (Nambiar and Sands 1992). Although only 0.2% of soil volume was perforated by simulated channels, water stress was significantly reduced. Parker and Van Lear (1996) showed that root densities were 17-fold greater in old root channels than in the physically restrictive soil matrix of a Piedmont site. These old root channels probably provided access to additional soil volume. Additionally, they were sites of favorable water and nutrient availability.

2.3 Soil Water Potential and Root Growth

All soil water is not equally available for plant use. Water held in small pores within the soil matrix is in closer contact with particle surfaces than water in large pores. Because of the affinity of water for surfaces, greater energy is required to remove water from these smaller pores. Matric potential is a measure of the *energy* associated with these water-surface interactions. For convenience, matric potential is often expressed as soil water tension (or suction). The water tension of saturated soil is 0. As the soil dries and more energy is required to remove water, tension increases. Water content is a measure of the *quantity* of water held in the soil. For any particular soil, water potential (tension) can be related to water content; however, soils of different textures that have the same water content will have different water potentials because of differences in the proximity of pore water to particle surfaces.

Most investigators have concluded there is a direct effect of soil water potential (tension) on tree root growth, at least in soils drier than field capacity. Costantini, So, and Doley (1996b) studied root elongation of Caribbean pine under conditions of low mechanical resistance. Across a range of soil water tensions (0.01 to 3.13 MPa), root elongation declined linearly to zero. There was no critical soil water tension above or below which root elongation was unaffected by moisture. In a series of studies, Torreano (1992) and Ludovici and Morris (1997) evaluated root growth of loblolly pine (*P. taeda* L.) seedlings in rhizotrons filled with an artificial soil medium of fine sand and fritted clay that provided low physical resistance at all soil water tensions (maximum resistance <0.5 MPa). Maximum root growth occurred near field capacity and declined linearly as water tension increased to 2.2 MPa. (Figure 2.2). Again, there was no water tension below which there was no effect on root elongation. Although the relationships were linear in both cases, absolute growth rates varied. Ludovici and Morris (1997) reported lower growth rates than Torreano (1992) at equivalent water tensions, apparently because of the additional effects of nutrient competition that were absent in that earlier study.

Squire, Attiwtill, and Neales (1987) demonstrated that increased water tension appears to have a greater effect on root extension than on root initiation. In their study, radiata pine seedlings were grown for 19 weeks at three different soil water tensions (0.01, 0.04 0.07 MPa) and three N fertilization regimes. Root length decreased at greater tension (increased water stress), but the number of actively growing tips did not.

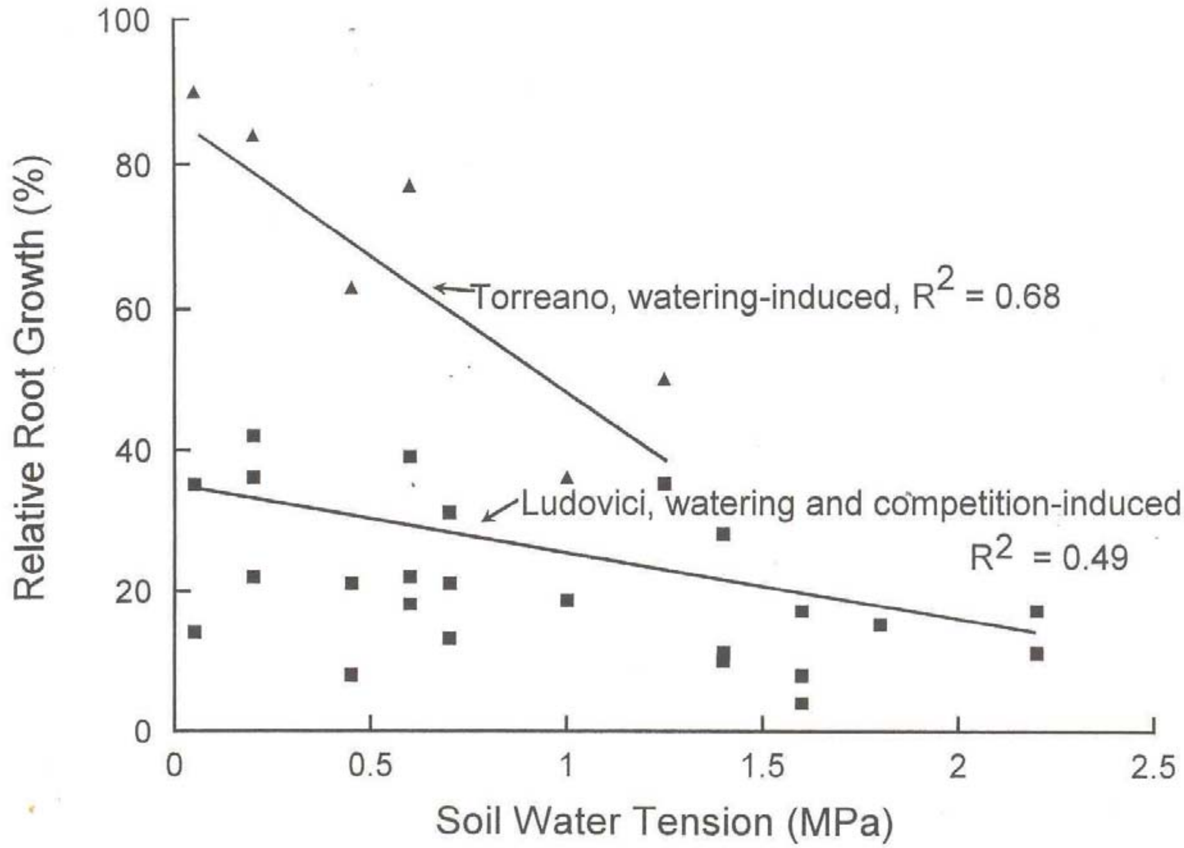

Figure 2.2 Influence of Soil Water Tension on the Relative Root Elongation of Loblolly Pine under Conditions of Low Mechanical Resistance [Adapted from Ludovici and Morris 1997; reprinted with permission from the Soil Science Society of America]

Warnaars and Eavis (1972) discussed how the effects of tension are not easily distinguished from the effects of mechanical resistance. These investigators studied root growth of pea (*Pisum sativum* L.), corn (*Zea mays* L.), and grass (*Lolium perenne* L.) in five soils varying in texture and maintained at six matric potentials. Aeration effects were distinguished from mechanical resistance effects by comparing root growth under conditions where mechanical resistance was imposed with good aeration versus root growth under conditions where both mechanical resistance and aeration were less favorable. At water tensions greater than field capacity (0.03 MPa), root growth declined with increased tension. At tensions below (wetter than) field capacity (0.002 to 0.03 MPa), these researchers failed to find any effect directly related to water tension.

2.4 Aeration Effects on Root Growth

Excess soil water does not directly injure tree roots; roots grow vigorously in solutions, if they are well-oxygenated. Adverse effects of poor aeration in soil are the result of insufficient air-filled pores to transfer oxygen to respiring roots, and transfer carbon dioxide and potentially toxic wastes away from roots. Diffusion of oxygen through water is 3 X 10^6 slower in water-filled than air-filled pores (Drew 1979). Thus, reductions in macropore volume (pores that drain under gravity and that are air-filled at field capacity) result in decreased diffusion and are a major consequence of soil compaction and destruction of soil structure (puddling).

2.4.1 *Diffusion of Oxygen and CO_2*

Tree root growth can be directly related to average soil oxygen concentrations. For instance, Gilman, Leone, and Flower (1987) correlated root systems development of honey locust (*Gleditsia triacanthos* L.) to compaction and mean soil oxygen concentrations under field conditions. They reported reduced root growth at soil oxygen concentrations less than 15%. Generally, however, root growth is more closely associated with oxygen-transport capacity than other measures. Oxygen diffusion rate (ODR) indicates the capacity of soil to transport oxygen to the root. ODR is measured with a platinum microelectrode (Glinski and Stepniewski 1985). Research with agronomic crops suggests ODR values less than 0.2 ($\mu g\ cm^{-2}\ min^{-1}$) will limit root growth due to inadequate oxygen supply (Stolzy and Letey 1964; Glinski and Lipiec 1990); however, this effect is strongly influenced by species-specific differences and temperature-dependent respiration rates. Torreano (1992) studied the effect of soil resistance and oxygen supply on root growth of greenhouse-grown loblolly pine seedlings. Average ODR rates of less than 0.35 to 0.45 $\mu g\ cm^{-2}\ min^{-1}$ in the growing season retarded root growth even under favorable soil resistance conditions of 0.6 MPa.

Generally, oxygen diffusion rates are sufficient to support uninhibited root growth in soils with air-filled porosity greater than 10-12% for both crop and tree species (Vomocil and Flocker 1961; Mukhtar, Baker, and Kanwar 1988; Simmons and Pope 1988). Oxygen diffusion rates fall to near zero in soils with air-filled porosities percentages less than this (Figure 2.3) leading to generally accepted critical value for aeration porosity (air-filled pore space at field capacity) of 10%. Aeration porosity (which can be readily determined for intact soil cones using a pressure-cell apparatus) has been measured in several harvesting and site preparation impact studies (Table 2.2). It is particularly useful for evaluating compaction impacts on tree growth in poorly and very poorly drained soils where soil water contents often are near saturation and lack of oxygen, rather than strong mechanical resistance or strong soil-water tension, limits root growth (Aust et al. 1993).

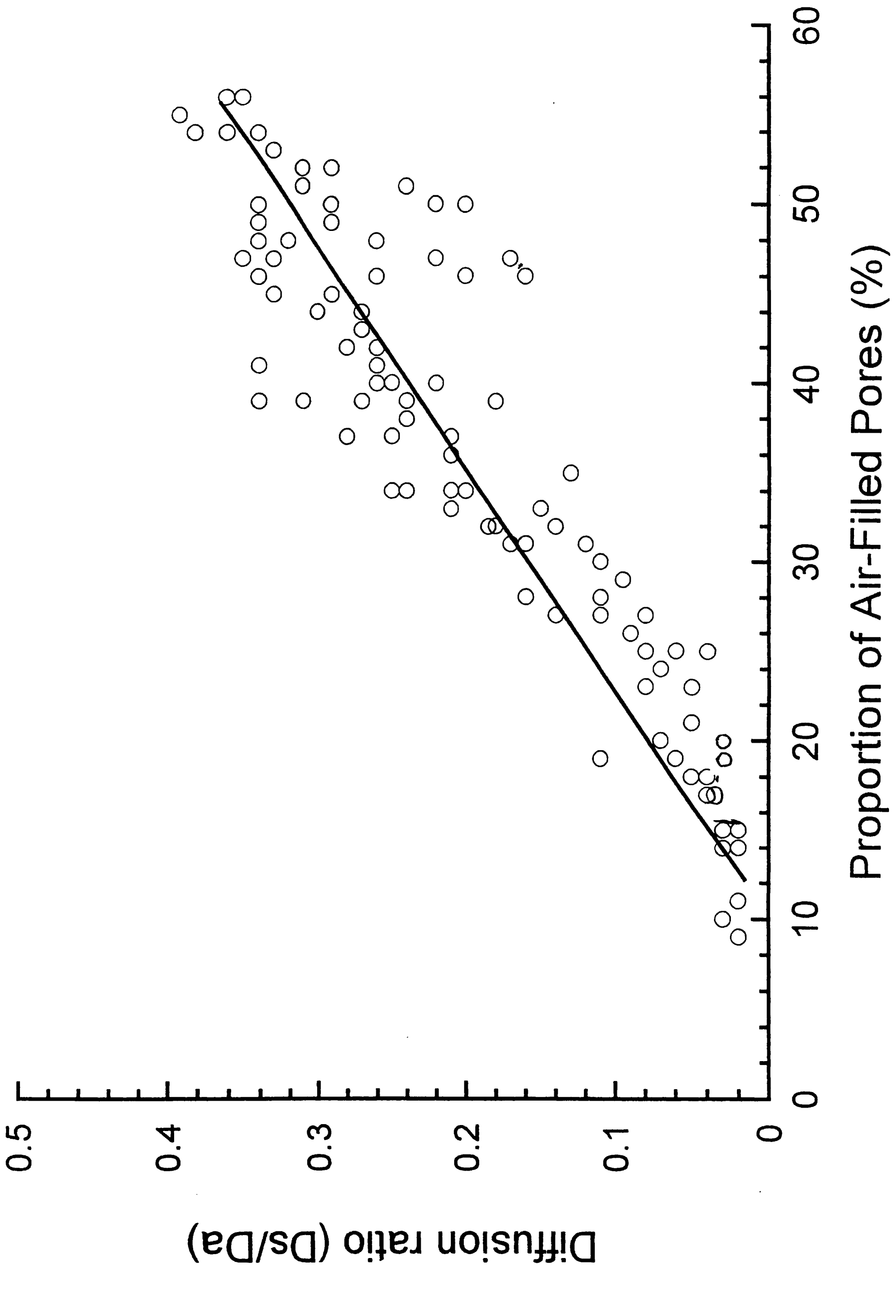

Figure 2.3 Relationship between the Ratio of Diffusion Rate of Oxygen in Soil (Ds) and Diffusion Rate of Oxygen in Air (Da) as a Function of Air-Filled Porosity in Soil [As air-filled porosity approaches 10% of soil volume, this ratio approaches 0. Adapted from Vomocil and Flocker 1961; reprinted with permission from the American Society of Agricultural Engineers.]

Table 2.2 Macroporosity in Undisturbed Surface Soil and after Intermediate or Severe Disturbance during Harvesting

	Disturbance Level			
Soil texture	Undisturbed	Intermediate	Severe[a]	Reference
	---------------------------%---------------------------			
Sandy loam	38.5	25	23.1-26.2	Hatchell, Ralston, and Foil 1970
Silty clay loam	12	9	4	Dickerson 1976
Fine loam	25.1	10.6[b]	6.3	Gent, Ballard, and Hassan 1983
Sandy clay loam	22.5	13.2	7.9	Gent et al. 1984

[a] primary skid trails and logging decks
[b] for tree-length harvested area

2.4.2 Ethylene Inhibition of Root Growth

In addition to lowering oxygen availability, compaction can limit gas diffusion and reduce root growth through buildup of both endogenously and exogenously produced ethylene. When the free oxygen content of the soil solution becomes depleted, anaerobes respire by using other compounds as terminal electron receptors (e.g., NO_2^-, Fe^{3+}, Mn^{2+}). This anaerobic respiration is less efficient than aerobic respiration and a number of intermediate organic compounds are produced. Ethylene ($CH_2 = CH_2$) is the most important of these compounds. Precursors to ethylene are produced in roots of flooded plants. These precursors can diffuse radially to more oxygenated areas at the soil-root interface (Jackson 1994) or into aboveground portions of the plant (Pezeshki, Pardue, and DeLaune 1996) where they are oxidized to ethylene. Reductions in root growth, formation of aerenchyma, and cell death are all associated with increased ethylene concentrations (Kawase 1976).

Under non-saturated conditions, diffusion of ethylene from the soil is relatively rapid. However, ethylene is not very soluble in water and, under saturated conditions, both endogenously produced and exogenously produced ethylene can accumulate around root tips. When soils are flooded or when wet soils are compacted to a low aeration porosity, this accumulation can contribute to reduced growth. The degree to which growth will be reduced is tree species-dependent. Generally, flood-tolerant species are more tolerant to toxic metabolites than flood-intolerant species and have greater capacity for physiological and morphological adaptation (Hook and Scholtens 1978). For instance, Pezeshki, Pardue, and DeLaune (1996) compared the response of seedlings of two oak species [overcup oak (*Quercus lyrata* Walt.) and cherrybark oak (*Q. falcata* var. *pagodaefolia* Ell.)] and bald cypress [*Taxodium distichum* (L.) Rich] to conditions of low oxygen or oxygen availability. The short-term response of bald cypress to low oxygen availability was to increase root alcohol dehydrogenase (ADH) activity and ethylene production. Although leaf and root dry weight and net photosynthesis was decreased in all three species following imposition of the low oxygen availability treatment, net photosynthesis began to recover in the bald cypress, but not in the oak species, within two weeks.

2.4.3 *Root Adaptation*

Roots adapt to anaerobic conditions in soil profiles both through distribution changes and morphological adaptations. Reductions in exogenous oxygen supply to root systems can be at least partially compensated for by an increase in internal oxygen supply. As a response to flooding and anaerobic conditions, many species, particularly species adapted to high water tables such as bald cypress and slash pine (*P. elliottii* Engelm.) can increase root porosity through formation of aerenchyma and interconnected air space within roots (Fisher and Stone 1990; Kludze 1994). Internal transport of oxygen through this system to roots has been shown for a number of woody species (Armstrong 1968; Coutts 1982; Fisher and Stone 1990). Species with a higher internal root porosity are more likely to tolerate anaerobic soil conditions (Topa and McLeod 1986a). The ability to form lenticels, which serve as primary pathways of oxygen entry into submerged roots, or to form adventitious roots, which replace root surface lost to dying roots (Kozlowski 1985; Topa and McLeod 1986b; Gilman, Leone, and Flower 1987), also help trees tolerate anaerobic conditions and may moderate whole plant response.

2.5 Bulk Density (Db)

Bulk density, defined as the mass per unit volume and expressed as g cm^{-3} or Mg m^{-3}, is the most common measure of soil compaction. For a specific site or soil condition, there is a reasonably strong relationship between bulk density (Db) and the aforementioned factors that directly affect root growth: mechanical resistance, water availability, and gas diffusion (Figure 2.4; Taylor and Gardner 1963; Jakobsen 1973). Consequently, a relationship between root growth and bulk density exists even though bulk density is not one of the physical factors directly controlling root growth.

For each field condition, there appears to be an optimal bulk density above or below which growth is reduced. Daddow and Warrington (1983) developed an approach for assessing growth limitations associated with high bulk density by superimposing bulk densities reported to severely restrict root growth of a variety of agronomic crops on a soil textural triangle (Figure 2.5). Although useful as a guideline, this approach has limited value for predicting soil bulk densities at which reductions in tree growth will occur or for predicting the extent of the growth reduction associated with a specific bulk density. Even if bulk densities remain below the critical growth-limiting bulk densities illustrated in Figure 2.5, substantial tree growth reductions can occur when soil is compacted (Table 2.3).

Table 2.3 Above- and Below-Ground Response of Tree Seedlings to Increased Soil Bulk Density

Species	Study Conditions	Soil Texture	Bulk Density Change	Final Bulk Density	Growth Response	Reference
			--%--	-Mg m^{-3}		
Eucalyptus nitens	Greenhouse; seeds germinated, measured after 2 weeks	clay	+42%	1.0	no change in shoot -66% primary root length, -33 % lateral root length	Misra and Gibbons 1996
Picea glauca	Greenhouse; seeds germinated, measured after 24 weeks	silty clay	+25	1.5	-94% shoot mass -91% root mass	Corns 1988
Pinus contorta	Greenhouse; seeds germinated, measured after 15 weeks	silty clay	+25	1.5	-70% shoot mass -80% root mass	Corns 1988
Pinus taeda	Greenhouse; seedlings transplanted, grown for 10 weeks	loamy sand	+46	1.9	-21% shoot mass, -81% root mass	Torreano 1992

(Continued on next page. See notes at end of table.)

Table 2.3 Continued

Species	Study Conditions	Soil Texture	Bulk Density Change	Final Bulk Density	Growth Response	Reference
Pinus taeda	Greenhouse; seeds germinated, grown for 28 weeks	sandy clay loam	46[a]	1.9	-63% shoot mass -76 root mass	Tuttle, Golden, and Meldahl 1988
		loamy sand	41[a]	1.9	-32% shoot mass -10% root mass	
Pinus taeda	Greenhouse for 19 weeks	sandy loam	+50	1.8[b]	-50% shoot mass -49% root mass	Mitchell et al. 1982
Pinus taeda	Greenhouse; seeds germinated, grown for one season	pooled data for sand, loam, and clay	88	1.5	-89% root mass[c]	Foil and Ralston 1967

[a] based on bulk density with best growth of 1.3 Mg m^3 for sandy clay loam and 1.4 Mg m^3 for loamy sand
[b] root growth into bulk density = 2.0 Mg m^3 was negligible
[c] estimated from regression in figure

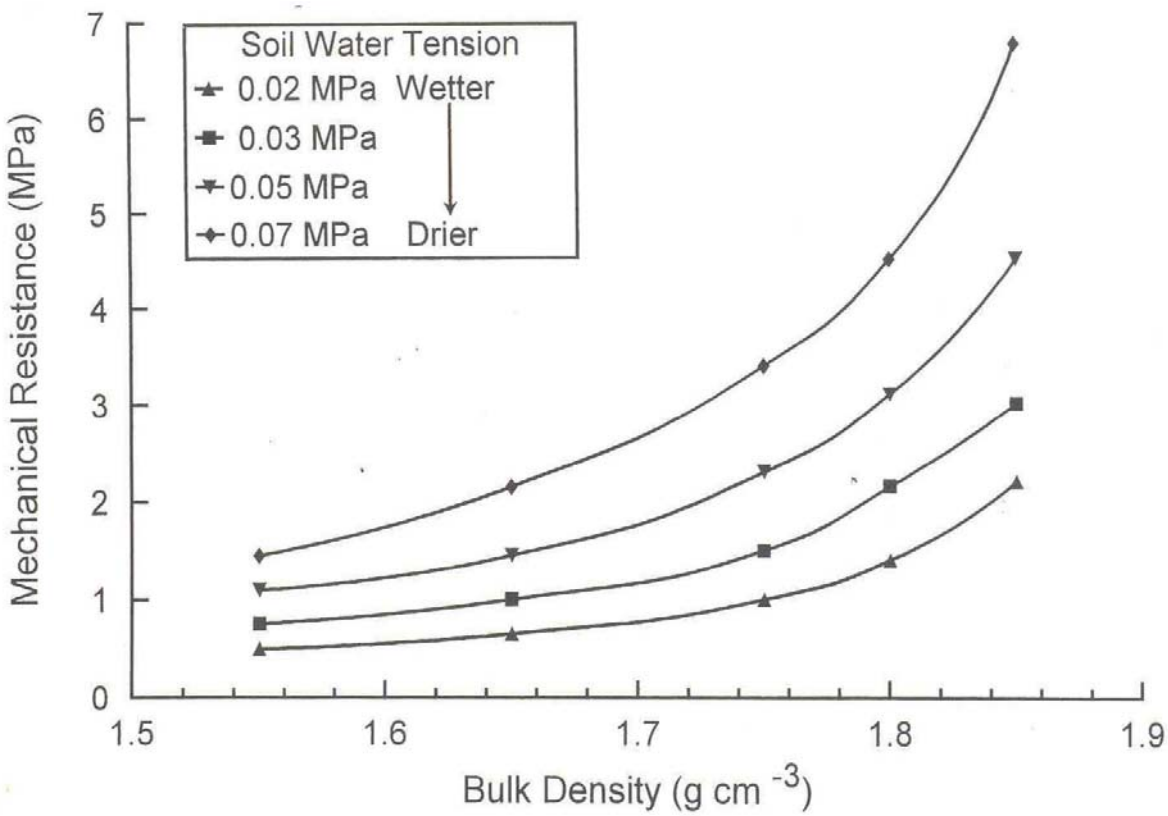

Figure 2.4 Relationship between Two Factors That Directly Limit Root Growth (Mechanical Resistance and Soil Water Tension) and the Indirect Measure of Soil Bulk Density [As redrawn from Taylor and Gardner 1963 by Unger and Kaspar 1994; reprinted with permission from the American Society of Agronomy.]

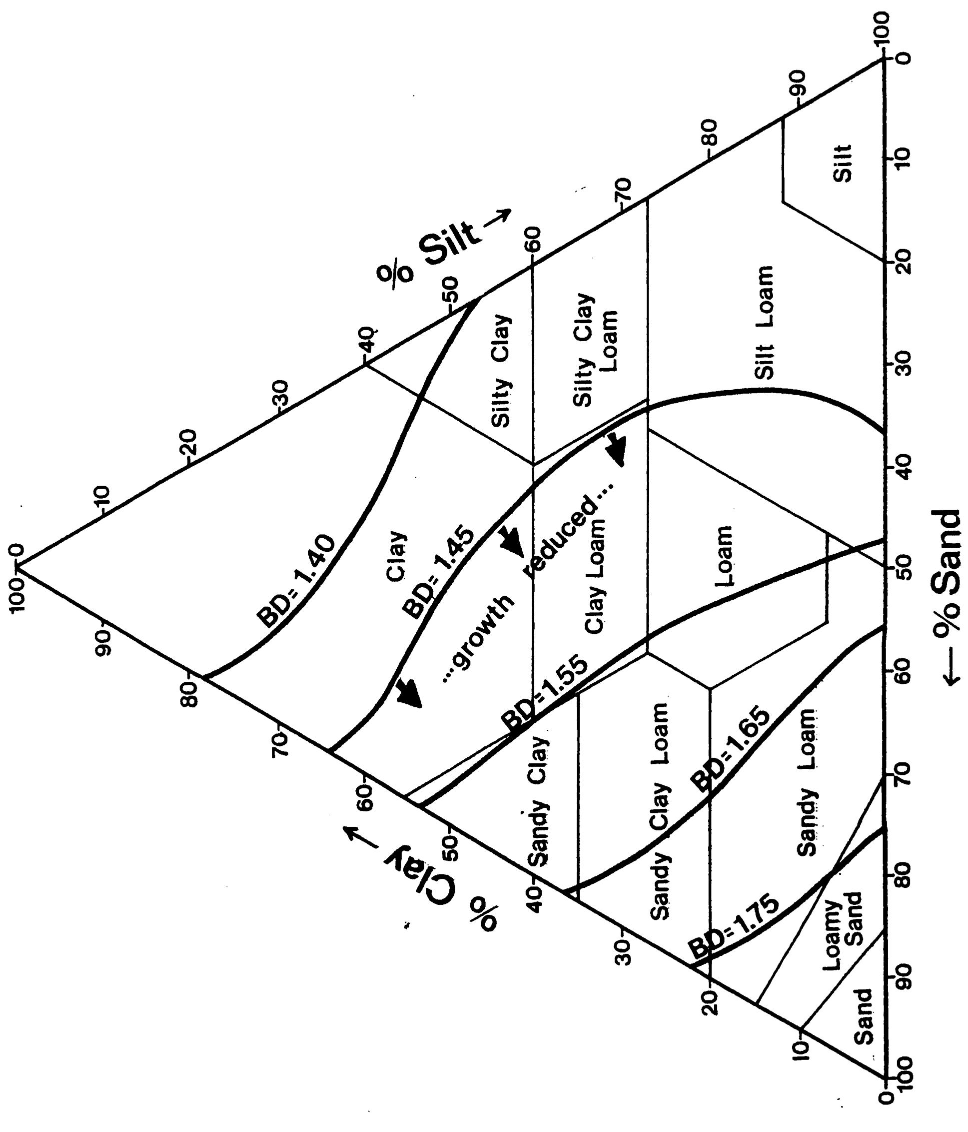

Figure 2.5 Growth-Limiting Soil Bulk Densities in Mineral Soils for a Variety of Different Crop Species [Redrawn from Daddow and Warrington 1983]

It is possible to develop a direct relationship between bulk density and root growth under controlled conditions. For instance, Foil and Ralston (1967) reported a linear decrease in both root length and root weight of loblolly pine seedlings grown in loamy sand to clay-textured soils as compaction increased bulk density from 0.8 g cm^{-3} to 1.5 g cm^{-3}. Pooling data for three different soil textures, these investigators were able to explain 68 % of the variation in root length by linear regression against bulk density (Figure 2.6). The relationship between root length and bulk density within the sandy loam and loam texture classes was stronger than this overall relationship. Similar relationships between bulk density and root density or root length, as well as other root parameters, have been developed for loblolly pine (Mitchell et al. 1982; Torreano 1992), yellow poplar and sweetgum (Simmons and Pope 1987), and shining gum eucalyptus (Misra and Gibbons 1996).

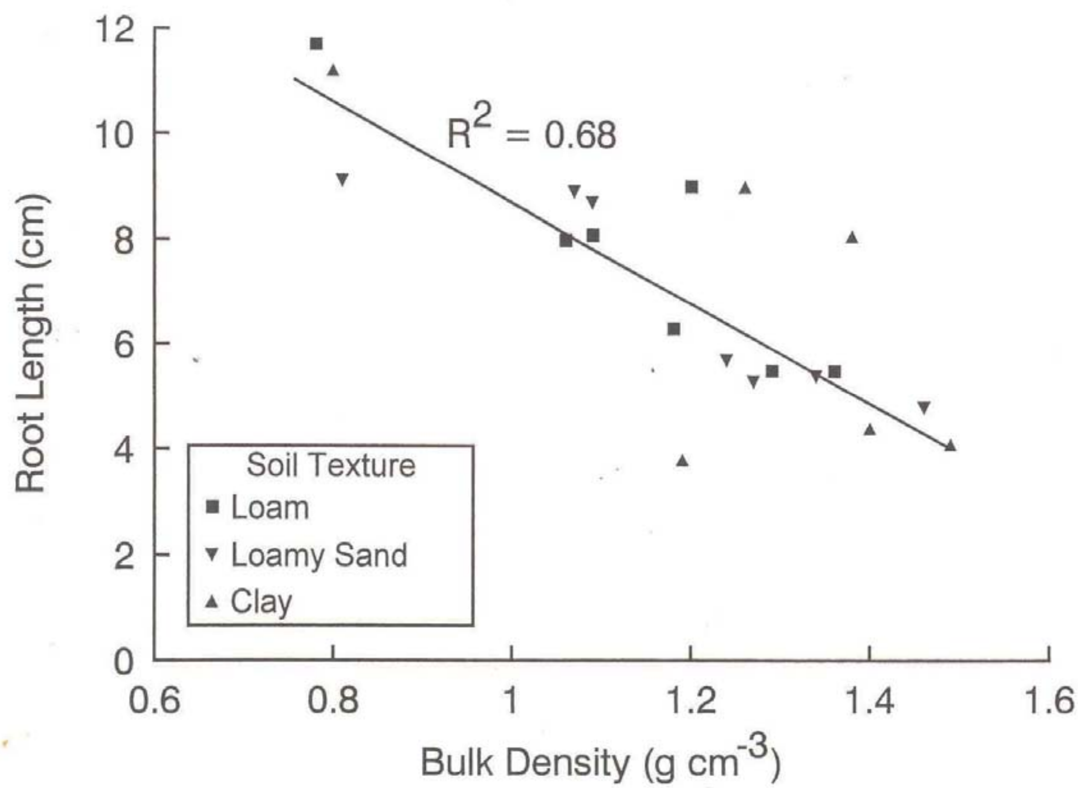

Figure 2.6 Relationship between Root Length and Soil Bulk Density for Loblolly Pine Seedlings Grown in Cores for One Growing Season [Redrawn from Foil and Ralston 1967; reprinted with permission from the Soil Science Society of America]

On soils with low organic matter content or with patterns of past use that have adversely affected physical properties, increases in soil bulk density are likely to result in a near-linear decrease in root growth. Exceptions to the pattern of reduced growth with increased bulk density occur where a) soils were too loose for optimal root growth because of poor water-holding and water supply characteristics (Shierlaw and Alston 1984), b) natural variability is high and natural processes rapidly ameliorate compaction, or c) organic matter content is high and initial bulk density is low.

2.6 Integrated Effects of Root Growth-Limiting Factors

Soil moisture near field capacity (ca. 0.03 MPa water tension) represents the soil water condition that provides the best balance among factors that control root growth. Root growth is generally greatest at or near this moisture condition (Figure 2.7; Eavis 1972; Costantini, So, and Doley 1996a). As soils dry below field capacity, water tension increases and mechanical resistance increases (note scale). Both contribute to reduced root growth in this moisture range and it is not easy to distinguish their effects. Root growth is also restricted in soils wetter than field capacity. In this range of soil moisture, low availability of oxygen and accumulation of toxic metabolites contribute to reduced root growth.

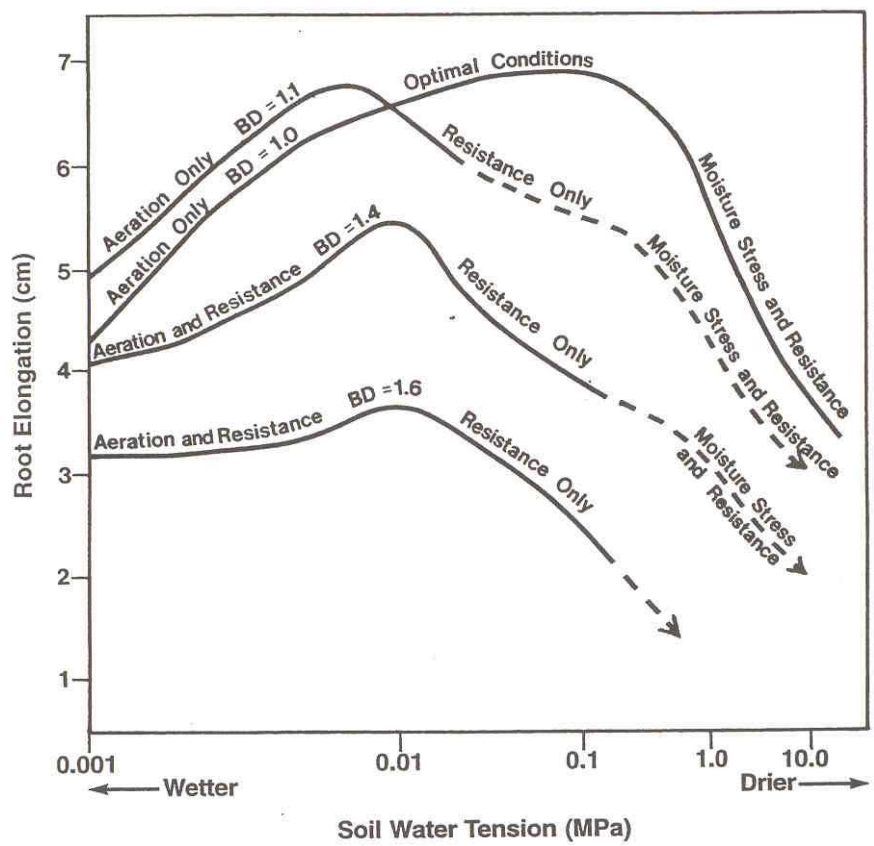

Figure 2.7 Relationship between Elongation of Cotton Roots, Soil Water Tension, and Other Factors Limiting Root Growth [Redrawn from Eavis 1972; note logarithmic scale]

Compaction reduces root growth and narrows the range of moisture potentials (tension) at which roots grow near their optimum. Eavis (1972) showed that, in a sandy soil, small increases in bulk density from 1.0 g cm^{-3} to 1.1 g cm^{-3} shifts the soil water tension at which optimum root growth occurs to wetter conditions. Soil resistance remained low and oxygen availability was not severely restricted by the small increase in bulk density of this soil; water availability was, apparently, increased. As bulk density increased from 1.1 g cm^{-3} to 1.4 g cm^{-3}, however, increased resistance limited root growth across all matric water potentials (Figure 2.7). An approach to integrating the effects of mechanical resistance, aeration, and soil water tension into a single variable that could be used to quantify the physical characteristics of soil for plant growth was proposed by Letey (1985) and modified by da Silva, Kay, and Perfect (1994). Da Silva, Kay, and Perfect termed the constructed variable the *least limiting water range* (LLWR). This range is the difference in moisture content between the upper limit and the lower, drier limit. The upper limit is either the moisture content at which field capacity is reached or at which less than 10% of the soil pores are air-filled (the lesser or drier of the two is the upper limit). The lower limit is the moisture content at which root growth is restricted by either mechanical resistance greater than 2.0 MPa or water tensions greater than 1.5 MPa (the lesser or wetter of the two is the lower limit). The LLWR varies for soils of different textures and bulk densities (Db). Under field conditions, the greater the volume of soil within the optimal moisture range defined by LLWR and the more time soils are within this range, the better are conditions for plant growth. Recently, Kelting, Burger, and Patterson (2000) found that 87% of the variation of loblolly pine growth on rutted and compacted sites prepared for planting with several different ameliorative treatments could be explained by a) the percent of the time soil moisture was within the LLWR, b) the depth of oxidation, and c) overall site fertility.

2.7 Indirect Effects

Compaction and associated reduction in soil structure can affect root growth indirectly by affecting temperature relationships, microbial and faunal activity, and pathogens. Changes in soil moisture-holding capacity, thermal capacity, and conductivity can modify temperature regimes. Root growth decreases approximately linearly below a temperature optimum (Warkentin 1971; Carlson 1986); thus, decreased soil temperature may be responsible for some of the reported reduction in root growth on compacted soil, particularly if soils remain wet in the spring. Soil organisms are also influenced by soil compaction. Populations of arthropods, fungi, nematodes, and bacteria are generally lower in compacted than noncompacted soils (Smeltzer, Bergdahl, and Donnelly 1986), and overall biological activity is reduced (Dulohery, Morris, and Lowrance 1996). Resulting decreases in nutrient mineralization and availability may also contribute to reduced root growth (Phillipson and Coutts 1977). Activity of fauna, which create macropores and soil structure, is often reduced in compacted soils (Dexter 1978; Whalley, Dumitru, and Dexter 1995). Finally, changes in oxygen availability and root physiology can increase incidence of pathogens (Jacobs and MacDonald 1990).

2.8 Summary

Much research has been directed to establishing relationships between root growth and growth-limiting soil factors. Most of the available research has been on agricultural crops and under carefully controlled laboratory and greenhouse conditions. Under field conditions, however, temporal variations in factors that limit root growth occur in response to short-term and seasonal cycles of soil wetting and drying. At a given site, root growth can be limited by poor aeration during wet periods and mechanical impedance during dry periods. Factors limiting root growth may also vary as a result of secondary environmental conditions. For instance, oxygen limitations may be less severe at lower soil temperatures; this shifts the range of soil moisture potentials under which optimal root growth can occur toward wetter conditions. Within the same soil texture, factors such as the roughness of sand grains may shift an established relationship between root growth and soil water potential.

Finally, unlike most agricultural plants, trees are long lived and have greater capacity to adapt to restrictive soil conditions through both morphological and distributional changes in their root system. This adaptive capacity limits our ability to predict how trees will respond to soil compaction under field conditions.

3.0 TREE GROWTH ON DISTURBED SOIL; NET EFFECT ON STAND YIELD

Section 2.0 provides evidence that traffic by heavy equipment usually degrades soil properties and the environment for roots. Seldom quantified, however, are the duration of these degraded soil conditions, and their subsequent effect on tree survival, tree and stand growth, and ultimately, stand yield of merchantable products.

3.1 Relationships among Site Productivity, Soil Productivity, Tree Growth, and Stand Yield

3.1.1 *Site Productivity, Soil Productivity, and Yield*

Maintenance and enhancement of long-term site productivity are easily understood objectives and concepts. But translating these objectives from concept to quantitative practice is not easy. What is site productivity and how should it be measured? In the National Forest Management Act of 1976 (16 USC 472a) "long-term productivity" is defined as the potential of the land to produce wood at consistent levels of quality and volume over hundreds of years without significant reduction in the quality of soil or water resources. If site productivity is defined in terms of potential wood production, then volume growth or yield per unit area are useful measures. Actual volume growth of wood, however, is influenced strongly by factors other than soil. In equation form, site productivity can be defined as

Yield of wood = f (soil, climate, tree species and genotype, and stand density, silvicultural practices, time, and their interactions)

It is important to recognize, first, that the effect of a change in one of these factors may be enhanced or counterbalanced by changes in other factors. For example, reductions in soil quality might be compensated for by silvicultural practices that alter tree species, stand density, competing vegetation, or nutrient availability. Thus, to isolate the effects of a forest practice on the soil resource, one must specify, hold constant, or separate the effects of silviculture and climate. Second, although soil is critically important to productivity and yield, soil is not a fully independent variable in the site-productivity equation. Rather, soil physical, chemical, and biotic properties interact with other site factors and especially with harvesting and site preparation. Soil conditions that are considered undesirable for some species-climate combinations may be acceptable for other species-climate combinations.

Long-term effects of soil disturbance (e.g., those that endure for the life of a forest stand, commercial rotation or centuries) on site productivity are not well quantified. Most predictions are based on extrapolation of short-term observations of soil properties and/or seedling growth. For judging whether a forest practice can have long-term effects on site productivity, Geppart, Lorenz, and Larson (1984) posed the following questions:

1. What properties or processes are changed by the practice?
2. What are the relative magnitude and direction of change?
3. What is the duration of the effect?

4. What interactions with other changes are likely?
5. Over what time and space are forest practices occurring on the site?

These questions may help readers to keep different components of long-term site productivity in perspective.

3.1.2 *Tree Growth and Yield*

Forecasts of timber yields often assume that inherent site productivity will be maintained or enhanced by intensive forest management. Is this assumption realistic and for how long? Timber harvest levels may, in fact, be sustained or increased by substituting intensive silvicultural practices such as fertilization and thinning. In the final analysis, however, the comparative costs of soil conservation and substitutions must be evaluated. The inherent weakness of these economic comparisons is the limited precision and scope of data about stand growth and yield.

3.1.3 *Selecting Growth Measures to Assess Change in Productivity*

The degree to which a site can supply physical support, water, and nutrients to trees, and the extent to which tree roots can grow through the soil to utilize these resources, largely determines the capacity of a site for tree growth. Theoretically, site productivity can be evaluated by any measure that accurately reflects changes in these soil resources. The merits of using net primary productivity (NPP), the total carbon fixed in organic matter minus respiration losses, as a measure of site productivity change has been discussed (Wisiol and Hesketh 1987). This measure clearly has value in ecological studies; however, from a practical standpoint, measurement of NPP is unworkable in long-term studies of forest management. Complete characterization of net primary productivity is difficult and subject to large measurement error, particularly where changes in species composition are involved. Hence, most long-term studies in forestry rely on growth of the target tree species for assessing changes in site productivity. Ultimately, the most useful measure of stand growth is the cumulative yield of bole volume or weight in one or more rotations on an area basis. As indicators or predictors of future yield, tree survival (stand density) or growth in tree height, stand basal area, or stand volume are used. Site index (height at a set age) has been the most commonly used measure of potential yield because height is readily measured and relatively less sensitive to stand conditions than other parameters. Stand basal area and bole volume growth, or especially biomass accumulation, provide more comprehensive measures of stand growth, but these can only be reliably interpreted as indicators of changes in soil quality when growth differences are not strongly confounded by differences in stand conditions.

3.2 Acceptable Field Trial Evidence for Productivity Change

Worldwide, numerous studies have been established to evaluate changes in site productivity resulting from forest management activities. Most studies have generally failed to provide a reliable answer to the question: *How do specific management activities affect long-term site productivity?* To be acceptable evidence for a change in long-term productivity, three conditions must be met (Morris and Miller 1994):

1. Growth results must be available for a sufficient duration of time, so that the influence of ephemeral differences in initial site conditions has diminished, and so that the capacity of the site to support tree growth is stressed.
2. Differences in tree growth must be attributable to differences in the soil resource rather than to differences in resource allocation among target and non-target species or to differences in plant potential.
3. Adequate experimental control must exist.

3.2.1 *Defining Long-Term Change in Productive Capacity*

A major consideration for evaluating results from field trials of long-term productivity involves the definition of "long-term". Many management practices have impacts on stand or site conditions that are ephemeral and poorly related to long-term site productivity. Control of herbaceous competition, for example, allocates a greater share of site resources to trees and often promotes survival and rapid tree growth in young stands. Generally, however, vegetation control has little influence on growth after crown closure (except, of course, in the case of nitrogen-fixing plants on nitrogen-deficient sites). Where soil disturbance results in severely degraded physical conditions or subsequent accelerated erosion or nutrient loss, total site resources or productive capacity are reduced. Where disturbance slows the rate at which roots fully exploit the soil, disturbance largely affects tree growth through changes in resource accessibility by trees, rather than through a change in total site resources or ultimate productive capacity. Such shifts in resource allocation or accessibility will appear as early differences in tree growth followed by a return to annual growth patterns that do not differ from growth patterns of undisturbed control stands (sens. Hughes et al. 1979).

For example, in Figure 3.1(a), an early reduction in cumulative height is maintained after crown closure, but further differences in growth are not evident or measurable beyond the initial effect. Rather, this height reduction reflects a delay in the rate at which the site was captured. It does not necessarily indicate a change in long-term productivity because when measured at a point after this initial delay, productivity is as high in impacted as in non-impacted areas. Yield, however, may be lower because of early cumulative deficits in growth. This exemplifies but one of three characteristic patterns of growth response to soil disturbance. Figure 3.1(b) illustrates a difference in site productivity that is maintained; the initial growth losses are compounding. Figure 3.1(c) illustrates a transient change in productivity; the initial growth losses were temporary and erased by subsequent growth increases. The distinction between Figure 3.1(a) and Figure 3.1(b) is important. The growth pattern of Figure 3.1(b) indicates a change in site productivity that will most likely continue throughout this and future rotations. Although the growth pattern of Figure 3.1(a) does not necessarily rule out the possibility that a reduction in long-term site productivity may yet occur, it is more probable that the soil capacity is not fundamentally different than the control. The growth pattern in Figure 3.10(c) also represents a change in site productivity that will likely continue into future rotations. In this case, the pattern indicates an increase in productivity after disturbance.

Until the pattern of growth is evident, one has little basis for predicting the consequences of management activities on long-term productivity. For slow-growing stands, a reliable pattern may require 20 or more years. For faster growing stands or short rotation plantations, 10 years may be adequate to observe these changes and to predict their longer term consequences for yield.

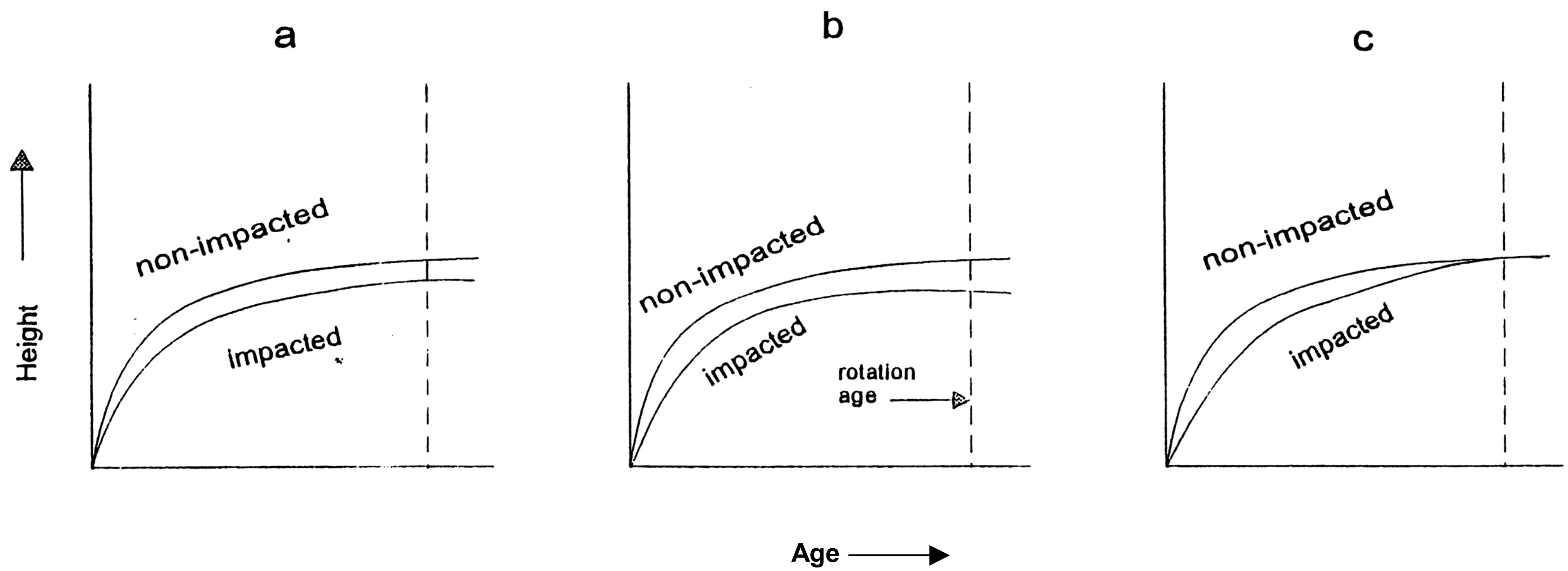

Figure 3.1 Possible Patterns of Dominant Tree Height Growth after Soil Disturbance: (a) Initial Decrease in Resource Allocation without Site Change in Soil Quality; (b) Decrease in Long-Term Soil Productivity (c) Transient Decrease Following by Recovery of Soil and Site Productivity

3.2.2 *Experimental Control and Methodology*

According to Mead et al. (1991), experimental designs for long-term studies require the following:

* at least four replications in randomized or randomized complete block designs;
* suitable pre-treatment site and crop information on individual experimental plots;
* minimum measurement plot areas of 400 m2 containing at least 12 remaining trees at the end of the experiment;
* buffer areas of at least 10-m width surrounding each measurement plot (the buffer receives the same experimental treatment).

Few studies of soil disturbance have been established which meet these experimental requirements. Frequently, conclusions about the consequences of heavy equipment used in harvesting have been based on retrospective sampling after commercial operations. Thus, tree growth on skid trails was compared to that off skid trails in clearcut areas or near skid trails versus away from skid trails in thinning or partial harvests. The off-skid-trail trees are considered controls that are not affected or only lightly affected by logging. The experimental unit for measurement can be individual trees or a group of trees in impacted and in control areas. Seldom can the differences in growth be expressed on an area basis (per hectare or acre) because treatment (skid trail) and control areas are too small.

An alternative approach to quantify the effects of operational skid trails is that used first by Wert and Thomas (1981). They categorized a 4.3-ha plot into skid trails, transition zones (3 m on each side of skid trails), and logged-only portions. They measured all trees in each stratum and computed average stand density and volume for each stratum and for the entire 4.3-ha plot by summation. Skid trail effects on stand yields were calculated in a similar manner subsequently by Scott et al. (1999). Yield per hectare on the total plot (V_t) was compared with that on the control, i.e., logged-only portions(V_c). The investigators assumed that V_c represented the yield potential of the site. Three outcomes are mathematically possible:

$V_t = V_c$, implying no change in the combined yield from skid trails and associated fringe portions; i.e., V_s (volume on skid trail + transition zone) = V_c.

$V_t < V_c$, implying stand yields were reduced because $V_s < V_c$. This is the expected outcome assuming that more trees die or grow more slowly on degraded soil (compacted, rutted, or displaced topsoil).

$V_t > V_c$, implying stand yields were increased because $V_s > V_c$.

Using this approach, all three outcomes were found among the seven locations that they assessed (Section 3.4).

Some researchers have used retrospective sampling coupled with multiple regression analysis to separate and quantify the relative contributions of soil factors (bulk density or penetration resistance) and other factors (competition, tree age) associated with tree growth (Helms and Hipkin 1986; Froehlich 1979a, 1979b; Froehlich, Miles, and Robbins 1986; Clayton, Kellogg, and Forrester 1987). Freese (1974, p. 66), however, cautions “against inferring more than is actually implied by a regression equation and analysis . . . no matter how well a particular equation may fit a set of data, it is only a mathematical approximation of the relationship between a dependent and a set of independent variables. It should not be construed as representing a biological or physical law . . . or cause and effect relationship." Further weaknesses of past applications of multi-factor prediction equations for relating tree growth to soil disturbance include a) application of equations is limited to a restricted range of conditions because the equations are based on sampling conditions at one or a few locations; and b) application of the equations requires that adequate data be collected for each of the multiple factors in the prediction equation. Most would agree that designed or controlled-treatment experiments are a more effective way to isolate the several possible effects of soil disturbance (Powers et al. 1994).

3.3 Tree Growth on Disturbed Soil after Clearcutting

Individual tree growth on soil disturbed by ground skidding and clearcutting has been reported for several coniferous species (Table 3.1). Most investigators report short-term growth of seedlings or saplings on skid trails is less than that on adjacent non-skid trail areas (Steinbrenner and Gessel 1955; Youngberg 1959; Perry 1964; Hatchell, Ralston, and Foil 1970; Moehring and Rawls 1970; Power 1974; Dickerson 1976; Froehlich 1979a, 1979b; Froehlich and McNabb 1984; Cochran and Brock 1985; Senyk and Smith 1991; Heninger et al. 1997a). In contrast, Butt (1989) reported no consistent inferiority of skid trail trees to off-skid trail trees in height or diameter growth among seven study sites in coastal British Columbia, and Miller, Scott, and Hazard (1996) reported similar growth on and off compacted skid trails at three coastal Washington locations. Compaction of a coarse sand soil in northern California improved growth of two conifer species (Powers and Fiddler 1997). Shepperd (1993) reported severe reductions in regeneration (suckering) of aspen (*Populus tremuloides*) when soil was compacted after clearcut harvesting.

In a comprehensive study at eight locations in Oregon, Heninger et al. (1997a) investigated bulk density of soil, and survival, height, and bole volume of Douglas fir [*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco] through 7 or 8 years after planting in plots established on and off skid trails. Soils on skid trails were compacted, churned, rutted, or displaced to varying intensities. Four or five years after logging, ruts still averaged 15 cm deep and bulk density in the 0- to 40- cm depth below ruts exceeded that in adjacent logged-only portions by an average of 11% among the eight locations.

Table 3.1 Summary of Some Investigations of Tree Growth on versus off Skid Trails

Area	Locations (No.)	Soil Texture	Tree Age (years)	Results	Source
		Pseudotsuga menziesii			
W. Washington	9	silty clay loam	2-4	-20% height	Steinbrenner and Gessel (1955)
W. Oregon	1	clay	2	-22, -43% height	Youngberg (1959)
W. Oregon	2	sandy loam	4	-11, -21% height	Froehlich (1979a)
W. Oregon	1	clay loam	5	-11% height	Froehlich (1979a)
W. Washington	3	silt loam	15	no effect on height, volume	Miller, Scott, and Hazard (1996)
W. Oregon	8	clay loam	9	-12% height	Heninger et al. (1997a)
W. Oregon	1	clay loam	32	-30% height, -28% DBH	Wert and Thomas (1981)
W. British Col.	7	clay to sandy loam	5-25	inconsistent	Butt (1989)
W. Washington and Oregon	7	loam to clay loam	28-35	-1% height, -38% stand volume	Scott et al. (1999)
		Pinus ponderosa			
E. Washington	3	loamy	9-18	-20% stem volume -5% tree height	Froehlich, Miles, and Robbins (1986)
E. Oregon	1	loamy	64	-6 to -12% tree BA growth	Froehlich (1979b)
W. California	1	loam	16	-55% stand volume	Helms and Hipkin (1986)
N. Idaho	1	silt loam	20-25	-20% in 10-yr radial growth -10 to 13% in tree height	Clayton, Kellogg, and Forrester (1987)

(Continued on next page.)

Table 3.1 Continued

Area	Locations (no.)	Soil Texture	Tree Age (years)	Results	Source
			Pinus contorta		
E. Washington	1	ashy	11	0% tree volume, height	Froehlich, Miles, and Robbins (1986)
N. Idaho	2	silt loam	15-19	-9% in 10-yr radial growth -14% in tree height	Clayton, Kellogg, and Forrester (1987)
			Several coniferous species		
E. British Columbia	3	sandy	9-22	18 to 22% tree height	Smith and Wass (1979)
E. British Columbia	4	loamy	16-18	-14 to +4% in tree height	Smith and Wass (1980)
			Pinus taeda		
Louisiana	1	silt loam	5	-88% in trees/ha -39% in height	Lockaby and Vidrine (1984)
Coastal plain		clay loam	1	no effect in height	Campbell, Willis, and May (1973)
Lower coastal plain	9	sandy loam	1	-21 to -53% in height	Hatchell, Ralston, and Foil (1970)
Lower coastal plain, SC	1	silt loam	5	-18% in height	Hatchell (1981)

Based on pooled data from 31 experimental blocks, some generalizations about tree performance at these eight locations are apparent. Trees planted in ruts averaged 4% more survival than in logged-only portions, but depending on study location, annual height growth was reduced for 3 to 8 or more years after planting. At year 7 or 8, height of seedlings planted in skid trail ruts averaged 12% less than seedlings planted in logged-only portions (Table 3.2). Height growth was reduced most in the early years; however, in growing season 7 or 8 height growth in skid trails averaged only 1% less than growth on logged-only portions. This corresponds to a response pattern of Figure 3.1 (a). Trees planted on non-tilled skid trails averaged 5.1 years to attain breast height compared to 4.4 years on tilled and logged-only portions. Tilling the soil to about 30 cm depth with tractor-mounted rock rippers improved average tree height in year 7 or 8 by 16% over that on non-tilled skid trails and by 2% more over that in logged-only areas (Table 3.2). Diameter growth was affected in similar magnitude and direction as height growth.

Bole volume integrates growth in tree height and diameter. Therefore, percentage response in volume is likely to exceed percentage response in height. For the eight locations, mean 7- or 8-year bole volume of trees on non-tilled plots averaged 29% less than that on logged-only plots (Table 3.2). Heninger et al. (2002) document later results. Thus, among the eight locations, mean height growth averaged slower for the first 7 years but was similar thereafter. Ten years after planting, trees in skid trail ruts averaged 10% less total height and 29% less volume than those in logged-only plots.

Table 3.2 Summary of Mean Relative Differences in Douglas Fir Seedling Performance in Oregon by Tree Variables and Treatments; Pools All Soil Disturbance Classes at Eight Locations (31 Blocks)

Tree Variable	Relative Difference by Comparisons[a]		
	NT – LO %	T – NT %	T – LO %
Survival percentage (yr.3)[b]	4	9	13
Incidence of terminal damage from browse[c] (mean of yr. 2 + 3)[b]	3	2	5
Total ht. (yr. 7 or 8)	- 12	16	2
Ht. growth (yr. 7 or 8)	-1	4	1
Bole volume (yr. 7 or 8)	-29	48	1

SOURCE: Adapted from Heninger et al. (1997a)
[a] NT = nontilled, LO = logged-only, T = tilled, NT-LO = NT less LO/LO
[b] = difference between percentage survival in each treatment
[c] = difference between percentage of damaged trees in each treatment

3.4 Stand Yields on Disturbed Soil after Clearcutting

Reduced growth of trees on skid trails implies reduced stand yield. Often because of the limited plot size, researchers do not attempt to estimate changes in stand volume or yield. This frequent omission in field research has practical implications for forest managers. Unless skid trails are adequately sampled on inventory or growth-monitoring plots, estimates of future yield could be biased.

Wert and Thomas (1981) reported yield loss after tractor yarding. They categorized a 4.4-ha plot in a 32-year-old, naturally seeded Douglas fir stand in southwestern Oregon into skid trails, transition zones (3 m on each side of skid trails), and logged-only portions. About 10% of the total area was in primary skid trails. Tree volumes on skid trails, transition zones, and control portions totaled 34, 97, and 129 m^3/ha, respectively. Reduced stocking in skid trails and transition zones largely accounted for a volume loss of 12% for the total plot.

Using similar procedures in 1984, Weyerhaeuser Company conducted a subsequent investigation of seven Douglas fir stands in western Washington and Oregon. Five of the seven stands were regenerated by natural or aerial seeding; two were planted. Tree numbers and size were measured within each of three strata: skid trails plus a 5.5-m-wide fringe, and the remaining area of each plot. There were two plots (0.5-1.1 ha) at each location. Among the seven locations, yield changes ranged from -21.3% to +12.8% (Miller et al. 1989); this range encompasses the -12% loss in Douglas fir yield reported by Wert and Thomas (1981). In four stands where competing vegetation was primarily herbaceous, stand yield averaged about 10% less because of reduced yield on skid trails. For three stands in Oregon, however, shrubs were prevalent in control portions but nearly absent on skid trails. Yield on control portions at these locations was equal or less than that of the whole plot. Consequently, average volume production at these three locations was 7.7% greater because of the relatively greater yield on skid trail-affected versus control portions.

Averaged for the seven locations, tree numbers and volume per hectare differed among some combinations of the three strata; however, mean DBH, height, and years for site trees to attain breast height did not differ (Scott et al. 1999). Stand density solely on skid trails averaged only 70% of density on control areas (687 versus 977 trees/ha). The mean difference (290 trees/ha) was statistically significant. This 30% reduction in average stem count on skid trails contributed strongly to a 38% reduction in average yield. Although greatest yields were measured on the 5.5-m wide fringe beside the skid trails, these yields were not significantly greater than control yields. Differences in stand yield among the skid trail, fringe, and control portions are related to both differences in stand density and to differences in average tree size. Butt (1989) also reported greater yield of Douglas fir on fringe (3-m wide flank) areas than on skid trails or most control areas at four study sites on Vancouver Island. In three of four sites, increased volume on the fringe more than compensated for the usually lesser volume in the skid trails.

Increased yields of Douglas fir in fringe areas can be expected to exceed those on major skid trails. Fringe areas usually contain topsoil displaced from adjoining skid trails. On sloping terrain, this fringe may include a cut bank on the uphill side and a fill slope on the lower side. Exposed mineral soil usually provides favorable conditions for Douglas fir germination and growth after natural or artificial seeding (Minore 1979). Planted seedlings are often placed near berms to avoid compacted skid trails yet maintain uniform spacing in the area. Establishing seedlings on more favorable microsites provides fringe trees an early competitive advantage over nearby skid trail trees.

3.5 Tree Growth near Disturbed Soil after Thinning or Partial Cutting

Ground-based equipment is commonly used for commercial thinning or non-clearcut harvests by group or individual tree selection. Because fewer trees are removed, soil disturbance is usually less widespread and less severe than with clearcutting. Roots or boles of residual trees, however, can be physically damaged by equipment and logs. The root environment can be degraded by soil compaction, churning, mixing, or displacement. Some researchers have attempted to compare growth of trees that were impacted to varying severity by ground-based extraction (Table 3.3). Short-term reductions in diameter or basal area growth of 15% or more are commonly observed. Larger growth reductions are associated with greater severity of soil disturbance.

Table 3.3 Summary of Some Investigations of Tree Growth on Soil Disturbed by Thinning

Area	Locations (no.)	Soil Texture	Tree Age At Start (years)	Tree Age At End (years)	Results	Source
			Pseudotsuga menziesii			
W. Oregon	5	loamy	22-71	34-80	-14% to -30% in tree BA growth	Froehlich and Berglund (1979)
			Pinus ponderosa			
E. Oregon	2	sandy loam	–	16	-6% to -12% in tree BA growth	Froehlich (1979b)
			Tsuga heterophylla			
W. Oregon	1	loam	22	27	-15% in 5-yr tree BA growth	Froehlich (1979a)
			Pinus taeda			
Arkansas	1	silt loam	40	45	no growth effect after dry-weather skidding; -37% to -43% DBH growth if trees trafficked on 3 or 4 sides when soil wet	Moehring and Rawls (1970)

3.6 Summary

With the possible exception of coarse-textured (sandy) soils, soil compaction will usually reduce tree growth *potential*. Actual or measurable reductions in growth do not always occur, however, in part because soil disturbance can reduce vegetative competition. The likelihood or severity of growth impairment from soil disturbance should not be generalized because the consequences of soil disturbance depend on (or interact with) other site-specific, growth-determining factors. Hence, the consequences for tree growth are site-specific. In most reports, short-term growth of seedlings or saplings on skid trails is less than on adjacent non-skid trail areas; this may or may not reduce ultimate stand yield. Inferring that soil disturbance is the cause of reduced growth is often uncertain, because the direct effects of disturbance on soil properties are usually masked or inconsequential relative to the effects of disturbance on other growth-determining factors, especially competing vegetation. Consequently, improved tree growth (over that in undisturbed areas) has been associated with disturbed soil at some study sites.

4.0 SOIL RECOVERY FROM COMPACTION AND PUDDLING

Soil resilience is defined as the soil's ability to recover after disturbance (Greenland and Szabolas 1994). Natural soil processes such as swelling and shrinking due to moisture changes, movement of soil particles by freezing and thawing (including frost heave), and biological activity tend to restore soil physical properties to pre-disturbance conditions. Froehlich and McNabb (1984) described three criteria necessary for these processes to be effective: 1) the soil must be sensitive to the process, 2) the climate must produce the temperature and moisture regimes necessary for the process to occur, and 3) the cycles or processes must occur with sufficient frequency and duration.

4.1 Processes of Natural Recovery

Cycles of wetting and drying cause soils alternately to swell and shrink. The resulting changes in volume break clods and large aggregates (i.e., reduce aggregate stability). This increases pore space and lowers bulk density (Larson and Allmaras 1971). Extremes in the wet-dry cycle are most effective at creating large volume changes. The amount and type of clay minerals are primary factors affecting volume change with wetting and drying. Soils with 2:1 layer silicates (e.g., smectite clays) expand when wet, yet crack to considerable depths when dry. Coarse-textured soils, by comparison, generally exhibit only minor changes in volume during wetting and drying cycles. Consequently, recovery of clayey soils from compaction may be much faster than in sandy soils. Compaction of coarse-textured soils may, in fact, present a problem of greater significance to productivity in the long-term than compaction of fine-textured soils, even if the immediate consequences appear trivial (Greacen and Sands 1980).

Temperature fluctuations disrupt soil aggregation during freezing, and restore it during thawing and drying. Freeze-thaw cycles, therefore, decrease bulk density in compacted soils and increase bulk density in loosened soils (Larson and Allmaras 1971). Changes in soil physical properties associated with freezing and thawing have been attributed to displacement and packing of soil by growth of ice lenses fed by capillary movement (Krumbach and White 1964). Freeze-thaw cycles alone do not result in large volume changes, because water only expands about 9% upon freezing. The simple process of water freezing within soil pores, however, reduces water potential in soil aggregates, thereby drying the soil. Thus, fracturing of soil aggregates by freezing is difficult to distinguish from that caused by wetting and drying.

Frost heaving results not only from the expansion of soil water upon freezing, but also from the accumulation of water at or near the soil surface into capillary ice lenses or columns which subsequently accumulate upward as more water freezes (Bouyoucos and McCool 1928). In addition to primary frost heaving as described by this “capillary theory” of ice lens growth, secondary frost heaving may occur when ice crystals form in soil pores below the existing ice lens (Goulet 1995). Although frost heaving has the potential to produce much larger changes in soil volume than freezing and thawing, conditions necessary for frost heaving to occur are much more exacting. Frost heaving is almost entirely dependent upon the force of crystallization and is largely controlled by soil moisture content and rate of freezing. At least 90% of soil pore space must be filled with water for frost heaving to occur (Dirksen and Miller 1966). At lower moisture contents, ice forms in larger capillary pores, but no growth of ice lens or subsequent movement of nonfrozen water occurs. Because unsaturated hydraulic conductivity (K) controls water movement up to the point of freezing, heave is more likely in soils with high conductivity (e.g., medium-textured soils or compacted, coarse- textured soils). Other factors critical to frost heaving (e.g., rate of freezing or of heat removal, particle size, overburden stress, ground cover, soil chemical composition) have been reviewed by Goulet (1995).

Loosening and mixing of soil by soil flora and fauna is well documented (e.g., Swaby 1950; Uhland 1950; Dexter 1978; Hole 1981; Levan and Stone 1983; Kalisz and Stone 1984). Compaction reduces soil biological activity and root growth, thereby decreasing the potential for these processes to return compacted soil to natural conditions (Skinner and Bowen 1974). Numbers of soil fauna, such as burrowing and mound-building insects, worms, and animals are reduced in compacted soils. Because of their mobility, however, these fauna can escape to more favorable soil conditions. Although actively growing roots can move soil particles, thereby creating channels and voids, the degree of soil loosening by roots may be reduced by their tendency to grow along old root channels and existing soil fracture zones. Deep-rooted plants can increase non-capillary pore space and, consequently, increase the percolation rate of the entire soil profile (Hatchell and Ralston 1971). The effectiveness of roots in loosening disturbed soil depends on the size, configuration, and number of macropores left after compaction. Biological processes become more important to natural recovery of soil physical properties when the soil is covered with forest floor sufficient to protect roots and soil fauna in the surface horizons from mechanical disturbance and extremes of temperature and moisture.

4.2 Rates of Natural Recovery

Published estimates of the time required for natural recovery of soils from compaction after forest harvesting vary considerably (Table 4.1). Early studies examined only recovery of surface horizons, while more recent studies have included both surface and subsurface horizons. Determining the time for soils to recover their original bulk density in the field is especially problematic. Perhaps the greatest difficulty in assessing recovery rates is that compaction, especially when rutting or puddling is involved, is often preceded or accompanied by removal of surface soil. As a result, comparisons of bulk density in the surface soil of heavily trafficked areas versus that in nearby non-trafficked areas may actually compare compacted subsoil versus non-compacted surface soil of inherently lower bulk density. Given this invalid comparison, apparent recovery is unlikely in any period of time.

Table 4.1 Summary of Some Investigations of the Estimated Time for Recovery of Soil Bulk Density in Surface Horizons

Location	Site Condition	Soil Texture[a]	Sample Years	Estimated Recovery Time	Source
				Years	
Virginia, USA	decks & skid trails	l, sil, sicl, cl	0-19 (various)	18	Hatchell & Ralston (1971)
Oregon, USA	landing & skid trail	sil, cl, ls, s	8-55 (various)	>55	Power (1974)
North Carolina, USA	logging road	sil	0-38 (various)	18	Drissi (1975)
Mississippi, USA	skid trails	ls-sicl	0-5 (annually)	8-12	Dickerson (1976)
Minnesota, USA	artificially compacted	ls-sl	0-9 (annually)	9	Thorud & Frissel (1976)
Maine, USA	skid trails	l	0-3 (annually)	>3	Holman, Knight, & Struchtemeyer (1978)
Oregon, USA	skid trails	c, cl, sil, l sl, ls	5-38 (various)	>38	Vanderheyden (1980)
Idaho, USA	skid trails	l, ls	0-23 (various)	>23	Froehlich, Miles, & Robbins (1985)
Alberta, Canada	logged (no skid trails)	sic, cl, sl, cl, sil	0-24 (various)	0-21	Corns (1988)
California, USA	skid trails	l, cl	7-48 (various)	>40	Reisinger, Pope, & Hammond (1992)
Indiana, USA	skid trials & landings	sil	0, 2, 4	>4	Stewart (1995)
North Carolina, USA	skid trails	sl, scl	0, 12	<12	

[a] soil texture: Natural Resource Conservation Service textural class (c=clay, l=loam, s=sand, si=silt)

Additional problems in estimating rates of natural recovery (soil resilience) arise from assumptions inherent in the methodology used. One of three methods generally has been used for soil recovery studies: 1) comparison of disturbed soil (e.g., on skid trails or landings) and adjacent undisturbed soils at one point in time, 2) sampling a chronosequence of stands growing on similar soils but harvested at different times, and 3) repeated sampling of the same disturbed area through time. Rates of natural recovery also have been estimated by burying, then recovering compacted soil cores (Garner and Telfair 1954; Telfair, Garner, and Miars 1957), although this method is not widely used. An important assumption underlying all of these methods is that the rate of recovery is linear throughout the period of recovery. As the length of time between the original disturbance and sample collection increases, the validity of this premise becomes more critical to interpretation of recovery rates. The first two methods also assume that the rate of recovery is the same for all soils examined and, therefore, rely heavily on accurate matching of disturbed and undisturbed horizons. In addition, the chronosequence method assumes that differences between disturbed and non-disturbed conditions are solely a function of the time since logging; thus, changes in equipment with time are not considered. This assumption can be justified if historical records of equipment used for logging and site preparation are available.

The following review of published literature on rates of natural soil recovery is presented geographically. Most studies were in three areas in North America: Southeast (Piedmont, Atlantic, and Gulf Coastal Plain), Northeast (including the Lake States), and Pacific Northwest (including western Canada) (Table 4.1). Where appropriate, results from additional studies in Australia, New Zealand, and Russia are also included.

4.2.1 *Southeast*

In one of the first published accounts of natural rates of recovery after compaction, Perry (1964) compared percolation rates of surface soils from three adjacent sites in the Piedmont of North Carolina: an abandoned agricultural field, old road ruts in a 26-year-old loblolly pine plantation, and ruts of a road still used regularly. Specific details regarding the origin of the roads, soil physical properties, and depth of sampling were not provided. The author conservatively estimated that recovery of normal infiltration capacity in the abandoned road ruts would require at least 40 years. Although lacking detailed site and soil description, this study highlighted the potentially lengthy time required for recovery to "natural" soil conditions and the negative impacts of compaction on tree growth. In this same area of the NC Piedmont, Drissi (1975) determined soil physical properties for cores collected from eight logging roads ranging in age from 0 to 38 years since the last disturbance. Neither precise definitions nor detailed descriptions were provided for the logging roads. Estimated recovery times in this chronosequence were 18 years for the 0- to 5-cm depth and 50 to 60 years for the 10- to 15-cm depth. In a third study in the NC Piedmont, Stewart (1995) examined recovery of soil physical properties for skid trail and non-skid trail areas 12 years after harvest. This harvesting operation was completed during dry conditions. Skidders averaged 105 round trips on major skid trails and only eight trips on secondary skid trails (Gent et al. 1984). They evaluated areas allowed to recover naturally without physical amelioration (chop + burn areas) as well as areas ameliorated by surface disking (see Section 5). n the non-skid trail portions of the non-tilled (chop + burn) plots, significant differences in physical properties occurred only in the 0- to 7.5-cm depth. For this depth increment, bulk density (Db) recovered to pretreatment by the 12th year after harvest. Within skid trails of non-ameliorated plots, Db remained 17% and 11% greater for the 0- to 7.5- and 7.5- to 15-cm depths, respectively. Bulk density for the remaining two depth increments (15-22.5, 22.5-30) did not differ from pretreatment bulk density or from that immediately after harvest and site preparation (Gent et al. 1984).

Slightly faster rates of recovery have generally been reported for soils in the Coastal Plain than in the Piedmont of the eastern U.S. Using a chronosequence based on 15 areas logged over a 19-year period, Hatchell and Ralston (1971) estimated an average recovery time of 18 years for surface soil Db in both logging decks and primary skid trails. Changes in skidder design through time (crawler tractors on older sites and rubber-tired tractors on newer areas) may have invalidated the assumption of a similar recovery rate throughout the 19-year period. Differences in equipment may have caused recovery times to be overestimated, because rubber-tired skidders have greater ground pressure than crawler tractors, and the arches used with crawler tractors may have reduced the degree of initial disturbance. Dickerson (1976) annually sampled Db of surface soil (0-5 cm) for 5 years after tree-length harvesting in the Coastal Plain of northern Mississippi. Controlled impact on skid trails was created by seven passes of rubber-tired skidders carrying a load of three logs. Samples were collected from three disturbance classes: soil compacted by skidder wheels (wheel-rutted), soil compacted by logs during skidding (log-disturbed), and soil from undisturbed areas adjacent to each skid trail. Recovery of both loamy sand and silty clay loam soils were estimated to require about 12 years for wheel-rutted soils and 8 years for log-disturbed soils (Dickerson 1976). Because soil samples collected in ruts are actually from deeper in the profile than samples collected from the surface 5 cm in non-disturbed areas, it is likely that the surface 5 cm of wheel-rutted treatments would have inherently higher Db. Consequently, recovery time could have been overestimated.

In contrast to these longer-term evaluations, Hatchell, Ralston, and Foil (1970) found no trend toward recovery of Db at 10- to 15-cm depths for log decks and skid trails sampled during the year after harvesting. This study was conducted at nine areas in the Atlantic Coastal Plain with tree-length skidding performed by either rubber-tired skidders or crawler tractors. It may be that recovery was delayed until herbaceous vegetation regrowth had become established.

4.2.2 *Northeast (Including the Lake States)*

Studies from colder climates (e.g., Lake States and Northeast USA) illustrate more rapid rates of recovery, at least for surface soils. On artificially compacted soil in Minnesota ranging in texture from loamy sand to sandy loam, Thorud and Frissell (1969) observed a decrease in Db from 1.45 to 1.24 g cm^{-3} in the surface (0-7.5 cm) during the first 4.5-year period after logging, and a further decrease in Db to 1.17 g cm^{-3} during the next 4.5-year period (Thorud and Frissel 1976). No change in Db occurred in the more compacted 15- to 23-cm depth during this time period. On relatively dry, coarse-textured soils in Minnesota, Db on medium-use skid trails returns to undisturbed values only 1 year after tree-length extraction with rubber-tired skidders (Mace 1971). The author noted that the initial increase in Db for the 5- to 15-cm depth was only 7% and that frost heaving was active on these soils. In this 1-year period, minimal recovery of Db was observed on more heavily used skid trails (Mace 1971). Relatively rapid rates of soil recovery were also reported after mechanized harvesting on a loam soil in north-central Maine (Holman, Knight, and Struchtemeyer 1978). For stands harvested in winter, bulk density on non-skid trail areas returned to preharvest values after one over-wintering period, but Db in skid trails required two over-wintering periods. On summer-harvested areas, Db in skid trails had not recovered after three over-wintering periods (Holman, Knight, and Struchtemeyer 1978). Finally, relatively fast recovery rates were also reported following logging of spruce (*Picea* spp.) forests in northern Russia, where 5 to 7 years were required for recovery of the original Db of well-drained soils and 15 years for semi-hydromorphic soils (Ivanov 1976 in Greacen and Sands 1980).

4.2.3 *Pacific Northwest Including Western Canada*

In contrast to the rapid recovery of bulk density observed in the Lake States and Northeast, slower rates of recovery have generally been observed in the Pacific Northwest. Froehlich (1979a, 1979b) reported no significant reduction in Db of compacted surface soil 4 to 5 years after tractor logging of young-growth Douglas fir on clay loam and sandy loam soils in western Oregon. The same author observed persistence of higher Db (1.24 vs. 0.84 g cm^{-3}) within the top 30.5 cm of surface soil 17 years after logging old-growth ponderosa pine (*P.* ponderosa Dougl. ex Laws.) in eastern Oregon. Power (1974) reported no trend in recovery through time in soil Db to a depth of 25 cm for landings or primary skid trails at three sites in western Oregon ranging in age from 8 to 55 years after harvest. Bulk density averaged 53% greater in landings and 40% greater on skid trails, compared to adjacent non-compacted areas. All three soils had surface textures ranging from loam through silt loam to clay (over subsoils of clay). In contrast, a fourth site with sandy texture exhibited similar Db in the surface 20 cm among areas identified as plank road, secondary truck-haul road, and non-compacted areas 40 years after logging. Vanderheyden (1980) detected no reduction in soil Db near the 5.1-, 15.2-, and 30.5-cm depths for skid trails at nine sites in the western Cascade Range logged from 5 to 38 years previously. In the Coast Range of Oregon, Wert and Thomas (1981) reported similar Db values for skid trails and non-disturbed areas near the 5-, 10-, and 15-cm depths 32 years after logging. At 20- and 30-cm depths, however, Db was 11 and 16% greater, respectively, in skid trails than non-disturbed areas.

In eastern Oregon, sixteen years after harvest of an old-growth ponderosa pine overstory from a stand of young pine, and relative to undisturbed soils, Db in skid trails was 18% greater near the 7.5- and 15-cm depths and 9% greater near the 23-cm and 30.5-cm depths (Froehlich 1979). Based on samples from the 10- to 15-cm depth at 11 sites ranging in age from 14 to 23 year, Geist, Hazard, and Seidel (1989) concluded that compaction may persist for more than 20 years in volcanic ash soils of the Blue Mountains of eastern Oregon and Washington.

The importance of soil parent material and texture to recovery rate is highlighted in several studies from the Pacific Northwest. Froehlich, Pope, and Hammond (1985) examined recovery of Db at 5.1-, 15.2-, and 30.5-cm depths on chronosequences (five sites each 5 years apart) on two soil parent materials (volcanic and granitic) in west-central Idaho. The rate of recovery in the 23 years since logging was similar for the two soils, although the initial increase in Db was greater for the volcanic soil. The volcanic sites exhibited a significant recovery for all depths except 15.2 cm, while only the surface depth of the granitic soil had returned to undisturbed Db. For both soil materials, recovery of surface layer was faster than at 15.2- and 30.5-cm depths. Corns (1988) used chronosequences ranging from mature uncut stands to 24 years after harvest to investigate recovery of soil from modal, upland conditions (i.e., skid trails and landings were not sampled). For four parent materials in west-central Alberta, the estimated time for recovery of Db ranged from 0 to 21 years, depending on soil type. Soils that developed on cobbly fluvial deposits of Tertiary age recovered the fastest, while soils developed on clay loam till recovered the slowest.

4.2.4 *Australia and New Zealand*

Relatively long recovery periods have also been reported for Australia and New Zealand. For example, 50 years after logging, skid trails on sandy soils planted to radiata pine in South Australia were still more compact than surrounding soils (Greacen and Sands 1980). The authors suggested that natural recovery from compaction may be slowest on sandy soils because processes such as shrink/swell and freeze/thaw are less effective in these soils. About 32 years after seed tree removal, Jakobsen (1983) found that Db in skid trails was greater than in adjacent non-disturbed areas. Differences in Db ranged from 19% (0.90 vs. 1.07 g cm^{-3}) for the 2- to 10-cm depth, 39% (0.98 vs. 1.36 g cm^{-3}) at the 10- to 30-cm depth, and 24% (0.91 vs. 1.13 g cm^{-3}) for the 30- to 50-cm depths. The author suggested that the smaller difference in Db observed in the surface 10 cm (which presumably was originally most compacted) indicates a faster rate of recovery at the surface compared to deeper depths.

Removal of the forest floor and surface soil creates additional risk. Significant decreases in nutrient concentrations in the soil solution were still evident 9 years after removal of the surface horizons (O and A) and compaction of a clay soil in the North Island of New Zealand (Zabowski, Rygiewicz, and Skinner 1996). Substantially less biological activity was also exhibited after surface removal and compaction. Where the O-horizon remained intact, an almost complete return to pre-disturbance conditions rapidly occurred. The authors suggest that more than one rotation length (25-30 years) could be required for complete recovery of soil organic matter, nutrient exchange sites, and soil structure after removal of surface horizons and compaction.

4.3 Summary

The time required for recovery of soil condition after compaction varies with the severity of compaction and with soil physical characteristics (e.g., depth, texture, structure, mineralogy), chemical characteristics (cation exchange capacity, soil solution composition, bonding agents), and climate (temperature and moisture regimes). For example, sandy soils that are low in organic matter may never return to a pre-compactive state without mechanical loosening and/or incorporation of organic matter. In contrast, recovery of soils dominated by smectite clays may be more rapid due to interlayer expansion and contraction during wetting and drying cycles. Soils subjected to frost heaving will generally recover more rapidly than soils in milder climates. In the absence of site-specific information, the effects of compaction on forest soils may be assumed to persist for several decades (Lull 1959; Greacen and Sands 1980; Froehlich and McNabb 1984; McColl and Powers 1984). More importantly, any reductions in tree growth during the recovery period (regardless of duration) can reduce overall forest productivity for the entire rotation.

5.0 AMELIORATING THE EFFECTS OF SOIL DISTURBANCE

5.1 Introduction

Because natural recovery from compaction and other soil disturbances is slow on most sites (see Section 4), one should either avoid or minimize such disturbances during forest harvesting (Froehlich, Aulerich, and Curtis 1981b; McKee, Hatchell, and Tiarks 1985; Reisinger, Simmons, and Pope 1988; Wronski and Murphy 1994). Where this is not possible, rehabilitation of compacted soil can be attempted by mechanical manipulation (e.g., bedding, disk harrowing, ripping, or subsoiling). If properly applied, tillage can favorably alter soil properties and enhance seedling survival and growth (Morris and Lowery 1988). Tillage under non-optimum conditions (e.g., excessive soil moisture), however, can cause additional soil compaction and/or puddling, and further risk to long-term productivity.

Agricultural research has shown that compaction can be minimized by reducing or controlling equipment traffic patterns [i.e., using distinct and permanently separated crop zone and traffic lanes (e.g., Orzolek 1987)]. While controlled-traffic systems are applied regularly in agriculture (e.g., with crop rotations), such practices are far less utilized in forestry. An extensive network of extraction trails characterizes most ground-based logging systems. Even if harvesting traffic is confined to designated skid trails, these can still represent 10 to 15% of the harvested area. Confining traffic to designated skid trails is more beneficial on fine-textured soils because much compaction or puddling in such soils occurs during the first few equipment passes (McKee, Hatchell, and Tiarks 1985). Increased availability and accuracy of Global Positioning Systems and Geographic Information Systems has improved the practicality of permanently documenting and re-using primary skid trails and landings.

Organic matter additions, fertilization, and competition control can also increase growth of seedlings planted in compacted soils (Berg 1975; Schuster 1979; Scheerer et al. 1995). Greacen and Sands (1980) hypothesized that efforts to ameliorate soil compaction through tillage would not result in growth responses as large as from fertilization or control of competing vegetation. Nutrient additions and vegetation control, however, do little to alter soil physical conditions; growth responses to such practices on compacted soils may be short-lived compensation and not representative of responses on non-compacted soils.

5.2 Soil Tillage

Tillage is designed to loosen soil into various-sized clods, to reduce soil strength, bury plant residues, incorporate fertilizers and soil amendments, and rearrange aggregates to promote movement of air and water (Cooper 1971). Tillage can also facilitate weed control and conserve soil moisture by increasing infiltration or decreasing runoff and evaporation (Hillel 1982).

The efficacy of tillage in improving physical properties of agricultural soils and growth of annual crops has been well documented (e.g., Cooper 1971; American Society of Agronomy 1982; Unger and Cassel 1991; Bathke et al. 1992). The effects most often demonstrated are decreased bulk density and mechanical impedance (Cassel 1982), increased macroporosity and infiltration (Klute 1982), and reduced runoff (Klute 1982). These beneficial effects, along with a potential increase in N and P mineralization rates (Wierenga et al. 1982), improve resource availability by enhancing the capacity of the soil to provide nutrients, water, and gas exchange for root growth. All contribute to increased rooting density and uniformity throughout the profile within the tilled areas (Taylor 1971; Trouse 1971; Whisler, Lambert, and Landivar 1982; Bathke et al. 1992). Recognition of the potential for increased crop yield and quality in agriculture has led to regular tillage in row crops (e.g., with every rotation).

Equipment used in forestry to till compacted soil or to prepare sites for regeneration is generally sturdier versions of agricultural implements that are pulled by crawler tractors or rubber-tired skidders (Lowery and Gjerstad 1991). Some equipment is specifically adapted for rocky or steep terrain, and post-logging conditions characterized by large roots, stumps, and abundant logging debris. Four general tillage options exist: disk harrowing, bedding, chisel plowing, and subsoiling. Each tillage option is appropriate under certain conditions. Combination plows, which combine several of these operations into one pass, have been used in the Southeast for the past 10 to 15 years.

Disk harrowing involves drawing a series of 80- to 90-cm diameter steel disks through the soil to depths ranging from 15 to 35 cm. Two axles of disks are usually employed and disks are either offset or opposed. Conventional disk harrowing is most effective when surface soils are compacted and contain a minimum of roots, stumps, and logging debris. Bedding plows both harrow and turns the soil into long beds through use of concave disks mounted in opposition to each other. Like disk harrowing, bedding can help ameliorate surface compaction. It is particularly useful on wet sites because the 15- to 40-cm high beds provide increased rooting zone above the water table. "Stump-jump" type harrows and bedding plows represent an improvement over conventional equipment; individually mounted arms allow each disk to roll independently over stumps, rocks, and logs. Chisel plowing involves pulling close-set tines through the soil to a depth of 20 to 40 cm. It can be useful for ameliorating compaction to a deeper depth than can be reached by harrowing. Subsoiling is the only commonly used operation capable of ameliorating physical restrictions in the subsoil. Single- or double-subsoil shanks can be pulled to depths of about 55 cm. The key to successful subsoiling is operating when the soil is sufficiently dry for shattering to occur (Lowery and Gjerstad 1991). The tip of each subsoiling tine may be equipped with replaceable shoes and small, horizontal wings to increase shattering (Page 1977). Deep loosening (vibration ripping) is a recent modification of subsoiling that incorporates an oscillating, sharpened vertical beam located immediately in front of a vertical stationary shank (Nadeau and Pluth 1997). Vibration ripping is designed to loosen soil by lateral fracture without major soil displacement and to function at greater depths than conventional rippers (70 versus 55 cm).

Success of tillage in loosening compacted soil depends on equipment factors (e.g., type, depth, and speed of the implement) and soil factors (e.g., initial soil physical properties, water content, clay mineralogy, texture) (Unger and Cassel 1991). Soil conditions controlling compaction are characterized by a high degree of complexity, as well as both temporal and spatial variability (e.g., Cassel 1982). Because tillage effects are transient and readily masked by seasonal and climatic factors, quantifying sequential changes in soil conditions after compaction and tillage is problematic (Raghavan, Alvo, and McKyes 1990).

To improve the effectiveness of tillage, it is important to consider "critical depth"—the depth of the implement in the soil that maximizes both shattering and loosening. Critical depth is principally a function of soil moisture, texture, and implement design (Andrus and Froehlich 1983). Tilling below the critical depth creates a zone of compression where soil is displaced to the side of the tine tip rather than upwards. As a result, the force required to move tines through the soil is increased. Tilling below the critical depth can also result in continuous, well-defined soil channels that direct water and cause erosion, especially in steep terrain (Andrus and Froehlich 1983). While the critical depth for agricultural tillage implements has been widely studied, little information of this type is available for the equipment and site conditions typical of forestry operations.

5.3 Forestry Experiences

Response of trees to tillage depends on the extent to which growth-limiting conditions are ameliorated by soil manipulation. Long-term response to tillage requires an increase in quality (e.g., ability to supply resources) and in absolute quantity of rooting volume, rather than just a temporary acceleration in root occupancy or a short-term increase in nutrient availability due to increased rate of mineralization (Morris and Miller 1994).

Changes in soil conditions after mechanical site preparation of forestland (e.g., Gent, Ballard, and Hassan 1983; Morris and Pritchett 1983; Slay et al. 1987; Sutton 1993) are similar to those reported for agricultural tillage. Improved soil conditions contribute to favorable planting practices (e.g., deeper planting, reduced J-rooting), increased survival, and increased rooting density and uniformity in the profile. Unfortunately, few studies have specifically investigated growth responses following amelioration of forest soils compacted during harvesting (Table 5.1). This type of information is essential a) to increase our understanding of the relationship between soil properties and tree growth, as well as b) to develop quantitative models to predict the effects of harvesting and site preparation on tree growth and to evaluate the economics of alternative methods (Morris and Lowery 1988).

The following review of the published literature on soil and tree responses to tillage is presented geographically. Most studies were in two areas in North America: Southeast (Coastal Plain and Piedmont) and Pacific Northwest (including western Canada). Where appropriate, results from additional studies conducted in Australia and New Zealand are also included.

Table 5.1 Summary of Some Investigations of Tree Growth after Remedial Tillage of Skid Trails

Area	Number of Sites	Species	Soil Texture	Years After Tillage	Results	Source
S. Carolina (Coastal Plain)	?	*Pinus taeda*	loamy	2	bedding increased height 35% more than disking	Scheerer et al. (1995)
N. Carolina (Piedmont)	1	*Pinus taeda*	sandy loam	12	tillage increased survival 178% and height 31%	Stewart (1995)
W. Washington	3	*Pseudotsuga menziesii*	silt loam	15	tree size unaffected by compaction or tillage	Miller, Scott, and Hazard (1996)
W. Oregon	8	*Pseudotsuga menziesii*	clay loam	8	tree size reduced by compaction, but increased by tillage	Heninger et al. (1997a)
W. Oregon	1	*Pinus ponderosa*	loamy	5	survival and height unaffected by tillage	McNabb and Hobbs (1989)

5.3.1 *Southeastern United States*

Impacts of forest harvesting and site preparation were examined at three sites in the Southeast (Lower Coastal Plain and Piedmont of North Carolina, and Upper Coastal Plain of Alabama) in an industry-university cooperative project ("Impact of Management Practices on Forest Site Productivity") at North Carolina State University. At each site, Db, air-filled porosity, and saturated hydraulic conductivity were determined to a depth of 30 cm within and outside skid trails before and immediately after harvest, then after site preparation.

At the Lower Coastal Plain site, bedding was effective at ameliorating compaction by forming a new surface approximately 19 cm above the previous one, rather than by altering Db of the original, trafficked surface (Gent, Ballard, and Hassan 1983). While Db in planting beds averaged 1.00 g cm^{-3}, Db in the 0- to 23-cm depth of the buried, trafficked surface ranged from 1.45 to 1.69 g cm^{-3} within skid trials, and from 1.26 to 1.45 g cm^{-3} outside skid trails. Bedding decreased air-filled porosity and hydraulic conductivity of the original trafficked surface at all depths. The reduction in hydraulic conductivity was statistically significant ($P < 0.05$) for the 0- to 7.6-cm depth outside and within skid trails, and for porosity in the 0- to 7.6 -cm depth outside, but not within skid trails. To loosen soils compacted during harvest, Gent, Ballard, and Hassan (1983) recommended that disking be done before bedding, especially on skid trails, or that a small, central ripper be pulled in series with a bedding plow.

In the wet pine flats of the Lower Coastal Plain, disking had no effect on saturated hydraulic conductivity of soil in skid trails rutted from logging (Scheerer et al. 1995). Although bedding increased hydraulic conductivity from 0.81 cm hr^{-1} after harvest to 2.07 cm hr^{-1}, the combination of disking and bedding further increased hydraulic conductivity to 3.23 cm hr^{-1}. Bedding increased loblolly pine height growth 35% over that obtained with disking. However, seedling responses to a combination of disking and bedding were similar to those from bedding alone. Fertilization had a more pronounced effect on 2-year seedling height than bedding or bedding and disking and increased 2-year height by 54% over that obtained after disking as a single treatment. Furthermore, effects of fertilization and site preparation on seedling growth were additive. The authors suggested that fertilization on wet sites may be an inexpensive and practical alternative to mechanical site preparation.

A series of studies to evaluate the effects of wet-weather harvesting and subsequent ameliorative treatments on Lower Coastal Plain sites were conducted following salvage harvest in the Francis Marian National Forest after Hurricane Hugo (Aust et al. 1995; Dulohery, Morris, and Lowrance 1996; Aust et al. 1998a, 1998b). Dulohery, Morris, and Lowrance (1996) investigated the effects of disking followed by bedding with and without NPK fertilization on soil conditions and biological activity in rutted skid trails and non-trafficked areas on a poorly drained clay (Bethera series-clayey mixed thermic Typic Palequult) and a moderately well-drained loam (Goldsboro series-fine loamy, siliceous, thermic Aquic Paleudult). Bedding decreased Db from 1.48 to 1.33 g cm^{-3} and improved air-filled pore space at saturation in trafficked areas from nearly zero to about 10%. Although this was a dramatic improvement, Db remained higher and air-filled pore space lower than occurred in either non-trafficked areas (without beds) or in beds created in non-trafficked areas. Associated with these degraded physical properties was an overall decrease in biological activity as measured by CO_2 evolution from the soil surface. In related work on these and additional sites, Aust et al. (1998b) reported that disking, bedding, or disking plus bedding were insufficient to restore trafficked areas to tree productivity on non-impacted areas. However, bedding plus fertilization resulted in loblolly pine (*P. taeda* L.) growth in trafficked areas equivalent to that in non-trafficked areas after 4 years. Together, these results underscore the difficulty of ameliorating changes in soil properties in some wet areas. Only when both physical characteristics and nutrient characteristics of the rooting zone were improved did seedling growth in trafficked areas compare with non-trafficked areas. It seems that soil damage that still remained after mechanical ameliorative treatments was compensated for by improved fertility in the available rooting volume after fertilization.

Laboratory studies also pertain to the Lower Coastal Plain. Foil and Ralston (1967) simulated trafficking and tillage by compacting (using a bearing-ratio test machine) then loosening (using a trowel) soils of three textures. Loosening reduced bulk density by 5% for loamy sand, 18% for loam, and 33% for clay. Loosening increased total porosity by 35, 55, and 61% for loamy sandy, loam, and clay soils, respectively. This increase in total porosity resulted primarily from greater macroporosity (non-capillary porosity), which increased by 76% for loamy sand, 241% for loam, and 460% for clay. The authors assayed each treatment in the greenhouse with loblolly pine (from seed) for one growing season. Averaged for all three soil types, soil loosening increased pine survival by 25%. Loosening coarse-textured soil (loamy sand), however, reduced height growth relative to undisturbed soil. This decline was attributed to reduced available water and nutrients resulting from limited lateral root proliferation into zones of high air-filled porosity (ca. 45%). By contrast, loosening clay soils increased root development and seedling growth. Foil and Ralston (1967) concluded that future research should focus on treatments to ameliorate soil compaction because damage equivalent to the levels tested was occurring during harvest. In a related study, Hatchell, Ralston, and Foil (1970) sowed loblolly pine seed on 10 x 15 cm (diameter and height) cores collected from compacted and undisturbed soils. Loosening the core (the entire core or to a 7.5-cm depth) greatly improved seedling survival, but growth was not significantly different between loosened and undisturbed soils.

At the Piedmont site of the "Impact of Management Practices on Forest Site Productivity" project, double-disking decreased Db (from postharvest values) in the surface horizon (0- to 8-cm) within and outside of skid trails, and also in the 8- to 15-cm depth within skid trails (Gent et al. 1984). Disking restored air-filled porosity to preharvest values only in the surface horizon and had no effect on hydraulic conductivity at any depth. The authors concluded that areas in primary skid trails should be disked or ripped to avoid growth limitations from mechanical impedance of root growth, and that adding a ripper in series with a disk harrow would be advantageous. Twelve years after tillage at this Piedmont site, Stewart (1995) remeasured soil physical properties and also measured tree performance. In previously disked plots, bulk density in the 0- to 7.5-cm depth had increased both within skid trails (1.10 g cm^{-3} after tillage to 1.22 g cm^{-3} after 12 years) and outside skid trails (from 1.13 after tillage to 1.28 g cm^{-3}). The increase in Db was attributed to resettlement of soil particles and impact of rain. Cassel (1982) reported similar increases in Db from resettlement after tillage in agricultural soils. Disking former skid trails increased loblolly pine survival by 178% and height growth by 31% (Stewart 1995). Disking improved survival and growth outside of skid trails by 50 and 20%, respectively.

Site preparation treatments at the Upper Coastal Plain site of the "Impact of Management Practices on Forest Site Productivity" project were restricted to chop/burn and shear/windrow. These treatments had little effect on soil physical properties at any depth examined (Gent and Morris 1986).

Members of the North Carolina State Forest Nutrition Cooperative (NCSFNC) initiated a regional study (referred to as Regionwide 16) in response to concerns about the increasing use of mechanical site preparation, particularly combination plowing, without knowing the benefits to pine survival and growth. Fifteen installations were established from 1994 to 1998 on recently harvested sites across a variety of soil and site types. Seven of these trials were located in the Piedmont physiographic province, six in the Upper Coastal Plain, and one each in the Lower Coastal Plain and Appalachian Plateau (NCSFNC 1998, 2000a).

Each site consisted of multiple replicates of a 2 x 2 factorial of surface tillage (disking at 14 sites and bedding at the remaining site) and subsurface ripping. All plots received fertilizer (N+P) at the time of planting and vegetation control repeatedly during the first two growing seasons. Seedling survival was measured at the end of the first and second growing seasons; diameter and height were measured every two years.

Across all sites, tillage had minimal benefits for pine seedling survival, with responses averaging 2, 5, and 7% for surface tillage, subsurface ripping, and ripping + surface tillage, respectively. Average growth responses of loblolly pine to tillage were relatively modest. Relative to non-tilled control plots, 4-year height and volume responses averaged 0.4 ft and 19 ft^3 $acre^{-1}$, respectively, for surface tillage; 0.6 ft and 30 ft^3 $acre^{-1}$, respectively, for ripping; and 1.0 ft and 67 ft^3 $acre^{-1}$, respectively, for ripping + surface tillage (NCSNFC 2000a).

Maximum height growth responses at individual sites were 1.4 ft for surface tillage, 1.7 ft for ripping, and 1.5 ft for the combination of ripping plus surface tillage. Maximum volume growth responses were 63 ft^3 $acre^{-1}$ for surface tillage, 99 ft^3 $acre^{-1}$ for subsurface tillage, and 153 ft^3 $acre^{-1}$ for ripping + surface tillage. The largest tillage responses were observed on well-drained, fine-textured soils with siliceous mineralogy. The authors hypothesized that combination plowing may increase the 25-year site index of loblolly pine as much as 7 feet (NCSFNC 2000a).

Detailed assessments of tillage effects on soil bulk density (Db), air-filled porosity (Fa), mechanical impedance (MI), and pine seedling root growth were made at one location in the Piedmont of North Carolina and one location in the Piedmont of South Carolina. At the NC site, surface disking significantly reduced Db and increased Fa in the 0- to 20-cm soil depth in the planting row at the end of the first growing season (NCSFNC 2000b). Ripping had a similar impact on Db and Fa; however, these effects extended downward to the 20- to 50-cm depth and outward to 30 cm from the planting row. MI was not measured at the NC site. At the SC site, neither surface disking nor subsoil ripping affected Db or Fa within the volume of soil hypothetically impacted by these treatments (Colbert 2001). Surface tillage at the SC site reduced MI in the 0- to 10-cm depth, and ripping reduced MI at all depths (10 cm intervals from 0 to 50 cm).

Rooting patterns differed among the treatments at both sites. Disking increased root density in the surface soil (0- to 40-cm depth). Ripping increased root density to a depth of 70 cm in the soil adjacent to the rip line, resulting in a more uniform distribution of roots with depth (Colbert 2001). While both tillage treatments increased the volume of soil exploited by pine roots, ripping had a greater effect on root density than disking due not only to a larger rooting volume, but also to generally greater increases in the number of roots per unit volume (Colbert 2001). Improvements in soil physical properties (i.e., increased Fa and reduced Db and MI) not only increased the volume of soil exploited by pine root systems, but also accelerated the rate at which the soil volume was occupied by roots (i.e., root closure).

The generally modest survival and growth responses in the Regionwide 16 trials may not be indicative of response to tillage in the absence of nutrient additions and competition control. Survival and growth on non-tilled control plots exceeded industry standards at most sites, presumably due to time-of-planting fertilization and repeated weed control during the first two growing seasons. The benefits of fertilization and weed control probably reduced the potential for response to additional tillage (rather than as a sole treatment). Moreover, the differences in growth on tilled and control plots in the Regionwide 16 studies indicate that soil physical conditions (whether excess moisture, high soil strength, or shrink/swell clay mineralogy) as growth-limiting factors must be evaluated on a site-specific basis. Maximum gains in productivity will be realized where tillage is applied judiciously and in combination with fertilization and competition control.

5.3.2 *Pacific Northwest (Including Western Canada)*

Andrus and Froehlich (1983) evaluated four tillage methods (winged subsoiler, rock ripper, brush blade, and dish harrow) on primary skid trails at several sites in Oregon and Washington. Winged subsoilers generally produced a broad, U-shaped shattering pattern that resulted in greater volume of fractured soil than conventional rock-ripping tines (64% more in moist, clayey soil and 35% more in rocky, granular soil). A three-tined, winged subsoiler easily shattered a dry loam soil in a single pass, thereby loosening 80 to 90% of the compacted soil volume. On a moist clayey soil, subsoiling followed by disking resulted in a) loosening of 70% of the compacted volume by subsoiling and b) a reduction in the percentage of large clods (>5 cm diameter) from 44% to 223% after disking. By comparison, rock-ripping tines produced V-shaped areas of shattered soil that loosened only 20 to 45% of the compacted volume. Brush blades loosened only the top 10 to 18 cm of soil (28-49% of the compacted soil volume); their effectiveness was limited by the build-up of logging debris between blade tines. Disk harrowing loosened only the top 10 cm of soil in skid trails, mainly due to the light weight of each disk and the obstruction of disks by logging slash and large rocks. Moreover, the overall width of this harrow (3.5 m) exceeded skid trail width, thereby causing the outside disks to be elevated on the skid trail berms, and the center disks not to contact the soil. At another site, however, two to three passes with a different disk harrow loosened the soil to 20 cm. Andrus and Froehlich (1983) concluded that minimal soil loosening resulted when spacing between brush blades or ripping tines was too great, ripping depths were too shallow, or tine design was ineffective. Placing tines closer, however, increased accumulation of logging slash. High soil moisture content (>32%) resulted in vertical slots to depths greater than 25 cm, although a second, offset pass with the rock ripper would have eliminated some of these problems.

The authors suggested several design changes to improve tillage effectiveness. For harrows, provide each disk with independent action to increase effectiveness in irregular terrain, rocky soils, or sites that have abundant logging debris and stumps. Increase average disk weight and use large, heavy-duty disks to allow deeper tillage. Arrange disks in opposed gangs, rather than offset, and mount disks to the prime mover so that they may be lifted off the ground to increase mobility and maneuverability. For subsoilers, attach wings to ripping tines to increase the amount of soil shattered per tine, the degree of loosening, and the critical depth of the equipment. Greater amounts of shattering per tine allow the spacing between tines to increase, thereby reducing the accumulation of logging slash and reducing the power required to loosen a given volume of soil. Many of these recommendations have been incorporated in “stump jump” and combination plow equipment currently used for site preparation.

McNabb and Hobbs (1989) examined the response of ponderosa pine to ripping (two 46-cm long rock-ripping shanks spaced 1.68 m apart) a compacted, moderately deep, fine loamy soil in southwest Oregon. Through age 5 years, no statistically significant differences in annual growth and total size of seedlings existed between ripped and non-ripped areas. This lack of differences was attributed to the fact that only 6% of the surface 30 cm of soil exhibited a significant reduction in Db and that less than 2% of the potential rootable volume (to 1 m depth) was affected by ripping. Clayton, Kellogg, and Forrester (1987) reported that ripping areas of former log decks on granitic soils in Idaho reduced soil resistance from 1580 to 485 kPa for surface horizons (0-7.5 cm). Ripping was not effective at improving penetrability at soil depths below 10 cm, except directly in the furrows.

Tilling skid trails at eight locations in western Oregon reduced bulk density and improved tree growth of planted Douglas fir so that it was similar to that on adjacent logged-only portions (Heninger et al. 1997a). Using rock rippers on skid trails improved average tree height in year 7 or 8 by 16% over that on non-ripped skid trails, and by 1% over that in logged-only (control) areas.

Increases in mean tree bole volume averaged about 48% over that on non-ripped plots and about 1% over logged-only plots.

For British Columbia, Louiser (1990) and Kranabetter and Osberg (1995) provided comprehensive reviews of efforts begun in the mid-1970s to rehabilitate compacted soils and restore site productivity. For reclamation of landings and skid trails, guidelines recommend loosening soil to a depth of 30 cm before reforestation. Field trials demonstrated the need to replace organic matter removed by harvest and site preparation in order to promote formation of stable soil aggregates after tillage. Although rock rippers proved ineffective at loosening compacted soil (<26% soil shatter to an average depth <30 cm), winged subsoilers provided >80% shatter to an average depth of 40-50 cm. Others have examined rehabilitation of compacted soils with winged subsoilers in British Columbia (e.g., Carr 1989; De Long et al. 1990; Rasmussen 1991; Kranabetter, Higginson, and Baxter 1996). In 1994, the British Columbia Ministry of Forests initiated a long-term screening trial examining logging road rehabilitation. Permanent growth plots of various forest species have been established on newly rehabilitated and planted logging roads on 47 sites in coastal British Columbia. Results are being used to develop a classification scheme for prescribing road rehabilitation activities that will help direct and improve management decisions.

In central Alberta, Nadeau and Pluth (1997) examined the soil volume colonized by roots of lodgepole pine (*P. contorta* var. *latifolia* Engelm.) and white spruce [*Picea glauca* (Moench) Voss] 10 years after vibration ripping on soils considered to have inherent physical restrictions to rooting. Ripping increased the density and depth of large (>2 mm diameter) coniferous roots in the 8.5- to 18.5-cm depth (Ae-horizon) and in the 18.5- to 48.5-cm depth (BA-horizon). The distribution of small roots was also increased in the 48.5- to 88.5-cm depth (Bt-horizon). Pronounced height growth responses to ripping were documented, but response was not strongly related to soil aggregate or Db values.

5.3.3 *Australia and New Zealand*

In western Australia, Schuster (1979) examined the effectiveness of ripping for ameliorating compacted logging deck areas and skid trails on shallow-to-clay podsols. Two-year height growth of planted karri (*Eucalyptus diversicolor* F. Muell) increased 62% with ripping to 1-m depth, 66% with fertilization (46 kg N ha^{-1} and 48 kg P ha^{-1}), and 247% with ripping and fertilization. The addition around each tree of a 5-cm deep x 15-cm diameter layer of N-enriched bark mulch (1.8 g N per kg of air-dry material) had no effect on karri height growth when applied alone, but increased 2-year height by 200% when applied with fertilizer, and 330% when applied after ripping and fertilization. In a second study, ripping skid trails to 1-m depth increased 2-year height growth by 60%. The combination of burning logging debris (60% reduction in fuel), ripping, and debris addition (1500 to 1900 t ha^{-1}) resulted in a 232% increase in 2-year height.

Nambiar and Sands (1992) reconstituted soil profiles (1.6 m^2 x 0.9 m deep) that were compacted (Db = 1.6-1.7 g cm^{-3}) in the 30- to 60-cm depth. One year after planting radiata pine seedlings, root channels were simulated on a 20-cm grid by pushing a 1-cm diameter sharpened steel probe to a depth of 1 m. At the end of three growing seasons, all perforations were occupied by roots with each simulated root channel containing a bundle of up to 74 roots. Perforations markedly increased the amount of root penetration below 1-m; these deep roots bypassed the compacted layer to extract water from deeper in the soil profile. Three-year height growth of radiata pine was increased 27% by the artificial root channels, relative to compacted but non-perforated profiles. Although only 0.2% of the soil volume consisted of vertical channels, the effect of compaction was largely overcome. The authors concluded that perforations through compacted soil layers at a relatively low frequency may be a practical solution to allow root development into deeper parts of the soil.

In New Zealand, deep ripping (45-60 cm) of log-deck areas on Kauri gumland clays increased survival of radiata pine by 22% and 3-year height growth by 25% (Berg 1975). In contrast, superphosphate fertilization (20 kg P ha^{-1}) decreased survival by 20% but increased height by 7%. The combination of ripping and fertilization increased survival by 23% and height growth by 52%, suggesting that a) both soil structure and nutrient deficiencies limited growth on these soils, but b) response to fertilizer was limited by non-ameliorated soil structure. Root systems had penetrated into and along the lines of fractured soil, spreading up to 120 cm along the rip lines and 50 cm below the planting spot; root spread in nonripped soils was seldom more than 30 cm in any direction. In a second trial, radiata pine height increased 10% with ripping to the 75-cm depth, 23% with fertilization (25 kg N ha^{-1} + 75 kg P ha^{-1}), and 72% with a combination of ripping and fertilizing. Berg (1975) concluded that the effect of ripping on these compacted clay soils was distinct from, and additive with, responses to fertilizer.

5.4 Summary

The most effective strategy for reducing the impact of soil disturbance on forest productivity is to avoid or at least minimize compaction, rather than rely on ameliorative treatments such as tillage. When applied correctly to compacted soils, tillage can improve the quality and quantity of rooting volume, thereby increasing the density and uniformity of roots throughout the soil profile. Ripping, in combination with disking, is the most appropriate treatment for most soils compacted during harvesting, particularly skid trails and landings. Disturbed soils that require mounding to improve drainage should be ripped or disked before bedding. Combination plows can be a practical and economical means for accomplishing ripping, disking, and/or bedding in one pass. While other methods to improve productivity (e.g., organic matter additions, fertilization, and competition control) may result in greater growth responses than tillage, these practices do little to alter inherent site productivity; therefore, their positive impacts may be short-lived.

6.0 PREVENTIVE MEASURES

Although soil disturbance is a normal consequence of using heavy equipment for harvesting or site preparation, the area and intensity of disturbance of forest floor and mineral soil can be minimized by preventive action. Remedial mitigation (see Section 5.0) is a less desirable option because of the expense, loss of productivity until mitigation occurs, and the possibility that original soil conditions may not be restored (Terry and Campbell 1981). To minimize negative impacts of trafficking on soil physical properties, soil management guidelines should emphasize minimal disturbance of vegetation, forest floor, and soil (McColl and Grigal 1979). Severity and areal extent of disturbed (compacted, churned, rutted, or displaced) soil by tracked and wheeled vehicles can be minimized by the following actions:

* identifying risks
* planning and scheduling operations
* selecting appropriate equipment
* controlling on-site activities to accommodate identified risks
* training and feedback during operations to increase operator awareness

6.1 Identifying Risks

Perhaps the most fundamental and important guideline is to recognize the relationship between soil moisture content and risk of soil disturbance. Maximum compaction (i.e., greatest increase in soil bulk density) is achieved in most soils when they are at field capacity (i.e., when large pores have been drained by gravity) because the remaining water lubricates soil particles as they move and pack against one another (Harris 1971). Churning, rutting, and displacement, however, are more likely when soils are saturated with water (i.e., before draining to field capacity) because water is non-compressible (Hillel 1982). Saturated soils also have weak load-bearing capacity and shear strength. Thus, trafficking saturated, wet, or moist soil increases the risk of soil degradation. This risk is greater a) in wet seasons of the year than in dry seasons, b) on slow-draining clayey soils than rapidly draining sandy or gravelly soils, and c) in drainageways and concave topography than in convex or sloping topography.

Development of "risk ratings" based on soil and site characteristics is useful for planning and scheduling operations (Smith and Wass 1980; British Columbia Ministry of Forests 1995; Heninger et al. 1997b). Soils or sites rated as low risk are least sensitive (or conversely, more robust) to site disturbance from trafficking. These ratings or interpretations are often based on inherent soil factors that affect trafficability: bulk density, liquid and plastic limits, porosity, saturated hydraulic conductivity, texture, and water table depth. Other factors can be used to predict soil trafficability for specific conditions and soil types. For example, Burger (1994) developed a trafficability hazard index for wetland soils in the Coastal Plain of South Carolina based on soil strength, as measured by penetration resistance and volumetric water content. Other hazard indices based on penetration resistance have been reported by Barnes et al. (1971) and Rounsevell and Jones (1993).

It is important to note that operability risk ratings are based on modal (typical) characteristics for each soil. Consequently, the reliability of ratings for specific locations depends on the accuracy of soil and location maps and on how well the soils in the field fit the modal characteristics of each soil mapping unit. On-site verification before harvesting or equipment usage is necessary to ensure optimal application of operability risk ratings for a particular soil or location. Another concern is that identification of low-risk sites could mislead operators to ignore soil management guidelines on these sites (Froehlich and McNabb 1984).

It should be noted that "risk" in this context has two components: a) likelihood that an activity like trafficking by heavy equipment could degrade soil physical properties, and b) likelihood or risk that these degraded soil properties will reduce tree growth or cause erosion and other unwanted results. Assigning either risk component is based on information and assumptions available to the rater. These assumptions can only be confirmed or improved by collection and analysis of new and reliable information about soil disturbance and tree performance. This continuous improvement has attendant benefits and costs.

Lacking better information, most raters or interpreters assume a general or quantitative relationship between degraded soil properties and particular variables of interest. For example, most people assume that soil compaction reduces subsequent tree growth. As illustrated in Section 3.3, this is not always appropriate. Although this conservative generalization can reduce risk, it can increase costs of mitigation unnecessarily. Additional and widespread investigations of tree performance on disturbed and remediated soil are clearly needed. The economic impact of soil disturbance and amelioration will depend on observed reductions in growth. Hence, relatively minor disturbances on highly productive sites have the potential for a greater economic impact than comparable or greater severity of disturbance on less productive sites.

6.2 Planning and Scheduling Operations

On-site evaluation of site characteristics and careful planning of operations help ensure that risks can be identified and alternatives to avoid or minimize soil damage can be developed (e.g., Reisinger, Simmons, and Pope 1988). Operability risk ratings (e.g., Table 6.1) can be used to make decisions about both harvesting and site preparation. Operations and equipment can be much more flexible for soils with low-risk ratings than for high-risk soils. Soil moisture before, during, and after harvesting and site preparation (e.g., drainage, water bars) should be taken into account to appropriately assign risks. Drainage can be performed before logging to improve access and reduce soil moisture. Specific suggestions for planning and layout have been widely reported (McColl and Grigal 1979; Miles et al. 1981; Froehlich, Aulerich, and Curtis 1981a, 1981b; Froehlich and McNabb 1984; Reisinger, Simmons, and Pope 1988).

Table 6.1 Options for Preventing or Minimizing Detrimental Soil Disturbance from Ground-Based Equipment (Rubber-Tired or Tracked) by Soil Risk Class

	Soil Operability Risk Rating[a]			
Item	Low	Moderate	High	Very High
	Layout and Equipment			
Skid Trails:				
No traffic on depressions	+	+	+	+
Re-use previous	+	+	+	+
Add slash	-	+	+	+
Designate routes	-	-	+	+
Add rock ballast	-	-	-	+
Equipment:				
Reduce weight of equipment or load	-	-	+	+
Reduce ground pressure; use tracked (not tired)	-	-	+	+
Use cable system	-	-	+	+
	Scheduling and Controlling Activities			
Scheduling[b]:				
Months (number)	all (12)	May-Oct (6)	Jun-Aug (3)	Jul-Aug (2)
Stoppage/shift[c]:				
Use tensiometer or wait for (hr)	4-8	48-72	48-72	48-72
Depth to free water (in)[d] :	24	36	36	48

SOURCE: These options were compiled from various published and unpublished sources.
NOTE: Symbols: "+" refers to use, "=" to consider, and "–" to not or seldom needed.
[a] Operability risk ratings indicate the relative potential for detrimental effects on soil properties by heavy-equipment trafficking; the rating is strongly related to slope percentage and the likelihood of saturated soil close to the surface (high water table or ponded water). Where either of these conditions exists, operate with additional care.
[b] appropriate to western Washington and Oregon, which usually have dry summers
[c] Temporarily stop or shift operations until surface soil is not wet (tensiometer reading exceeds 0.3 bar at 12 inches depth or soil is drained of free water to depth shown)
[d] Observe water level in soil pits that are about 36 inches deep.

Harvesting and mechanical site preparation can be scheduled to coincide with soil conditions appropriate to operability risk ratings (e.g., operate on high-risk sites in dry months and low-risk sites in wet months). Both activities can also be scheduled in sequence to take advantage of optimum soil moisture conditions (Reisinger, Simmons, and Pope 1988). Yarding operations can be scheduled immediately after felling, especially on high-risk sites, since reduced evapotranspiration following harvest will increase soil moisture. Areas targeted for skid trails can be harvested first, then the setting harvested from the back to the front; thereby reducing trafficking outside of designated skid trails. Specific recommendations for well-planned operations include the following:

* Identify areas that pose a particularly high risk for erosion and productivity loss: unstable slopes, streams, drainageways, depressions, and other particularly sensitive areas. Activities (e.g., trafficking) in these areas may need to be more restricted than on the remainder of the site. In some years, no activity may be possible or prudent.

* Design and locate haul roads, landings, and skid trails on areas that will minimize growth impacts. For example, consider favoring a) areas that can be reused in the future, restored by tillage, or designated for non-crop use (e.g., heliports for fertilizer application); b) areas of lower productivity soils; and c) areas in which amelioration may be more successful.

* Designate skid trails before felling and logging; this action alone can usually limit the area in skid trails to approximately 10 to 20% of the harvest area.

* Follow BMPs with respect to avoiding trafficking streams, some wetlands, drainageways, and depressions with ground-based equipment.

* On high-risk sites, minimize the extent of skid trails and reuse former skid trails when possible to reduce the cumulative area of disturbed soils.

* On clayey sites, restrict or minimize area trafficked because a few trips can cause compaction or churning. Conversely, a few trips on sandy soils cause less change and can even improve soil moisture relations by reducing large pore volume or too rapid percolation.

* Fell trees to orient with designated skid trails and attempt to de-limb on the subsequent traffic routes; add slash to trails to improve traction.

* Use processor-forwarder operations whenever possible to minimize the amount of extracted material hauled on skid trails and to leave logging slash in place or in skid trails.

6.3 Selecting Appropriate Equipment

Equipment must be heavy and powerful enough to perform efficiently while minimizing detrimental soil disturbance. Although initial equipment choice could be based on specification sheets that provide estimates of static and loaded weights and, preferably, ground pressure (psi or MPa), operator skill and local soil conditions also strongly determine the severity of soil disturbance. Equipment and operator performance are best evaluated during and after operations and documented evaluations can improve future equipment decisions. On high-risk sites that must be harvested under adverse soil conditions (e.g., wet or moist soil), disturbance can be minimized by using aerial or cable systems. Specific suggestions concerning equipment (McColl and Grigal 1979; Miles et al. 1981; Froehlich and McNabb 1984) include

* using suspension systems to minimize compaction (e.g., arches, traces);
* using the smallest size skidder appropriate for the objective (e.g., match equipment to size of material);
* using low ground pressure (high flotation) skidders or tracked machines;
* winching logs from stump to skidder rather than traveling to the stump.

6.4 Controlling On-Site Activities

Frequent on-site visits to harvesting and site preparation operations can help insure strict adherence to soil management guidelines. Adding and maintaining a cushion of organic matter (slash and other vegetation) in trafficked areas can help reduce compaction and churning. Log corduroy or rock ballast may be needed occasionally to support equipment and avoid deep ruts or de-arranged drainage. Soil moisture can be assessed during operations by using portable, quick-reacting tensiometers [for measuring soil moisture tension (suction)] to show when soil is too moist for heavy ground-based equipment. When soil is saturated with water, the gauge on the tensiometer will indicate 0 bars (or centibars). As moisture drains or evaporates from the soil, the tensiometer measures increased tension; however, it is not possible to know if a particular suction value represents field capacity unless the moisture-release characteristics of the specific soil are known. Effective use of tensiometers to minimize soil disturbance requires understanding relationships between hydraulic properties and soil strength (e.g., Burger 1994).

After harvesting is completed, appropriate soil management may include creating water bars (cross ditches) on temporary roads and skid trails, disking or subsoiling disturbed areas where appropriate (see Section 5.0), and reforesting or revegetating (Table 6.2). The purpose of creating water bars in former skid trails or temporary roads is to ensure that surface water will not create unreasonable erosion and delivery of sediment to streams. Water bars should be spaced at sufficient frequency to allow water to be dispersing onto the forest floor before it can concentrate and flow down the trail or road surface for long distances. Water bars should not be located where natural or potential drainageways can deliver sediment directly to streams. Slope percentage and the soil's operability risk rating are further considerations for prescribing the need and depth of water bars (Table 6.2). As slope increases, water and soil particles have an increasing potential to move, and greater care is required to ensure that spacing and depth of water bars are adequate. Sowing seed on skid trails and landings can minimize erosion, and provide wildlife forage in some areas.

Table 6.2 An Example of Remedial Measures to Prevent or Ameliorate Detrimental Soil Disturbance from Ground-Based Equipment (Rubber-Tired or Tracked)

	Soil Operability Risk Rating[a]			
Priority for Remediation	Low	Moderate	High	Very High
Water bar[b]:				
<10% slope	low	low	Moderate	high
10-30% slope	low	moderate	High	very high
>30% slope	moderate	high	very high	very high
Grass seeding:				
<10% slope	low	moderate	Moderate	high
10-30% slope	low	moderate	High	high
>30% slope	moderate	high	very high	very high

[a] See Table 6.1 for description of operability risk ratings
[b] The need, interval, and depth of water bars largely depends on the local pattern of natural and artificial (created by harvest operations) drainage ways. Create water bars wherever necessary to ensure that surface water will flow across and not down skid trails.

6.5 Training and Feedback

Educate operators about the importance of desired soil conditions and about the need to follow soil management guidelines to avoid detrimental impacts on soil physical properties. By sharing results of periodic monitoring, operators will be encouraged to do the job correctly.

7.0 DISCUSSION

Heavy machinery for yarding felled trees or logs can create visible patterns of soil disturbance. Within harvested areas, trees planted on skid trails and landings are subjected to the most disturbed soil in the mosaic of soil conditions. Altered soil properties, however, do not always result in poorer tree growth (Greacen and Sands 1980; Miller, Scott, and Hazard 1996; Miller et al. 1989; Powers and Fiddler 1997). At some locations, the favorable influence of disturbance on other growth-determining factors can counter the generalization that soil compaction reduces subsequent tree and stand growth.

7.1 Growth Determining Factors and Their Interactions

Butt (1989) and Miller et al. (1989) report greater yields on the combined skid trail and associated fringe than on nearby logged-only portions of some former clearcuts regenerated to coast Douglas fir. This non-conventional outcome could occur because a) yield on skid trails and associated fringes was enhanced or b) yield on minimally disturbed control areas was reduced by factor(s) other than soil disturbance. Expressed mathematically: yield on each stratum = f (soil condition, regeneration method, vegetative competition, animal damage, microclimate, interactions, and error). Further examination of these growth factors can help explain the inconsistency of results in the literature:

1. Soil condition. The negative effects of soil disturbance on soil properties are well documented by measured increases in bulk density, implied or measured reductions in macro-pore space, measured increases in soil resistance, observed degraded soil structure, or displaced top soil. Yet, the likelihood or severity of growth impairment after soil disturbance depend on (interact with) other factors. For example, some tree species are more susceptible to soil compaction than others (Minore, Smith, and Wollard 1969; Corns 1988; Miller, Scott, and Hazard 1996; Wass and Smith 1997). Moreover, we can assume *a priori* that growth of most tree species is more limited by degraded soil conditions in stressful climates than in mesic climates.

2. Regeneration method. Trees are established from either natural or artificial regeneration. In retrospective investigations, one must assume that all strata at each location had the same frequency of seeds or planted seedlings. Subsequent survival and growth of these seeds or seedlings determine yield on each stratum. Seedlings that have been planted are probably less affected by unfavorable soil and microclimate than are germanents from either natural or artificial seeding. This implies that planted stands would be less likely to display reductions in growth and yield from soil disturbance. This speculation about the interaction of regeneration method and skid trail disturbance and its significance to ultimate stand yield has not been evaluated in either retrospective or controlled treatment studies. Planting has been preferred in recent decades to ensure prompt regeneration. Moreover, in seven side-by-side comparisons, planted stands of coast Douglas fir averaged 40% greater volume yields at age 40 than naturally regenerated stands (Miller, Bigley, and Webster 1993).

3. Vegetative competition. Early survival and growth of trees are usually reduced by associated vegetation. Where no silviculturally imposed vegetation control is used, soil disturbance can change the amount and species of competing vegetation. Consequently, tree performance on skid trails or other disturbed soil at some locations can be relatively better than that on non-disturbed portions. Depending on soil texture, local climate, and competitive species, soil

disturbance that reduces vegetative competition may mask or reverse the poorer growth generally associated with compacted soil (Powers and Fiddler 1997). At other locations, where vegetative competition is controlled or is less important to tree performance, the growth limitations imposed by degraded soil conditions are relatively more important to yield. We assume that interactions among site, climate, and vegetation help explain the inconsistency in results among published reports.

4. Animal damage. The potential interaction of animal damage and skid trail location can also confuse interpretation. To what extent does poorer seedling growth on skid trails reflect degraded soil conditions versus greater incidence or severity of animal damage? Slower initial growth on skid trails means seedlings require more years to attain a safe height from browsing. Thus, animals can affect seedling survival and growth to the extent that tree measurements will not be reliable indicators of soil conditions. With no knowledge about the relative amounts of animal damage on and off skid trails, one must assume that the influence of this factor is similar for all strata. To strengthen inferences about tree performance, researchers should either minimize animal damage or compare height and bole volume after seedlings are above browse height.

   Animal damage also complicates research design and interpretations. If uncontrolled, this source of variation reduces sensitivity of field experiments by increasing variation among replicate plots; this inflates the mean square error used to detect differences among treatments. Excluding animals from research plots, however, may be neither feasible nor desirable if these plots are to simulate operational settings. If animals have free access, one may assume that animal damage on experimental plots better reflects operational situations, but must also accept the uncertainty that treatment comparisons can either be uniformly affected or selectively biased by animal damage.

5. Climate. Site-to-site differences in stress due to moisture, temperature, or other factors also weaken generalizations about tree performance in response to disturbed soil. Trees are probably most affected by soil compaction and puddling where climatic conditions are most stressful. Differences in early survival and growth on skid trail versus non-trafficked portions also reflect the influence of microclimate. This is more significant at areas that were naturally or artificially seeded more than areas that were planted.

6. Time. Short-term investigations can be misleading. The duration of reduced growth by seedlings is uncertain because soil properties ameliorate naturally and trees eventually exploit more favorable soil conditions nearby. The extrapolation of reduced heights of tree seedlings to reduced site index and future yields is irresponsible.

In summary, the effects of heavy equipment and transported logs on soil physical properties are well documented. Effects may include degradation of the soil environment for plant growth, yet the observed consequences of soil disturbance to tree growth range from negative to positive and are not sufficiently investigated to warrant the commonly expressed generalization that soil disturbance reduces subsequent tree growth. Inferring that soil disturbance is the cause of reduced growth is often uncertain, because the direct effects of disturbance on soil properties are usually masked or even inconsequential relative to the effects of disturbance on other growth-determining factors (e.g., competing vegetation, animal browse, microclimate). Consequently, at some locations, improved tree growth (over that in undisturbed areas) can be associated with disturbed soil.

7.1.1 *Soil Depths Must Be Comparable*

Greater Db in former skid trails could be explained, in part, by discrepancies in sampling depths between disturbed and non-disturbed soils, especially where Db normally increases with soil depth. For example, Heninger et al. (2002) reported that, 4 or 5 years after harvesting, average Db in the 0-30 cm depth below ruts on non-tilled skid trails still exceeded that on tilled and non-skid trail areas.

The authors assumed that mean rut depth approximated the start of the corresponding sample depth in the pre-harvest soil profile (i.e., the 0-10 cm soil depth below a 15 cm deep rut would correspond to the 15-25 cm depth in the preharvest profile). With this assumption, Db below ruts was greater to about 40 cm deep in the original profile. Sampling depths on tilled plots were adjusted by only one-half the average rut depth to compensate for berms pushed into deep ruts prior to ripping. Results from this study highlight the uncertainty of inferring duration of increased Db on skid trails on by retrospective comparison with Db on nearby non-skid trail areas (e.g., Wert and Thomas 1981). Such comparisons are invalid if surface soil of lower Db was displaced during harvesting operations.

7.1.2 *Short-Term Observations of Tree Growth Should Not Be Extrapolated*

Effects of skid trail disturbance on height growth of seedlings may be of only short duration, perhaps until tree roots grow beyond the skid trail. In Heninger et al. (2002), annual height growth became similar between compacted and non-compacted areas after seedlings exceeded about 1.4 m in height. Furthermore, the trees averaged 5.1 years to attain breast height on non-tilled skid trials, compared to 4.4 years on tilled and logged-only areas; the lag in plantation development among the treatments may be less than one year. The authors suggest that the maximum difference in tree heights between non-tilled and logged-only plots has already occurred by age 7 or 8 after planting and that the differences will be either maintained or decrease with time. In either case, the percentage differences or loss will become smaller as the total height increases.

Differences in seedling and sapling growth are weakly indicative of differences in future stand yields. Seedlings planted in or near skid trails may show normal growth, yet their root growth could be restricted on one or more sides; this could increase susceptibility to windthrow. This speculation, however, is not supported by retrospective studies in Douglas fir stands in British Columbia (Butt 1989) and Washington and Oregon (Miller et al. 1989). In most locations, the increased volume per ha adjacent to the skid trails more than compensated for volume in the skid trail.

In western Oregon, Hansen et al. (1986) suggest that soil compaction increases the susceptibility of Douglas fir trees to black-stain fungus (*Verticicladiella wageneri*) transmitted by a root-consuming beetle (*Hylastes nigrinus*) and weevils (*Pissoides faceiatus* and *Steremmius carinatus*). Whether incidence of black-stain fungus, which kills Douglas fir, is influenced by severity of compaction or of other soil disturbance, or by soil characteristics is unknown, however.

7.2 Amelioration by Tillage

Improved tree survival and growth are the expected benefits of remedial tillage of skid trails. When interpreting results from past investigations, the following concepts should be considered:

1. As discussed earlier, tillage can change soil physical properties, and concurrently change other factors that affect tree performance (i.e., vegetative type and cover percentage, soil temperature and moisture regimes). These changes affect tree growth directly and indirectly through soil processes like decomposition, nutrient cycling, and losses from leaching and volatilization.
2. As documented in Sections 5.1 and 5.2, the benefits of remedial tillage to tree performance can be expected to be small where a) soil compaction or puddling minimally reduced tree performance (Miller, Scott, and Hazard 1996); b) tillage affects only a small portion of the potential rooting volume (McNabb and Hobbs 1989); and (3) other growth-determining factors are favorable (careful planting of vigorous stock, mesic climate, minimal competing vegetation). Conversely, the benefits of remedial tillage to tree performance can be expected to be large where soil disturbance strongly reduced tree performance (Heninger et al. 2002) and when tillage strongly reduces cover of competing vegetation.

8.0 RESEARCH AND INFORMATION NEEDS

Based on the content of this review, the following research and information needs have been identified:

- Improve the capability to predict tree growth response to soil disturbance and identify degrees of risk to soil properties, soil functions, and vegetation across important site types.
- Develop better means of assessing site disturbance.
- Establish long-term studies across different site types and controlled studies that can be used to evaluate the effects of disturbance and ameliorative treatments across an entire rotation.
- Improve assessments of disturbance effects on vegetative composition and other secondary factors influencing productivity and forest health.
- Assess root responses of important tree species to different types of disturbance.
- Improve information on the spatial effects of disturbance on root distribution and tree growth.
- Develop models capable of integrating tree root growth response with water supply and nutrient uptake in disturbed soils.
- Develop economic (e.g., cost-benefit) analyses of disturbance effects on stand productivity and remediation measures.

9.0 CONCLUSIONS

1. Risk of soil disturbance and site degradation exists whenever ground-based equipment is used in forest operations. Compaction is one type of soil disturbance; churning, mixing, and displacement are other types. Failure to recognize this distinction has led some observers to ascribe changes in soil properties and tree performance to compaction when, in fact, other types of disturbance were involved and were probably more influential. For example, displacement or removal of organic- and nutrient-rich surface soil can detrimentally affect physical, chemical, and biological properties and processes, especially on juvenile soils that characteristically have thin A-horizons. Moreover, this removal or displacement exposes deeper soil, which usually has greater bulk density and soil strength. Consequently, greater bulk density in former skid trails could be explained, in part, because soil is sampled lower in the original profile where bulk density is inherently greater.
2. Negative effects of soil disturbance on soil properties are well documented in both forestry and agricultural literature. Most of the available research on root growth, however, relates to agricultural crops under carefully controlled laboratory and greenhouse conditions. In contrast, trees are long-lived and have great capacity to adapt to restrictive soil conditions through both morphological and distributional changes in their root system. This adaptive capacity limits our ability to predict how trees will respond to soil compaction under field conditions. Tree root growth is greatest at soil water contents near field capacity. In drier soil, root growth is restricted by increased soil strength and low water availability. At water contents above field capacity, lower gas diffusion rates can lead to inadequate oxygen supply. Soil disturbance can exacerbate existing factors restricting root growth under both dry and wet soil conditions. In most soils, compaction reduces subsequent root growth under all moisture conditions in direct proportion to the degree of compaction. Short-term reductions in root growth of 30 to 50% are common on soils compacted to 30% or more of their initial bulk density. The long-term effects

of compaction, however, will depend on whether reduced root growth is associated with a) an overall reduction in rootable soil volume and quality or b) simply a slower rate at which the original pre-disturbance rooting volume is exploited. In thinning or partial cutting operations, soil compaction near and severed roots of residual trees add further risks to stand yields.

3. Some soils are more resilient to physical impact than are other soils, and corrective treatment is not needed. Compaction of some coarse-textured soils can actually improve moisture relations for tree growth. Loamy soils are more susceptible to compaction; clayey soils are more susceptible to rutting and churning.

4. The likelihood or severity of growth impairment from soil disturbance should not be generalized because the consequences of soil disturbance depend on (or interact with) other site-specific growth-determining factors. Hence, the consequences for tree growth are site-specific. In most reports, short-term growth of seedlings or saplings on skid trails is less than on adjacent non-skid trail areas; this may or may not reduce ultimate stand yield. Inferring that soil disturbance is the cause of reduced growth is often uncertain, because the direct effects of disturbance on soil properties can be masked or inconsequential relative to the effects of disturbance on other growth-determining factors, especially competing vegetation. Soil disturbance at some locations can enhance seedling growth by controlling competing vegetation. Consequently, at some study sites improved tree growth (over that in undisturbed portions) has been associated with disturbed soil.

5. Severity and areal extent of disturbed soil (compacted, churned, rutted, or displaced) from tracked and wheeled vehicles can be minimized by a) identifying risks at the project area; b) planning operations, layout, and equipment appropriately; c) scheduling and controlling activities to accommodate identified risks; and d) training and communicating feedback during operations to increase operator awareness.

6. The period of time for natural recovery from compaction varies with soil physical characteristics, chemical characteristics, climate, and the severity of compaction. Recovery may be faster where soils are subjected to freezing-thawing or wetting-drying cycles. In the absence of site-specific information, the effects of compaction on forest soils may be assumed to persist for several decades.

7. Rehabilitation of compacted soil can be attempted by mechanical manipulation, such as disk harrowing, bedding or mounding, subsoiling or ripping, and spot cultivation. If properly applied, these tillage practices can favorably alter soil properties and enhance seedling survival and growth. Tillage under non-optimum conditions (e.g., wet soil), however, can cause additional soil compaction and/or puddling and create further risk to long-term productivity.

8. Consequences of most current practices need evaluation and research. Smaller trees are being harvested; felling, delimbing, and bucking are accomplished by machines; and yarding by forwarders and tracked shovels. The pattern of soil disturbance is shifting from a dendritic pattern of clearly defined skid trails to that of a less well-defined pattern of lighter but more widely distributed disturbance. This shift to a diffuse pattern and more variable intensity of soil disturbance will require innovative procedures to quantify soil disturbance and its subsequent consequences to stand yields. Moreover, the increase in commercial thinning and partial cutting adds more risk to residual trees when roots are severed or nearby soil is compacted.

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