**JAAKKO PÖYRY**
**JAAKKO PÖYRY CONSULTING, INC.**

A. R. EK

# Forest Soils

## A Technical Paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota

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Prepared for:

Minnesota Environmental Quality Board
658 Cedar Street
St. Paul, Minnesota 55155

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October 16, 1992

Dr. Michael Kilgore
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Dear Dr. Kilgore:

Pursuant to the State of Minnesota's GEIS contract (No. 30000-18408-01) with Jaakko Pöyry Consulting, Inc., as formally executed on May 15, 1991, and amended with Supplement No. 1 on July 10, 1991, and Supplement No. 2 on July 27, 1992, the sixth task included preparation of technical papers. One of these papers, Forest Soils, is hereby submitted for review and approval.

The material contained in this document is presented in accordance with the terms outlined in Attachment A to the base contract, Section III, Subsection F.

We look forward to a favorable review and approval of this work product in due course.

Respectfully yours,

James A. McNutt

James A. McNutt
Executive Vice President
and GEIS Project Manager

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## SUMMARY

This Technical Paper assesses the impact of timber harvesting and forest management on forest soil properties, including nutrient status and physical properties. The latter properties are affected by soil compaction and erosion. The timber harvesting scenarios that were developed from the forest planning model were evaluated in terms of their impact on soil properties. This evaluation was carried out by dividing the state into seven ecoregions, and considering the harvest of seven forest types on seven soil groups (49 combinations) in each ecoregion. Separate analyses were conducted for impacts on nutrient loss, soil compaction and puddling, and soil erosion.

A significant impact on nutrient cycling, an impact that merits further consideration, was considered to occur when the nutrient removal associated with the harvest exceeded the natural rate of nutrient replenishment on that site over the length of the rotation. The principal evaluation was based on harvest removal of the merchantable bole, or the wood plus bark to a three inch top. Another secondary evaluation of nutrient loss, also considering the seven forest types and seven soils, was based on three different levels of utilization; the merchantable bole, the full-tree including branches and leaves, and bole-only, defined as the merchantable bole wood *without* the bark. This comparison of levels of utilization dealt with the entire state as a whole, and did not segregate the data by ecoregion.

The assessment indicated that current or base levels of forest harvesting are ***mining*** some forest sites; that is, they are removing nutrients at a greater rate than natural replenishment. Over a fifty-year period at the curretn (base) rate of harvest of merchantable bole, potassium is being removed at rates greater than those of natural replenishment on about 1.5 million acres, calcium on about five million acres, and magnesium on about 2.5 million acres. Removal of nitrogen and phosphorus do not exceed natural rates of replacement. The majority of the area affected is associated with harvest of aspen-birch. Coarse-textured (sandy) and organic soils are most commonly affected, but significant areas where calcium loss exceeds replenishment also include some medium-textured soils.

At the highest harvesting scenario, areas where nutrients are being mined increase by about 0.5 million acres for potassium, two million acres for calcium, and 1.2 million acres for magnesium. Most of the increase associated with potassium loss is aspen-birch on coarse or organic soils; calcium losses increase with many forest type/soil combinations, but over 25 percent of the increase in area occurs with harvest of upland hardwoods. Increased areas affected by magnesium loss are especially associated with spruce-fir harvest on both mineral and organic soils.

In any harvest scenario, increasing the intensity of utilization from removal of only the merchantable bole (plus bark) to removal of the full-tree nearly triples the area affected by both potassium and magnesium loss. When removal of merchantable bole is compared to removal of full-tree, differences in area affected by calcium loss are not large. This is because a large proportion of the calcium in a tree is in the bark. Harvest of bole-only, or wood without bark, decreases the area affected by calcium loss by over six million acres over the 50-year planning horizon. Such a harvest also decreases the area associated with potassium and magnesium loss, but this is a much smaller area than that affected by calcium loss.

The initial nutrient capital of a site (i.e., the nutrients stored in the soil) should also be considered when nutrient removal is assessed. Although the criterion for a significant impact is not influenced by the initial nutrient capital of a site, that capital affects the degree of nutrient depletion at a site over a rotation. Although a site may irreversibly lose nutrients, the amount may be a small proportion of the nutrients that are present on a site with high initial capital. In that case, the mining may be considered to be relatively insignificant and therefore economically and biologically justifiable. Sites with low capital will be more heavily impacted by equivalent amounts of nutrient removal without replenishment. Impacts will be increasingly severe as the nutrient capital of a site is depleted over many rotations.

Impacts of the harvest scenarios under the second model run were not appreciably different than those from the initial run. The model did not explicitly deal with different levels of utilization, nor with altering rotation lengths in relation to soil properties, and hence the areas at risk for nutrient loss remained nearly the same.

A variety of mitigation measures can be followed to minimize the impacts of nutrient loss associated with harvesting. One of the most effective measures to minimize nutrient loss is to retain as much material as possible on the site. Leaving the slash at the stump is partially effective, and should be preferred over full-tree harvesting in nearly all cases. Harvesting techniques that retain the bark at the stump, so that only the wood is removed from the site, are probably the most effective strategies for retaining nutrients.

Soil compaction and related disturbances were evaluated based on site sensitivity and equipment configuration. Three levels of site sensitivity (low, medium, and high) were defined using soil texture, soil drainage class, and season. Analyses were conducted for hand felling and mechanical felling operations. Significance criteria were established based on the percent of a site impacted. Impact thresholds were 5 percent of the site for highly sensitive sites, 10 percent of the site for moderately sensitive sites, and 20 percent of the site for sites with low sensitivity. Haul road area was considered separately from the actual harvest unit. All areas occupied by haul roads were significantly impacted.

Under the base scenario it was estimated that significance criteria for soil compaction would be exceeded on sites representing about 840,000 ac. This area would increase to about 1,050,000 and 1,240,000 ac under the medium and high scenarios, respectively. In each case, this represents about 13 percent of the total area harvested. All additional area occupied by forest roads would be significantly impacted.

The amount of compaction and related disturbances were largely a function of season and soil type. Significance criteria were rarely exceeded for winter operations while spring operations exceeded the criteria on all soils except for well-drained, coarse-textured soils. Poorly-drained, fine-textured soils were generally the most sensitive, followed by poorly-drained medium-textured soils, well-drained fine-textured soils, well-drained medium-textured soils, and coarse-textured soils.

Limiting operations to periods of adequate soil strength, concentrating equipment trafficking, and development of long-term transportation plans are the preferred mitigation strategies. These are all potentially feasible under current conditions, though they would require the commitment of additional resources to planning and management. They would effectively reduce compaction and related disturbances.

Soil erosion was evaluated using a version of the Unified Soil Loss Equation that was modified for use in forested areas. Erosion was considered significant if it occurred at a rate greater than the soil loss tolerance value (T value) as defined by the Soil Conservation Service.

It was estimated that timber harvesting and forest management activities would lead to erosion rates greater than T-values only in some skid trails and haul roads. On a statewide basis, the significance criteria were exceeded on less than one percent of the area harvested. The erosion risk is greatest in southeastern Minnesota, which has the steepest slopes and the highest rainfall intensity.

Proper road engineering, revegetating bare soil areas, and closing temporary roads after harvest are the preferred mitigation strategies. These activities would reduce soil erosion along forest roads and major skid trails which are the predominant source of erosion problems caused by forest management activities. The additional expense incurred in implementing these measures would lead to important and long-term reductions in erosion problems.

## TABLE OF CONTENTS

## TABLE OF CONTENTS (continued)

## TABLE OF CONTENTS (continued)

## LIST OF FIGURES

## LIST OF FIGURES (continued)

## LIST OF FIGURES (continued)

## LIST OF TABLES

## LIST OF TABLES (continued)

## LIST OF TABLES (continued)

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# 1
# INTRODUCTION

The objectives of this Technical Paper are to assess the impact of timber harvesting and forest management activities on forest soils. The specific objectives have been defined as (Environmental Quality Board 1990):

> *Forest Soils. Forest soils are a fundamental resource on which rests the ability of forests to provide a wide variety of benefits. Considering previously specified timber harvesting levels and looking at timber harvesting and management activities statewide:*
>
> 1. *To what extent does soil erosion occur as a result of timber harvesting, and how does this rate of erosion compare with forest soil erosion rates in undisturbed forests? What specific timber harvesting and management activities are major contributors to the erosion of forest soils?*
>
> 2. *To what extent do timber harvesting and management (e.g., short cycle rotations) activities impact nutrient cycling and the productivity of forest soils? To what extent do specific management and timber harvesting practices impact the productivity of forest soils?*
>
> 3. *To what extent do timber harvesting and management activities impact the compaction of forest soils? To what extent does soil compaction impact forest productivity and the growth of forest plants?*
>
> 4. *To what extent does the time of year in which timber harvesting occurs impact forest soil productivity and the success of forest regeneration?*

These issues were analyzed from three distinct levels of statewide timber harvesting activity that depict the full range of possible harvest levels. These levels were described in the FSD. The base scenario (4.0 million cords/annum) describes current levels of harvesting. The medium scenario (4.9 million cords/annum) represents the level of harvest if all planned industrial developments take place. The high scenaro (7 million cords/annum) describes the theoretically maximum level of sustained harevst.

Maintenance of site productivity is a key to sustainable forest management. Therefore, identifying and reducing impacts on forest soils will be an essential part of any strategy to achieve sustainable forest management. Adverse impacts on soil resources are strongly linked to the other issue areas. Eroded soil affects water quality, aquatic ecosystems and water-based recreational and tourist uses. A decrease in site productivity could affect wildlife populations and ultimately the level of harvesting the forest can sustain.

Soil plays an important role in forest growth and management. It provides moisture and nutrients for tree growth, serves as the medium for root growth, and provides the physical support for the equipment used in harvesting, yarding, and other operations. Forest management activities can have a diverse impact on soil properties, and these in turn affect forest productivity. Nutrient depletion reduces soil fertility, directly affecting tree growth. Soil compaction and associated disturbances reduce and disrupt soil porosity, thereby restricting water and air movement into and through the soil. This results in poor soil aeration, which negatively affects plant root growth and the activity of soil organisms responsible for nutrient cycling and other processes. Compaction also increases soil resistance to root penetration, thus limiting the volume of soil available for root exploitation. Accelerated soil erosion leads to the removal of surface soil material and increased sedimentation of surface waters. Surface soil is particularly important to forest growth because it contains a disproportionate amount of soil nutrients.

The harvesting scenarios that were developed from the forest planning model were evaluated in terms of their impact on soil properties. Possible mitigation strategies to reduce some of the potential impacts of the harvesting are suggested and discussed.

Throughout this paper, three definitions will be used when discussing removal of material with forest harvest. This removal is especially important when considering effects of forest harvest on nutrient status. Consistent with the overall GEIS document, ***full-tree*** harvest is defined as removal of the entire tree biomass above the stump, including bole, branches, bark, and foliage. For purposes of this paper, ***merchantable bole*** harvest refers to removal of the bole and associated bark to a three-inch top diameter. The form in which this material is removed, whether as roundwood, as bolts, or as long-length, is immaterial to the discussion in this paper. Finally, ***bole-only*** harvest refers to the removal of the bole to the three-inch top, but ***without*** the bark. Although not common, this practice can reduce nutrient removal from a site and hence is discussed in the paper.

## 2
## EXISTING ENVIRONMENT

### 2.1
### Nutrient Cycling

Trees, as do all plants, require appropriate combinations of resources in order for them to grow. Within limits, the greater the amount of resources that are available, the greater the growth and productivity of the forest. Resources that a tree (or any plant) needs for growth include energy from solar radiation, water, and nutrients. Those resources are listed in descending order of control by management; man has little control over solar radiation, some control over water through irrigation, and substantial control over nutrients by either removal or replacement (i.e., fertilization). The objective of this portion of the report is to consider *nutrients*, including a definition, a discussion of their behavior in forest ecosystems, and the influence of forest management on that behavior. The central perspective of this review is the influence of forest harvesting on quantity of nutrients, and the potential for depletion of that quantity. Although quantitative relationships between amounts of nutrients on a site and the productivity of that site are very limited, an attempt will be made to discuss the relationship between the absolute amount of nutrients, their availability, and the effect of that availability on forest productivity.

This paper will not be a comprehensive review of nutrients in forests. Many review papers and books thoroughly consider that topic. An example of such a text is Binkley (1986), who devotes nearly 300 pages to *Forest Nutrition Management*. This paper will provide an overview of nutrients in forests, with a strong focus on conditions and available data from Minnesota.

### 2.1.1
### Definition

The Periodic Table of Elements includes 103 elements, or regular assemblages of neutrons, protons, and electrons, that form the building blocks for matter. Of those 103 elements, 17 have been identified as being required by plants for them to grow (Brady 1984). These essential elements are termed nutrients. Although by definition all of these 17 elements are essential, the amounts that are required vary widely. Carbon (C), for example, constitutes approximately 50 percent of dry plant material, while molybdenum (Mo) may constitute only about 0.00001 percent; less than 2 ounces of Mo occurs in each million pounds of plant material.

As a result of these wide differences in amounts, nutrients are considered to fall into one of three groups. The first group contains C, oxygen (O), and hydrogen (H). These nutrients are readily obtained from the atmosphere as either gases ($CO_2$ and water vapor—$H_2O$) or as liquid water. A second group of nutrients are termed macronutrients, and includes nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). They constitute from about 1 to 2 percent of plant material in the case of N to 0.05 percent in the cases of P and S. Micronutrients include iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), chloride (Cl), cobalt (Co), and Mo (Brady 1984). They occur in very small quantities in plants, usually less than about 0.01 percent of plant material.

The nutrients that are directly supplied by the atmosphere; C, H, and O; are usually not considered to be limiting to plant growth because they are so readily available. Conversely, micronutrients are needed in such small quantities that they rarely limit forest growth; limitations only occur under special conditions (Binkley 1986). Macronutrients, however, are more problematic. Relatively high demand by plants for them coupled with potentially low availabilities can lead to deficiencies, where insufficient quantities are available for plant growth.

A very brief explanation of the role of each macronutrient in plant processes can be largely abstracted from the discussion in a recent Swedish report (Andersson and Persson 1988). Nitrogen is part of all amino acids and proteins, and is essential for nearly every physiological process in plants. Phosphorus is a component of nucleic acids and in compounds such as ATP that are involved in energy transfer. Potassium is important for cell plasma, and is involved in enzyme activation. Calcium is an important constituent of cell membranes. Magnesium is a key part of the chlorophyll molecule, and activates enzymes during phosphorylation or energy transfer. Finally, sulfur also occurs in and is an essential part of some amino acids and proteins.

In the case of agricultural crops, cultivation and harvest have often depleted the available pool of these macronutrients and fertilization is a routine practice to restore that pool. Fertilizers are commonly labeled with three numbers, such as 10-10-10. These numbers refer to the relative amounts of N, P, and K, respectively, in that fertilizer. Liming, another common agricultural practice, not only raises the pH or *sweetens* the soil, but it also adds Ca and Mg. Under current conditions, rainfall delivers sufficient quantities of S to crops so that deficiencies rarely result.

Using agricultural experience as a guide, a potential may exist for deficiencies of N, P, K, Ca, and Mg to occur in forest systems. In agriculture, deficiencies have arisen when the rate of nutrient removal via harvest has exceeded the reserves in the soil and the annual replenishment through natural processes. Forest harvesting also has the *potential* to create nutrient deficiencies through removal of nutrients. Whether or not that potential is likely to be realized is the focus of this paper. Before a detailed discussion of that question can be begun, a general discussion of the behavior of nutrients in forests, termed nutrient cycling, will be presented.

The term *nutrient cycling* is appropriate, because nutrient elements move through forest ecosystems, passing from one component to the other, with varying residence times within each component. The cycle is not closed, however, and nutrients continuously enter and leave the system. The magnitude of nutrients entering or leaving is usually a small fraction of that present within the system.

### 2.1.2 Inputs

There are three sources of additions of nutrients to forest ecosystems: the atmosphere, the geologic substrate, and management practices (fertilization).

**Atmospheric Inputs**
The atmosphere is a continual source of nutrients to forests. Every rain or snowfall brings with it dissolved nutrients, and between these events solid and liquid aerosols and gases are continuously being deposited. This material deposited during dry periods, or *dry deposition*, includes what is commonly termed dust. Neither wet nor dry deposition contributes large amounts of nutrients to forests on an annual basis, but over the life-span of a tree, or the rotation length of a forest stand, the amount of nutrients derived from the atmosphere can be significant.

**Deposition**
*Wet Deposition.* Concentrations of macronutrients in precipitation in Minnesota are low. The Minnesota Pollution Control Agency (MPCA) maintains a network of five monitoring stations in the eastern (forested) portion of the state, at Birch Lake on the Gunflint Trail, at Cedar Creek Natural History Area near East Bethel, at Finland, near Sandstone, and at Voyageurs National Park. Based on the data collected during 1990 (MPCA 1991a) average concentration of nutrients in precipitation was 0.44 parts per million (ppm) N, 0.03 ppm K, 0.24 ppm Ca, and 0.03 ppm Mg. Phosphorus concentrations are so low that they are not routinely monitored, but a compilation of data from monitoring throughout the north central region (Tabatabai 1981) indicates an average concentration of about 0.04 ppm for stations in Minnesota, Wisconsin, and Michigan. When multiplied by the average amount of precipitation received at the MPCA stations in 1990 (29.5 inches), the annual deposition of nutrients ranged from 0.2 lbs per acre for K and Mg to 0.3 lbs per acre for P to 1.6 lbs per acre for Ca to 3.0 lbs per acre for N.

Concentrations of nutrients in precipitation vary across the state (MPCA 1991b), as does the amount of precipitation (Baker et al. 1979), and thus the total annual wet deposition of nutrients also varies. Multiple regression equations, using latitude and longitude of measurement stations as independent variables, can be used to estimate the concentration of elements in precipitation. Such equations, developed from monitoring data from Minnesota, Michigan, and Wisconsin (NADP 1986-90; MPCA 1991b), explain from 76 percent of the variation in concentration of nitrate-N to less than 10 percent of the variation in K (table 2.1). In the latter case, the relatively low explanation of variation indicates that a simple mean value for estimating concentration is nearly as good as a spatially varying value. When these relationships are combined with the variation in annual precipitation from some selected locations across the forested portions of

Minnesota, annual wet deposition of K and N ranges about 1.5 times from Baudette to Caledonia (table 2.2) to almost twofold for Ca (0.99 and 1.92 lb $ac^{-1}yr^{-1}$) to about 10-fold for Mg (0.01 to 0.1 lb $ac^{-1}yr^{-1}$ at Baudette and Caledonia, respectively) (table 2.2). The deposition for the midpoint of the forested area of the state, or for the mean of the selected stations, is about 1.5 lb $ac^{-1}yr^{-1}$ of Ca, 0.1 lb $ac^{-1}yr^{-1}$ of Mg, 0.3 lb $ac^{-1}yr^{-1}$ of K, 4.3 lb $ac^{-1}yr^{-1}$ of N, and 0.2 lb $ac^{-1}yr^{-1}$ of P (table 2.2).

**Table 2.1. Relationship of concentration of nutrients in precipitation to latitude and longitude of location. Data from NADP and MPCA monitoring for Michigan, Minnesota, and Wisconsin for 1985 through 1989. Equations of the form Y (mg/L) = b0 + b1*latitude + b2*longitude, where b0 is pooled from categorical variables specific for each year.**

| Element | b0 | b1 | b2 | n | $R^2$ | $S_{y.x}$ |
|---|---|---|---|---|---|---|
| Calcium | 0.465 | -0.023 | 0.009 | 72 | 0.58 | 0.047 |
| Magnesium | 0.200 | -0.006 | 0.001 | 72 | 0.58 | 0.009 |
| Potassium | -0.043 | -0.002 | 0.002 | 72 | 0.09 | 0.017 |
| Sodium | 0.248 | -0.003 | 0 | 72 | 0.31 | 0.016 |
| Ammonium-N | 0.094 | -0.028 | 0.017 | 63 | 0.42 | 0.074 |
| Nitrate-N | 2.134 | -0.025 | 0.007 | 62 | 0.76 | 0.035 |

**Table 2.2. Predicted wet elemental deposition at selected Minnesota locations based on relationships in table 2.1 and on normal precipitation for the period 1941–70.**

| Location | Lat. | Long. | Pcp. | Deposition | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Ca | Mg | K | Na | N | P |
| | (o) | (o) | (in.) | (lb/ac/yr) | | | | | |
| Baudette | 49 | 95 | 23 | 0.99 | 0.01 | 0.25 | 0.52 | 3.00 | 0.20 |
| Bemidji | 48 | 95 | 24 | 1.24 | 0.05 | 0.28 | 0.57 | 3.59 | 0.22 |
| Brainerd | 46 | 94 | 26 | 1.47 | 0.10 | 0.31 | 0.64 | 4.23 | 0.24 |
| Caledonia | 44 | 92 | 30 | 1.92 | 0.20 | 0.36 | 0.79 | 5.59 | 0.27 |
| Cloquet | 47 | 93 | 30 | 1.51 | 0.08 | 0.33 | 0.73 | 4.58 | 0.27 |
| Grand Marais | 48 | 90 | 27 | 1.08 | 0.02 | 0.25 | 0.63 | 3.61 | 0.24 |
| Int'l Falls | 49 | 94 | 26 | 1.11 | 0.01 | 0.27 | 0.59 | 3.43 | 0.23 |
| Milaca | 46 | 94 | 27 | 1.57 | 0.12 | 0.32 | 0.68 | 4.52 | 0.24 |
| Rochester | 44 | 93 | 28 | 1.78 | 0.18 | 0.34 | 0.72 | 5.11 | 0.25 |
| Avg. of above | 47 | 93 | 27 | 1.40 | 0.09 | 0.30 | 0.65 | 4.19 | 0.24 |
| Midpoint of Minnesota | 47 | 94 | 27 | 1.48 | 0.09 | 0.32 | 0.66 | 4.30 | 0.24 |

*Dry deposition.* Dry deposition, including solid particles, liquid aerosols, and gases, is much more difficult to measure than is wet deposition (Dasch 1985, Cadle et al. 1985, Lindberg et al. 1986). The concentration of the material in the air, the characteristics of the receiving surface (e.g., is it wet or dry; smooth or hairy; vertical or horizontal; etc.?), and the speed and direction of air movement through the forest must all be measured simultaneously to make a precise estimate of dry deposition. However, each of these variables are continuously changing, often many times within a minute. Such measurements can only be attempted at a very few well-instrumented sites. In lieu of those measures, various techniques have been used to estimate dry deposition, from computations based on both wetfall and throughfall (e.g., Ulrich 1983) to precisely measuring concentrations of material in air and using generalized deposition velocities to calculate deposition (e.g., MPCA 1991b).

Using the best available technology, dry deposition has recently been measured at 11 forest sites in the United States, with an additional site in Norway (Johnson and Lindberg 1991). If attention is focused on low elevation, inland forest sites, excluding two mountainous sites that were often immersed in clouds and two near-coast sites in western Washington, the ratio of dry deposition to wet deposition is surprisingly uniform. The annual dry deposition of base cations (Ca, Mg, K, and Na) was nearly equal to that from wet deposition, with an overall ratio of 1.02. In the case of N, a regression estimating total (wet plus dry) deposition on the basis of wet deposition yielded an $r^2$=0.9, with a intercept that was not different than 0 and a slope of 2.1. A reasonable estimate of total deposition of nutrients to forests of Minnesota is therefore twice the wet deposition; dry deposition is approximately equal to wet deposition. The wet deposition calculated in table 2.2 can be doubled to estimate total deposition of nutrients. The total atmospheric deposition (table 2.3) can thus be placed in the context of other components of the nutrient cycle.

### Biological Fixation

Another source of nutrient input from the atmosphere is by biological fixation, wherein $N_2$ gas in the atmosphere is converted to a biologically available form. All nutrients are supplied to forest systems from wet and dry deposition, and P, Ca, Mg, and K are also made available for plant growth by weathering of primary minerals. This process will be described below. However, N is nearly absent in primary minerals, and although some N compounds may occur in sedimentary rocks, release of N by weathering is usually not considered to be a significant source to forests.

In a recent review, Boring et al. (1988) assessed the importance of the various sources of N to forested ecosystems. There are three main classes of organisms that are involved in biological fixation of N. The most widely studied system of N fixation is that of *Rhizobium* and *Bradyrhizobium*

**Table 2.3.** Examples of estimated inputs and outputs of nutrients to forest systems in Minnesota in the absence of timber harvesting or other disturbance.

| Location/ Soil | Source | Nutrient Element | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ca | Mg | K | Na | N | P |
| | | (lb/ac/yr) | | | | | |
| NW Minnesota/ coarse-texture | Inputs: | | | | | | |
| | Atmosphere[a] | 2.0 | 0.1 | 0.5 | 1.0 | 6.0 | 0.4 |
| | Weathering | 3.7 | 2.0 | 1.9 | 1.7 | 0 | 0.6 |
| | Biological fix. | | | | | 2.0 | |
| | Output: | | | | | | |
| | Leaching[b] | 3.7 | 1.3 | 0.8 | 1.8 | 0.2 | 0.1 |
| | Balance | +2.0 | +0.8 | +0.6 | +1.1 | +7.8 | +0.9 |
| NC Minnesota/ medium-texture | Inputs: | | | | | | |
| | Atmosphere[a] | 3.1 | 0.2 | 0.6 | 1.4 | 9.0 | 0.5 |
| | Weathering | 13.0 | 6.0 | 4.6 | 7.2 | 0 | 0.6 |
| | Biological fix. | | | | | 2.0 | |
| | Output: | | | | | | |
| | Leaching[c] | 11.4 | 3.2 | 2.1 | 4.1 | 0.2 | 0.2 |
| | Balance | +4.7 | +3.0 | +3.1 | +4.5 | +10.8 | +0.9 |
| NE Minnesota/ fine-texture | Inputs: | | | | | | |
| | Atmosphere[a] | 2.6 | 0.1 | 0.6 | 1.4 | 8.2 | 0.5 |
| | Weathering | 32.0 | 7.6 | 4.0 | 9.2 | 0 | 0.6 |
| | Biological fix. | | | | | 2.0 | |
| | Output: | | | | | | |
| | Leaching[d] | 33.7 | 12.5 | 2.4 | 4.0 | 0.3 | 0.2 |
| | Balance | +0.9 | -4.8 | +2.2 | +6.6 | +9.9 | +0.9 |

[a] Assuming dry deposition equals wet deposition.
[b] Assuming 6 inches of runoff (leaching) per year.
[c] Assuming 8 inches of runoff per year.
[d] Assuming 12 inches of runoff per year.

bacteria; in order to fix nitrogen they must be associated with legumes such as beans. In Minnesota, few forest plants are legumes; black locust is the only legume tree that occurs in Minnesota and it is rare. Another N-fixing association involves *Frankia*, an actinomycete that fixes nitrogen in association with a wide range of woody species. Some of the species that fix nitrogen with *Frankia* in Minnesota include tag alder (*Alnus rugosa*), green alder (*Alnus crispa*), and sweetfern (*Comptonia peregrina*). Data from other locations indicate that large quantities of nitrogen can be fixed by this process. In general, the greatest rate of biological $N_2$ fixation occurs early in succession, and may supply 9 to 140 lb N $ac^{-1}yr^{-1}$ (Boring et al. 1988). Simply the presence of the appropriate species do not ensure high rates of $N_2$ fixation; good growing conditions for those plants are also necessary. In early succession, the $N_2$-fixing higher plants have a competition-free and resource-rich environment in which to grow. In Minnesota, however, N-fixing species either occur in the understory and must compete for resources with overstory trees, or occupy sites for a short time early in secondary succession following harvest or other disturbance.

Early successional conditions only occur for a short time, and may not occur following every forest harvest. As a result, N additions during succession are not important in any long-term assessment of the N economy of forests. In contrast, a third class of organisms that are involved in biological fixation of $N_2$ are some free-living microorganisms; they do not require a symbiotic relationship with a higher plant. This nonsymbiotic $N_2$ fixation is spatially and temporally variable, and usually occurs at low rates. In their summary, Boring et al. (1988) consider inputs via nonsymbiotic fixation to range from less than 1 to about 5 lb N $ac^{-1}yr^{-1}$. Although this is a low rate, the continuity of this input over the entire rotation makes it an important source of N. For purposes of assessment of the nutrient economy of Minnesota forests, a value of 2 lb $ac^{-1}yr^{-1}$ of nonsymbiotic $N_2$ fixation can be assumed (table 2.3).

### Geologic Inputs

Although roots of trees and other plants are intimately intertwined with soil particles, not all of the nutrient elements within those particles are equally available to plants. Nutrients that are in solution, or are chemically combined with only weak chemical bonds with soil materials, are available for use by plants. Many nutrients, however, are tightly bound in chemical compounds within primary and, in some cases, secondary minerals in the soil. These minerals must be broken down, or *weathered*, before the nutrients that they contain become available to plants.

Rates of weathering of most minerals are slow, and their contributions to the nutrient cycle are small. Yet, as in the case with nutrient inputs via atmospheric deposition, even small rates of inputs from weathering can be significant when considered over the length of the forest rotation.

The results of many weathering studies have been summarized in review papers (Kimmins et al. 1985, Freedman 1981, White et al. 1988). Even when restricted to humid temperate forest areas, a compilation of those summaries and of other reports in the literature offer a wide range of rates (table 2.4). The data in the table are ranked by rate of Ca release, although they could be ranked by other attributes. Rates of weathering range over more than two orders of magnitude for Na, about two orders of magnitude for Ca and K, and 1.5 orders of magnitude for Mg. Variation in rates is related to mineral composition, climate as it influences both temperature and hydrology, and a myriad of other poorly understood factors, such as presence of organic ligands.

Table 2.4. Estimated weathering rates of primary minerals based on field studies in humid temperate forested areas.

| Location | Parent Material | Vegetation | Rates | | | | | Ref. |
|---|---|---|---|---|---|---|---|---|
| | | | P | Ca | Mg | K | Na | |
| | | | (lb/ac/yr) | | | | | |
| Oregon | andesitic tuffs | conifer | 0.2 | 107 | 6.4 | 4.2 | 42 | a |
| California | dolomite | conifer | | 77 | 46 | 3.6 | 1.8 | b |
| Oregon | tuffs-breccias | conifer | | 42 | 10 | 1.4 | 25 | c |
| Br.Col. | plutonic | conifer | 0.3 | 31 | 5.9 | 1.5 | | d |
| Idaho | plagioclase-K-feldspar | conifer | | 23 | 8.9 | 20 | 46 | e |
| New York | glacial outwash | mixed | | 22 | 7.4 | 9.8 | 6.1 | f |
| Wisconsin | glacial outwash | mixed | | 20 | 4.5 | 6.1 | | g |
| New Hampshire | quartz-plagioclase-biotite | mixed | | 19 | 3.1 | 6.3 | 5.2 | h |
| Scotland | | | | 18 | 5.3 | 1.1 | 2.0 | i |
| Geometric Mean top 1/3 | | | 0.2 | 32 | 7.6 | 4.0 | 9.2 | |
| Idaho | quartz monzonite | | | 18 | 2.1 | 3.8 | 12 | j |
| Czechoslovakia | biotite gneiss | | | 17 | 12 | 20 | 12 | k |
| Australia | dacite | broadleaf | 2.4 | 17 | 7.5 | 19 | 15 | l |
| Idaho | plagioclase | | | 16 | | | 11 | m |
| Scotland | | | | 15 | 4.7 | 2.1 | 9.0 | i |
| California | adamellite | conifer | | 15 | 1.8 | 7.1 | 0.9 | b |
| Maryland | metabasaltic | | | 11 | 14 | 0.00 | 6.50 | n |
| Luxembourg | metashale | broadleaf | 7.7 | 14 | 0.2 | 8.1 | | o |
| Czechoslovakia | quartzitic gneiss | | | 7.6 | 5.6 | 12 | 5.3 | k |
| Geometric Mean mid 1/3 | | | 2.4 | 13 | 6.0 | 4.6 | 7.2 | |
| Virginia | granite | | | 7.0 | 2.3 | 1.2 | 22 | p |
| Wisconsin | glacial till | broadleaf | 0.8 | 6.3 | | 3.2 | | q |
| Sweden | | | | 5.5 | 4.7 | 1.6 | 0.2 | r |
| Sweden | | | | 5.2 | 2.3 | 0.9 | 0.4 | r |
| Sweden | | | | 5.0 | 2.5 | 0.9 | 0.4 | r |
| Czechoslovakia | biotite-muscovite gneiss | | | 3.3 | 2.6 | 8.4 | 4.4 | k |
| New York | | | | 2.5 | 1.1 | 4.8 | 3.6 | s |
| Colorado | | | | 2.4 | 1.0 | 0.9 | 2.0 | t |
| Maryland | schist | mixed | | 1.1 | 1.5 | 2.0 | 2.3 | u |
| Geometric mean low 1/3 | | | 0.8 | 3.7 | 2.0 | 1.9 | 1.7 | |
| Geometric mean all | | | 0.6 | 12 | 4.6 | 3.2 | 4.7 | |

a. Sollins et al. 1980, cited in Kimmins et al. 1985
b. Marchand 1971, cited in Kimmins et al. 1985
c. Fredriksen 1972, cited in Kimmins et al. 1985
d. Zeman 1975, cited in Freedman, 1981
e. Clayton 1979, cited in Kimmins et al. 1985
f. Woodwell and Whittaker 1967, cited in Kimmins et al. 1985
g. Bockheim et al. 1983, cited in White et al. 1988

h. Likens et al. 1977, cited in Kimmins et al. 1985
i. Creasey et al. 1986
j. Clayton 1984, cited in White et al. 1988
k. Paces 1986, cited in White et al. 1988
l. Feller 1981, cited in Kimmins et al. 1985
m. Clayton 1986
n. Katz et al. 1985
o. Verstraten 1977, cited in Kimmins et al. 1985
p. Papvich 1986, cited in White et al. 1988
q. Boyle et al. 1973, cited in Freedman, 1981
r. Sverdrup and Warfvinge 1988
s. April et al. 1986
t. Mast et al. 1990
u. Cleaves et al. 1970, cited in Kimmins et al. 1985

Extrapolation of those data (table 2.4) to Minnesota conditions is very uncertain. For example, a logical assumption is that minerals in soils formed from materials of gray glacial drift, such as those from the northwest part of the state, weather more rapidly than those formed in parent material derived from low-base minerals in the northeast part of the state. The gray drift is rich in free carbonates or calcite, an easily weatherable mineral, while glacial drift from the northeast contains igneous and metamorphic rocks with an abundance of quartz and feldspars. Such minerals are considered to be more difficult to weather. There are additional factors that should be considered, however. For example, there is good evidence that most weathering in soil occurs near the surface (April et al. 1986), and free carbonates are absent in the surface of all forest soils in Minnesota. On soils formed in glacial materials rich in such carbonates, the carbonates have either been weathered or leached to depths ranging from about 30 to 40 inches since deglaciation about 10,000 years ago. Particle size is also important to weathering, and smaller size particles of primary minerals generally weather at higher rates than larger particles because of increased surface area for the weathering reactions.

In order to establish crude estimates of mineral weathering rates for forested soils of Minnesota, an assumption was made that finer-textured soils have higher weathering rates than do coarse-textured soils, no matter what their glacial origin. The compiled data on weathering rates (table 2.4) were ranked, based on Ca release per annum. The data were then divided into thirds, and geometric mean rates calculated for each third (geometric means were used because such data tend to follow a Poisson distribution). The rates of weathering thus derived (table 2.4) were considered applicable to Minnesota, with highest rates on fine-textured soils with an abundance of weathering surfaces, middle rates on medium-textured soils, and slow rates on coarse-textured soils.

Based on those assumptions and calculations, weathering supplies about 32 lb $ac^{-1}yr^{-1}$ of Ca to fine-textured soils and only about one-tenth that much, or 3.7 lb $ac^{-1}yr^{-1}$, to coarse-textured soils (table 2.4). Rates of release for other elements do not vary as widely, with a range of less than fourfold for Mg and only twofold for K. Data for P are so limited that the overall geometric mean from all studies, 0.6 lb $ac^{-1}yr^{-1}$, is a reasonable estimate of release by weathering. As discussed above, release of N by weathering is not considered to be important. The N content of primary minerals is very low; significant N only occurs in a few sedimentary rocks, and then in organic-rich materials (i.e., coal).

**Summary**

The annual inputs of nutrients to Minnesota forests can be summarized in a simple tabulation (table 2.3). These data would indicate that weathering is the primary continuing source of nutrients for nearly all nutrients (excluding N), even on coarse-textured soils. However, the data (table 2.3) are clouded by great uncertainty. Variation in estimated weathering rates from soil to soil may far exceed differences in rates of atmospheric inputs. It is clear that any precise budget of nutrients for forest systems in Minnesota is lacking a key piece of data.

### 2.1.3 Intracycle

**Throughfall and Litterfall**

Forest ecosystems cycle nutrients; nutrients move from compartment to compartment within the system. The pathways of that movement include washoff of material from the tree canopy by precipitation, termed *throughfall*, and shedding of leaves and branches, termed *litterfall*. Nutrients that are contained in throughfall and litterfall are either immediately available for plant growth (especially those in throughfall) or must be biologically released by breakdown of the organic matter (mainly in the case of litterfall). The decomposition or mineralization of organic matter is an important process in maintaining an integrated and functioning forest ecosystem. Although both throughfall and litterfall are important processes of nutrient cycling, they are internal to the forest ecosystem. That is, they simply involve movement of nutrients from one part of the system to another.

A long-term view of forest nutrient status of an ecosystem must focus on the balance of inputs and outputs as they affect the nutrient capital. That capital can be considered to be a resource that can be used by plants (trees), but whose availability depends on the internal dynamics of the system. Nutrients can be sequestered in both wood of living trees and in organic litter as part of the forest floor, and hence be unavailable. Temporary accelerated release of stored nutrients, such as that related to disturbance, may lead to higher nutrient availability in spite of a long-term decline in capital. Changes in the system related to forest succession, natural disturbance, or management activities can all affect the rate of sequestration and release of nutrients, masking the long-term input/output balance. However, if inputs of nutrients to a forest ecosystem exceed outputs from that system, then nutrient capital in the system will increase. Conversely, if outputs exceed inputs, nutrient capital will decrease. Although changes in internal cycling rates, such as rates of throughfall and litterfall, are important, they are also ephemeral. They are not related to the input/output balance of the system as affected by harvesting. Details of throughfall and litterfall will therefore not be further directly considered.

### Nutrient Accumulation in Trees

An important part of the cycle of nutrients within the forest, and one that is significant to forest harvesting, is the amount of nutrients that are retained in trees as they grow. Each species of trees, and each part of those trees (i.e., roots, bark, branches, etc.), retain differing amounts of nutrients. This has been routinely reported in the literature. One of the clearest studies of this differential accumulation, and one that was carried out in Minnesota, was conducted by Alban and colleagues. They examined plantations that had been established at the same time on the same two soils, but were planted in species-specific blocks. Perala and Alban (1982) reported that differences among species (red pine, *Pinus resinosa*; jack pine, *Pinus banksiana*; aspen, *Populus tremuloides*; and white spruce, *Picea glauca*) in both mass and nutrient accumulation were similar on the two soils, and that some components of the trees had much higher nutrient concentrations and amounts than did other components.

Differences in the amount of nutrients that are accumulated in tree species are important for two reasons. First, a species that accumulates relatively more of a nutrient per unit production of mass can be assumed to be more demanding or have a higher requirement for that nutrient than does a species with a lower accumulation rate. Second, the nutrients that are contained within trees can be removed by forest harvesting, and harvest of species with larger amounts of stored nutrients leads to greater rates of nutrient drain from a site.

A simple tabulation of inventories of tree mass and nutrient content provides a starting point for discussion of the role of tree accumulation in nutrient cycling. Although many studies to determine mass and nutrient content of forest stands have been carried out, few studies are restricted to Minnesota, and those studies do not encompass the range of commercial species in the state. To achieve a useful compilation of such information required two compromises. First, all studies that included species that are commercially harvested in Minnesota were consulted. Because of the geographic distributions and site requirements of the species, these studies were carried out in areas of similar climate and soils as Minnesota. Although elemental concentrations range over a few orders of magnitude in the soil system, their range is narrow within the plant (Miller 1981). Second, because of data limitations, species were aggregated into groups (table 2.5). These groupings will also be used in other parts of this analysis.

**Table 2.5. Species groups used in analysis of nutrient cycling in relation to timber harvest.**

| **Group (Forest Type)** | **Species** |
|---|---|
| Aspen-birch | *Betula papyrifera*<br>*Populus balsamifera*<br>*Populus grandidentata*<br>*Populus tremuloides* |
| *Black Spruce* | *Picea mariana* |
| *Lowland Conifers* | *Abies balsamea*<br>*Larix laricina*<br>*Picea mariana*<br>*Thuja occidentalis* |
| Lowland Hardlands | *Acer rubrum*<br>*Betula papyrifera*<br>*Fraxinus nigra*<br>*Ulmus americana* |
| Pine | *Pinus banksiana*<br>*Pinus resinosa*<br>*Pinus strobus* |
| Spruce-Fir | *Abies balsamea*<br>*Picea glauca* |
| Upland Hardwoods | *Acer saccharum*<br>*Betula alleghaniensis*<br>*Quercus alba*<br>*Quercus ellipsoidalis*<br>*Quercus rubra*<br>*Tilia americana* |

The tabulated data (table 2.6) show trends that are consistent with the nutrient requirements and morphology of various species as reported in the literature. For example, the average above-ground biomass of each species group is well within the range reported in other studies in the Lake States (Grigal and Ohmann 1992, Ohmann and Grigal 1985, Crow 1978); the data are representative (table 2.6). Mass of N is highest in the crowns of upland hardwoods and spruce-fir. This is consistent with the large crowns, and abundant, high N leaves in these predominantly late-successional species.

**Table 2.6. Nutrient content of forest stands growing in Minnesota or similar climatic areas. Tabulated data are means of available studies.**

| Species Group | No. of Studies[a] | Above-ground Biomass Entire Tree | N | | P | | K | | Ca | | Mg | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Crown | Stem | Crown | Stem | Crown | Stem | Crown | Stem | Crown | Stem |
| | | (T/ac) | (lb/ac) | | (lb/ac) | | (lb/ac) | | (lb/ac) | | (lb/ac) | |
| Aspen-birch[b] | 19 | 57 | 119 | 166 | 15 | 16 | 68 | 131 | 167 | 419 | 18 | 37 |
| Black Spruce[c] | 8 | 31 | 73 | 70 | 10 | 8 | 30 | 28 | 90 | 141 | 11 | 12 |
| Lowland Conf.[d] | 14 | 40 | 154 | 86 | 13 | 9 | 54 | 40 | 112 | 138 | 14 | 14 |
| Lowland Hdwds[e] | 8 | 48 | 109 | 140 | 14 | 15 | 47 | 71 | 86 | 177 | 13 | 20 |
| Pine[f] | 12 | 64 | 130 | 151 | 14 | 9 | 53 | 49 | 77 | 140 | 16 | 22 |
| Spruce-Fir[g] | 11 | 59 | 220 | 100 | 25 | 12 | 91 | 58 | 196 | 183 | 18 | 17 |
| Upland Hdwds[h] | 7 | 75 | 224 | 173 | 21 | 12 | 112 | 93 | 257 | 347 | 25 | 28 |

[a] Many of the studies that were consulted reported mean values from more than one stand; others reported single-stand values.

[b] Aspen-Birch; Freedman et al. (1982), Malkonen (1977), Pastor and Bockheim (1984); Perala and Alban (1982), Ribe (1974), Ruark and Bockheim (1988), Silkworth (1980), Van Cleve (1981), Van Cleve et al. (1983)

[c] Black Spruce; Freedman et al. (1982), Grigal (1991), Van Cleve (1981), Van Cleve et al. (1983), Weetman and Webber (1972)

[d] Lowland Conifer; Freedman et al. (1982), Grigal (1991), Sprugel (1984), Van Cleve et al. (1983), Weetman and Webber (1972)

[e] Lowland Hardwoods; Ribe (1974), Malkonen (1977), Van Cleve (1981), Van Cleve et al. (1983)

[f] Pine; Alban (1988), Green and Grigal (1980), Foster and Morrison (1976), Hendrickson et al. (1987), Morrison and Foster (1979), Perala and Alban (1982), Shepard and Mitchell (1990)

[g] Spruce-Fir; Freedman et al. (1982), Kimmins (1974), Perala and Alban (1982), Sprugel (1984), Van Cleve et al. (1983), Weetman and Webber (1972)

[h] Upland Hardwoods; Duvigneaud and Denaeyer-De Smet (1970), Freedman et al. (1982), Harris (1981), Hornbeck (1977), Whittaker (1981)

Phosphorus follows the same general trends as N, but is about one order of magnitude lower. Potassium is high in crowns of upland hardwoods and spruce-fir, but it is also relatively high in the woody stems (especially in bark) of aspen-birch. Calcium is especially high in the woody stems of aspen-birch; it is also high in both the crown and stems of upland hardwoods (table 2.6). Magnesium tends to follow the same trends as Ca, but is about an order of magnitude lower. Per unit of biomass, pines and black spruce contain lower amounts of nutrients in tissue compared to the other species. It is clear from the distribution of nutrients within trees (table 2.6) that nutrient depletion associated with harvest is very dependent on the species being harvested and on the components, or parts of that species, being removed.

### 2.1.4 Outputs

The nutrient cycle of forest stands is not closed. As discussed above (table 2.6), nutrients enter forest ecosystems from the atmosphere or by weathering. Similarly, nutrients exit forests. The amount of nutrients that leave forests depends on many factors, but some generalizations can be drawn by comparing nutrient behavior in forests without recent disturbance and nutrient behavior in forests immediately following disturbance.

#### Paradigm

The fundamental pattern of nutrient loss in forests was well-described in a paper by Vitousek and Reiners (1975). That pattern can be summarized by considering the growth of a forest stand. Following successful regeneration, forest stands grow in volume (and biomass) with time until they reach an asymptote or plateau. In other words, the annual or current annual increment (CAI) of volume or biomass will initially be positive, and then will decline to zero as the stand ages over time (figure 2.1). Depending on the tree species and on the success of reproduction, total standing volume may remain relatively constant as individual trees senesce and younger individuals continuously invade and reach maturity, or it may enter into cycles of declines and increases as groups or cohorts of trees senesce and are replaced by groups of younger trees.

All tree components, including leaves, branches, and woody stem, contain nutrients in specific concentrations unique to that component and species. No matter what the species or component, increase in tree size as reflected by volume growth leads to increased storage of nutrients within the tree. As long as forest stands have net volume growth, or a positive CAI, additional nutrients will be stored. When CAI declines to zero, nutrient storage will cease and nutrients will simply cycle within the stand as part of the intracycle. After a stand has reached the stage of zero CAI, nearly all inputs of nutrients into that stand will be lost, usually through leaching in solution to groundwater or to nearby streams. Under that steady-state condition (zero CAI), outputs will equal inputs.

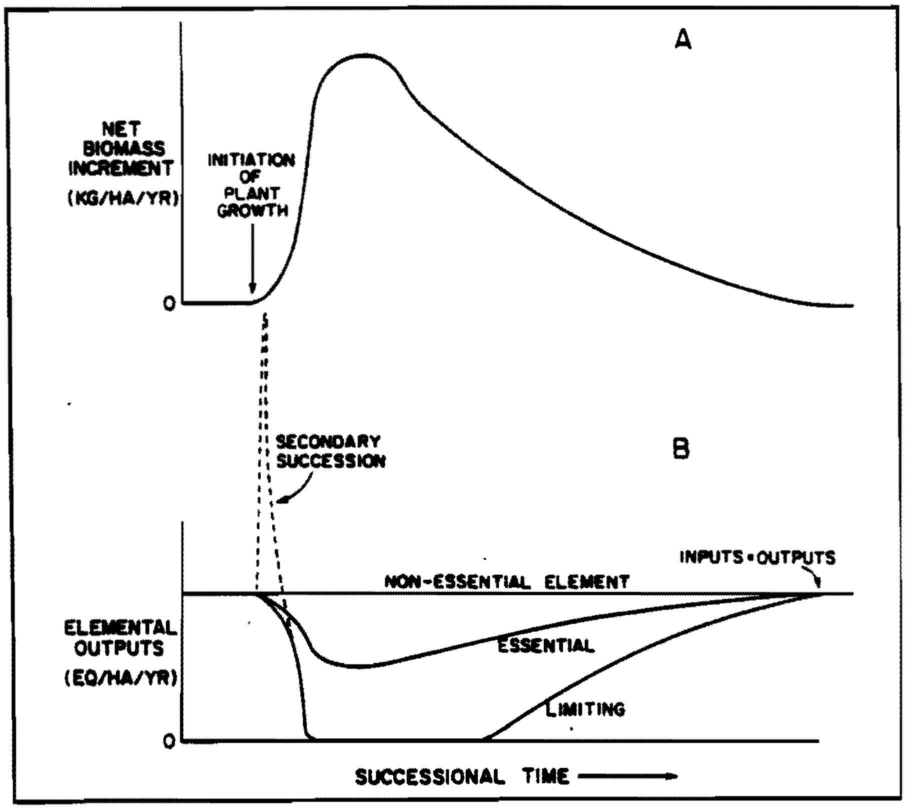

**Figure 2.1.** Change in net annual increment of stand biomass with time, declining to zero as stands reach maturity (A). As net increment reaches its maximum, nutrient requirements also reach their maximum and outputs of nutrients reach their minimum. With declining net biomass increment, outputs of nutrients increase (B) (from Vitousek and Reiners 1975).

In stands with positive CAI, the degree to which nutrient inputs exceed outputs (i.e., storage) depends on the biological demands of the particular species of tree, and on the availability of nutrients from the capital stored in the soil. Nutrients for which the requirements exceed the availability can be considered limiting, and none will be lost from the stand until CAI declines to near zero (figure 2.1). Nutrients that are required, but whose availability exceeds requirements, are essential, and outputs will be less than inputs but will not entirely cease (figure 2.1). Finally, elements that are nonessential will have a rate of output that is equal to the rate of input (figure 2.1).

Vitousek and Reiners (1975) studied balsam fir stands in New Hampshire. In that case, outputs of N ceased for most of the period of positive CAI, while outputs of Ca, Mg, and K declined for shorter periods of time and more nearly equaled inputs even before CAI reached zero. Because Vitousek and Reiners (1975) only considered atmospheric inputs, they interpreted this behavior to indicate that N was most limiting to the fir forests that they studied; although Ca, Mg, and K were essential, requirements for them in volume growth were more easily met by internal sources such as weathering. This pattern of behavior—with N being required in largest amounts relative to input—is likely for most forests in Minnesota.

As a postscript, a logical consequence of this paradigm is that a negative CAI, or decline in volume, will lead to an excess of nutrients above requirements. Inputs plus internal sources of nutrients will exceed demands, and a potential for nutrient loss will exist. In summary, in forests without recent disturbance and with positive CAI, outputs are less than inputs. As forests mature to zero CAI, outputs via leaching to groundwater and streamflow will equal inputs.

**Leaching Losses**

***Without Recent Disturbance***. An estimate of leaching losses in Minnesota can be derived from studies of soil solution chemistry that have been carried out both in Minnesota and in adjacent areas. Leaching losses are a function of both the concentration of nutrient elements in solution and of the quantity of solution passing through the soil and out of the system. Assessment of nutrient losses therefore requires estimates of both solution concentration and hydrologic fluxes from the system.

Soil solution data from the Great Lakes Region can be subdivided into three groups, associated with *good* or high-fertility sites, *medium*, and *poor* or low-fertility sites. This relative site quality is usually reflected by either the soil texture (with finer textures having higher fertility) or landform (moraines usually higher than outwash), and may not be directly reflected in relative measures such as site index. This subdivision of data into groups indicates higher concentrations on better sites; they have greater nutrient capital (table 2.7). As a result of the greater concentrations, these sites also have the potential for greater nutrient losses via leaching.

The amount of water leaving a forest system in the liquid phase is referred to by hydrologists as *runoff*, as compared to that either leaving as evapotranspiration or remaining in the system as storage (Hewlett 1982). This runoff is the medium by which nutrients leave forest systems in solution. Using average runoff data for selected areas of Minnesota (Baker et al. 1979), Ca loss from high-fertility sites in the northeastern region of the state would be about 34 lb $ac^{-1}yr^{-1}$, from medium sites in the north central region about 11 lb $ac^{-1}yr^{-1}$, and from poor sites in the northwest about 4 lb

**Table 2.7.** Concentration of soil solution sampled below rooting depth at sites in Great Lakes Region. Annual or multiyear means.

| Location | Soil Texture | Species Group[a] | Concentration (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Ca | Mg | K | Na | P | $NO_3$-N | $NH_3$-N |
| **Good Sites** | | | | | | | | | |
| Michigan[b] | sand (moraine) | AB | 10.4 | 4.8 | 2.0 | 1.8 | 0.08 | 0.08 | 0.03 |
| Michigan[c] | clay | AB | 50.7 | 16.9 | 0.6 | | | | |
| Minnesota[d] | clay loam | AB | 3.6 | 1.2 | 0.7 | 1.2 | 0.07 | 0.05 | 0.07 |
| Geometric Mean | | | 12.4 | 4.6 | 0.9 | 1.5 | 0.07 | 0.06 | 0.05 |
| **Medium Sites** | | | | | | | | | |
| Michigan[b] | sandy/till | AB | 7.7 | 1.9 | 2.0 | 2.8 | 0.08 | 0.03 | 0.05 |
| Minnesota[d] | sandy loam | AB | 7.8 | 3.1 | 1.0 | 5.0 | 0.20 | | |
| Michigan[e] | sandy loam | SF | 6.4 | 1.6 | 1.5 | 1.7 | | 0.01 | 0.04 |
| Michigan[f] | sandy loam | AB | 4.3 | 1.1 | 0.6 | 1.1 | | 0.08 | 0.14 |
| | | | | | | | | 0.02 | 0.07 |
| Geometric Mean | | | 6.4 | 1.8 | 1.2 | 2.3 | 0.13 | 0.02 | 0.07 |
| **Poor Sites** | | | | | | | | | |
| Minnesota[g] | outwash sand | UH | 4.1 | 1.0 | 0.4 | 1.3 | | 0.70 | |
| Minnesota[g] | outwash sand | P | 3.5 | 0.6 | 0.4 | 1.1 | | 0.20 | |
| Minnesota[g] | outwash sand | AB | 2.4 | 1.0 | 0.3 | 0.8 | | 0.20 | |
| Minnesota[g] | sandy loam/rock | P | 1.7 | 1.0 | 0.6 | 1.1 | | 0.00 | |
| Minnesota[g] | outwash gravel | P | 2.3 | 0.9 | 0.5 | 1.2 | | 0.00 | |
| Michigan[b] | outwash sand | AB | 5.2 | 0.8 | 1.4 | 3.0 | 0.08 | 0.03 | 0.03 |
| Minnesota[h] | sandy loam | SF | 3.3 | 1.1 | 1.7 | | 0.08 | 0.07 | |
| Wisconsin[i] | outwash sand | UH | 2.1 | 1.7 | 0.6 | 1.7 | | 0.01 | 0.02 |
| Wisconsin[i] | outwash sand | P | 2.0 | 1.5 | 0.6 | 1.8 | | 0.04 | 0.02 |
| Ontario[j] | sand | UH | 2.9 | 0.5 | 0.4 | 0.7 | | 0.81 | 0.01 |
| Geometric mean | | | 2.8 | 1.0 | 0.6 | 1.3 | 0.08 | 0.11 | 0.02 |

[a] AB = aspen-birch, SF = spruce-fir, UH = upland hardwoods, P = pine

[b] Richardson and Lund (1975)

[c] Stone (1991)

[d] Verry and Timmons (1982)

[e] Silkworth (1980)

[f] Stottlemeyer and Hanson (1989)

[g] Grigal et al. (1987)

[h] McColl and Grigal (1985)

[i] Bockheim et al. (1984)

[j] Foster (1985)

$ac^{-1}yr^{-1}$. A similar sequence of 12.5, 3.2, and 1.3 lb $ac^{-1}yr^{-1}$ losses, respectively, occurs for Mg. Losses of K for all systems range from 1 to 2 lb $ac^{-1}yr^{-1}$, and those for P and N are very low; about 0.2 lb $ac^{-1}yr^{-1}$. These losses can be compared to estimated inputs (table 2.3). Calcium and Mg would appear to be about in steady-state, but high leaching losses in the northeast may lead to net losses from those systems (table 2.3). Potassium and P show slight accretions; inputs of N clearly exceed losses. However, because of uncertainties, especially in rates of weathering, these conclusions are speculative. As described above, as volume or biomass of forests increase over time (positive CAI), the inputs of N are retained in that volume and outputs are minimized.

***Immediately Following Disturbance.*** Forests are subject to many disturbances that can affect the nutrient cycle. These disturbances include natural phenomena such as windstorm or insect infestation, or phenomenon that are natural processes but that are affected by man, such as forest fire. In most of these disturbances, the trees are not removed from the site and the nutrients that are stored within the trees remain on site; those nutrients are not immediately *lost* from the ecosystem. Although physical removal of material from the site, such as in timber harvest, obviously removes nutrients from a site, even those disturbances in which material is not removed will alter the nutrient cycle and potentially lead to nutrient loss.

Disturbances that weaken or kill trees will reduce or halt uptake of nutrients by the trees that are affected. In addition, nutrients that are stored in the trees that have died are released by decomposition of the organic material. For the first few years following disturbance, uptake of nutrients by a regenerating forest is usually not sufficiently large to sequester all the nutrients that become available, and *leakage* from the system can occur. This leakage due to reduced uptake is exacerbated by an increase in runoff because transpiration has also been reduced (Stone et al. 1978). This above-normal runoff or leaching loss usually continues for six to ten years following disturbance (Stone et al. 1978). Increased nutrient loss associated with this runoff usually continues for a shorter period of time than the increased runoff because the regenerating forest rapidly reaches sufficient size so that its positive CAI sequesters the available nutrients.

The amount of leaching loss that occurs immediately following disturbance depends on the rate of inputs to the system, the amount of nutrients that are available to be released by organic matter breakdown, and by the amount of water passing through the system. The best known work that assessed loss of nutrients by increased leaching following disturbance was done at Hubbard Brook, NH. In those northern hardwood forests, a combination of large quantities of nutrients at the soil surface, stored both in dead trees and in the forest floor, and a relatively moist environment with high precipitation and moderate evapotranspiration led to a very high, albeit brief, flux of nutrients to streams (Hornbeck et al. 1986). Even in those cases, which can be considered to represent an extreme (Stone 1973), losses by leaching were not large. In the ten years following cutting at Hubbard Brook (by which time nutrient losses were similar to those on undisturbed sites), total leaching losses associated with disturbance by clearcutting were equivalent to four years of natural leaching losses of Ca and three of Mg; there was no detectable loss of P (Hornbeck et al. 1986). Potassium had relatively high loss; 45 years of natural leaching. As in Minnesota, losses of N without disturbance are usually much less than inputs; cutting led to losses that exceeded inputs. After 10 years, total N loss was equivalent to that received from the atmosphere over a five-year period (Hornbeck et al. 1986).

Because the early reports from Hubbard Brook indicated relatively large nutrient losses and hence gained wide attention, similar research was carried out in many other systems, including aspen forests in Minnesota (Verry 1972, Silkworth and Grigal 1982). These studies did not find the same magnitude of losses in solution that were found at Hubbard Brook. For example, although water yield increased 42 percent in Minnesota following aspen harvesting, there was no change in the chemistry of that water (Verry 1972). The reasons for the lack of such large losses in Minnesota are likely related to differences in forest types, nutrient storage in the forest floor, and climate of Minnesota (lower precipitation and higher evaporation) compared to New Hampshire. Based on the available evidence, leaching losses following forest harvest in Minnesota are not of serious consequence.

**Harvest (Product) Losses**

When forest disturbance is associated with removal of material, then nutrients in that material are removed from the site. The amount removed is some proportion of the amount of nutrients that are stored in the standing trees on the site (table 2.6). That proportion depends on the kind of harvest and the degree of utilization. For example, a growing season full-tree harvest will remove virtually all the nutrients stored in the above-ground part of the trees. In the case of merchantable bole harvest, with limbing at the stump, the nutrients in the crown and in the upper portion of the woody stem (above the merchantable top diameter) are retained on the site. A thinning, or a selective harvest, will remove a portion of the nutrients that are contained in the trees that are removed. If trees are skidded to a landing before limbing, then the nutrients in the crown are removed from the actual site of growth as surely as if the tree had been wholly removed to the mill.

To estimate the quantity of nutrients removed by harvest from a site, the starting point is the quantity contained in the above-ground parts of the trees (table 2.6). The approach used in this analysis was to develop species-specific ratios of mass of nutrients in crown and in bark plus bole to total aboveground mass of dry matter, and ratios of leaf nutrients to total crown nutrients and bark nutrients to bole plus bark nutrients. These ratios can be used to determine nutrient removal based on volume removed at harvest, including the degree of utilization. Conversion of volume removed to total aboveground mass depends on wood density, may depend on volume of bark in the product, on merchantable versus total volume, and of the proportion of crown and bark mass to woody bole mass. These data have been compiled for the species groups used in this part of the analysis (tables 2.5, 2.8 and 2.9).

**Table 2.8. Data used to convert volume of harvest wood to mass of tree component for computation of nutrient depletion.**

| Species Group | Bark Volume[a] | Wood Density[b] | Merch./ Total Vol.[c] | Mass[d,e] Bark | Crown |
|---|---|---|---|---|---|
| | (% wood) | (lb/ft³) | (%) | (% of stem) | |
| Aspen-Birch | 12 | 27 | 92 | 21 | 21 |
| Black Spruce | 12 | 26 | 93 | 10 | 34 |
| Lowland Conif. | 12 | 24 | 90 | 12 | 37 |
| Lowland Hdwds | 15 | 32 | 92 | 11 | 40 |
| Pine | 15 | 24 | 94 | 10 | 15 |
| Spruce-Fir | 13 | 22 | 91 | 13 | 32 |
| Upland Hdwds | 18 | 41 | 93 | 14 | 51 |

[a] Gevorkiantz and Olsen (1955)
[b] Alemdag (1984a)
[c] Honer (1967) (to 3-inch top)
[d] Alemdag (1984b)
[e] Alemdag (1983)

**Table 2.9. Ratios of nutrient content to total aboveground mass.**

| Species Group | Nutrient | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N | | P | | K | | Ca | | Mg | |
| | Stem/ Total | Crown/ Total | Stem/ Total | Crown/ Total | Stem/ Total | Crown/ Total | Stem/ Total | Crown/ Total | Stem/ Total | Crown/ Total |
| | (lb/T) | | (lb/T) | | (lb/T) | | (lb/T) | | (lb/T) | |
| Aspen-Birch | 3.0 | 2.1 | 0.29 | 0.27 | 2.3 | 1.2 | 7.2 | 2.8 | 0.64 | 0.32 |
| Black Spruce | 2.5 | 2.7 | 0.28 | 0.34 | 1.0 | 1.1 | 4.6 | 3.0 | 0.40 | 4.1 |
| Lowland Conif | 2.4 | 3.8 | 0.27 | 0.36 | 1.0 | 1.4 | 3.8 | 2.9 | 0.38 | 0.39 |
| Lowland Hdwds | 3.0 | 2.3 | 0.34 | 0.28 | 1.6 | 0.9 | 4.0 | 1.7 | 0.43 | 0.26 |
| Pine | 2.4 | 2.1 | 0.14 | 0.22 | 0.8 | 0.8 | 2.1 | 1.2 | 0.33 | 0.25 |
| Spruce-Fir | 1.8 | 4.1 | 0.19 | 0.38 | 1.0 | 1.6 | 3.0 | 3.2 | 0.29 | 0.32 |
| Upland Hdwds | 2.3 | 3.2 | 0.16 | 0.30 | 1.3 | 1.6 | 4.9 | 3.9 | 0.39 | 0.37 |

A full-tree harvest during the growing season can be assumed to remove the entire above-ground portion of the trees (excluding the stump), and hence the entire quantity of nutrients in that material (table 2.6). This is an overestimate of nutrients removed because it does not consider residual material such as branches and tops that break off during the harvest and remain on the site. Full-tree harvest of deciduous trees during the dormant season can be assumed to retain the nutrients in the leaves on the site. This is an underestimate of the total nutrient removal because translocation of nutrients from leaves back into woody twigs occurs before leaffall (Ryan and Bormann 1982); translocation can lead to retention in wood of about half of the N and P in the leaves, only 10 percent of the K, and negligible amounts of Ca and Mg (Ryan and Bormann 1982). Because nearly all nutrient inventories of forest stands are conducted during the growing season (table 2.6), this translocation has not yet occurred and nutrient concentrations in leaves are high. Removal of nutrients by tree-length or shortwood harvest can be estimated from the quantity of nutrients in the merchantable bole of the trees, adjusted by the ratio of bole volume to some merchantable top diameter to total bole volume (table 2.10). Nutrient removal by thinning can simply be based on the volume removed in the thinning (table 2.10). The data in this table are based on nutrient content of forest stands (table 2.6), but because of adjustments made for merchantability and stand volume, they are not precisely equal.

**Table 2.10. Estimated nutrient removal per cord of harvested wood.**

| Forest Type[a] | Aboveground Mass of Trees Cut | | | Nitrogen | | Phosphorus | | Potassium | | Calcium | | Magnesium | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stem | Crown | Total | Merch Bole | Full Tree | Merch Bole | Full Tree | Merch Bole | Full Tree | Merch Bole | Full Tree | Merch Bole | Full Tree |
| | (lbs/ac) | | | | | | | | | | | | |
| AB | 2,775 | 500 | 3,275 | 4.5 | 8.4 | 0.4 | 0.9 | 3.4 | 5.3 | 10.8 | 15.4 | 1.0 | 1.5 |
| BS | 2,475 | 775 | 3,250 | 3.8 | 8.5 | 0.4 | 1.0 | 1.5 | 3.3 | 6.9 | 11.8 | 0.6 | 1.3 |
| LC | 2,375 | 775 | 3,150 | 3.4 | 9.8 | 0.4 | 1.0 | 1.5 | 3.7 | 5.3 | 9.9 | 0.5 | 1.1 |
| LH | 3,025 | 1,100 | 4,125 | 5.8 | 10.9 | 0.6 | 1.3 | 3.0 | 5.0 | 7.6 | 11.2 | 0.8 | 1.3 |
| P | 2,225 | 300 | 2,525 | 2.8 | 5.6 | 0.2 | 0.4 | 0.9 | 1.9 | 2.5 | 3.9 | 0.4 | 0.7 |
| SF | 2,150 | 600 | 2,750 | 2.3 | 8.1 | 0.2 | 0.8 | 1.3 | 3.4 | 3.8 | 8.3 | 0.4 | 0.8 |
| UH | 3,975 | 1,800 | 5,775 | 6.1 | 15.9 | 0.4 | 1.4 | 3.5 | 8.2 | 13.2 | 24.4 | 1.0 | 2.1 |

[a] AB = aspen-birch, BS-black spruce, LC = lowland conifers, LH = lowland hardwoods, P = Pine, SF = spruce-fir, UH = upland hardwoods.

## 2.1.5
## Nutrient Capital

Although both nutrient inputs and outputs must be considered when the impact of timber harvesting on nutrient status is evaluated, perhaps the key datum to consider is the initial nutrient capital of the site. Nutrient capital on a site, those nutrients stored in the soil, varies with all the soil-forming factors (time, organisms, topographic position, climate, and parent material). Although it is not unreasonable to collect data for tree tissue nutrient content from anywhere within a species' geographic range, soil data should only be collected from the region under consideration because of the complex interplay of the soil-forming factors.

A simple quantification of the amount of nutrients present in a soil may not be sufficient for evaluating nutrient status. There is considerable question and concern in the literature with the definition of nutrient availability, both chemically and spatially. No chemical extractant is completely analogous to the dynamics of a plant root-soil system, so that laboratory analyses of soil can only approximate the actual levels of nutrients that are available to trees. Second, nutrient availability to trees also depends on the relative location of the nutrients and of the tree roots. Nutrients located many meters below the surface cannot be considered to be as available as are those occurring within the dense root mat at the surface of most forest soils. Both those factors will be discussed in more detail.

Estimation of nutrient capital for forest soils in Minnesota followed a multiple step process. First, representative soils in the forested areas state, by physiographic unit (Wright 1972), were determined. Seven representative soils were identified for each unit; a well-drained and a poorly-drained pair of mineral soils representing the textural categories of coarse, medium, and fine, and an organic soil. The data base of the Minnesota Cooperative Soil Survey was then used to determine the basic properties of each of the representative soils. Quantities of nutrients were estimated from those basic properties, and finally these quantities were converted to nutrient capital based on depth of tree rooting.

## Inventory

### *Data Base*

The Minnesota Cooperative Soil Survey, an organization with representatives from the USDA Soil Conservation Service, the University of Minnesota Agriculture Experiment Station, the University of Minnesota Extension Service, the Minnesota Department of Natural Resources, the USDA Forest Service, and the Minnesota Board of Soil and Water Conservation Districts, maintains a data base of properties of soils that have been sampled and analyzed as part of the soil survey (mapping) program in the state. That data base contains information from 4,000 pedons, or individual soils that have been sampled and analyzed (S. Smith 1991, personal communication). Most of these soils have been analyzed for a basic suite of properties that are used for characterization as part of the mapping program. These properties include particle size (proportion of sand, silt, and clay), organic carbon content, and pH. Also included in the data base is depth of individual horizons within each pedon.

As described above, for each of the forested physiographic areas of Minnesota (20 of the 27 units described by Wright 1972), representative soil series that occurred in the data base were selected. This selection was based on soil survey reports for individual counties, and on two statewide compilations of geographic distribution of soils (Cummins and Grigal 1981, Minnesota Soil Survey Staff 1983). On each physiographic area, these series represented a well-drained and a poorly-drained pair of mineral soils representing the textural categories of coarse, medium, and fine, and an organic soil (table 2.11). In some cases, the selected soil may not have been the *best* representative for a physiographic area, but choices were restricted to soils that were found in the data base. In other cases, the choice may have been very arbitrary. For example, Physiographic Area 12, the Anoka Sand Plain, is dominated by outwash sands; the choice of a fine-textured soil to represent that area was moot. Similarly, Physiographic Area 9, the Glacial Lake Duluth Area, is dominated by fine-textured soils and so choice of a coarse-textured representative was arbitrary.

**Estimation of Properties**

*Mineral Soils.* Although the Soil Survey data base does not contain direct nutrient information, it does contain the most comprehensive soil data for Minnesota. To determine nutrient concentration of those soils, two other sources of information were used. In one study (Ohmann et al. 1989), 169 forest stands, representing five covertypes, were sampled in a transect across the forested portions of Minnesota, Wisconsin, and Michigan. Detailed soil information was collected in each stand. In the second study (Bloom and Grigal 1985), a large data base of properties of representative Minnesota soils was assembled from many sources including graduate theses, detailed soil investigations, etc. Data from these two sources were combined and predictive equations were developed that estimated nutrient content of soils using properties available in the Cooperative Soil Survey data base. Cation content was based on simple regressions using loss on ignition, clay content, and pH in $CaCl_2$ (table 2.12). If only pH in $H_2O$ was reported, pH in $CaCl_2$ was estimated as

$$pH_{CaCl2} = -0.56 + 0.96{*}pH_{H2O} + 0.024{*}C + 0.006{*}clay \qquad [1]$$

(Grigal and Bloom 1985, unpublished). Loss on ignition was determined from carbon content using the relationship developed by David (1988),

$$LOI = (C * 0.0134)/0.52. \qquad [2]$$

Nitrogen content was also based on C content, and on a C:N ratio from the 169 sampled stands mentioned earlier (20:1, David et al. 1988).

Table 2.11. Physiographic Areas (Wright 1972) that lie within the forested portions of Minnesota, and the soil series that were used to represent each area. Mineral soil series represent coarse, medium, and fine textures with a well- and a poorly-drained representative of each texture.

| Physiographic Area | | Representative Soils | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Coarse | | Medium | | Fine | | Organic |
| | | Well | Poorly | Well | Poorly | Well | Poorly | |
| 1 | Border Lake States | Toivola | Cormant | Mesaba | | Taylor | Indus | Greenwood |
| 2 | North Shore Hlnd | Cloquet | Newson | Ahmeek | Ronneby | Duluth | Dusler | Greenwood |
| 3 | Toimi Drumlin Area | Toivola | Cormant | Newfound | Ronneby | Duluth | Dusler | Greenwood |
| 5 | Aurora-Alborn Clay Till Area | Menahga | Cormant | Newfound | Ronneby | Nashwauk | Keewatin | Mooselake |
| 6 | Glacial Lakes Upham and Aitkin | Menahga | Cormant | Baudette | Spooner | Taylor | Indus | Greenwood |
| 7 | Chisholm-Embarrass Area | Menahga | Cormant | Newfound | Ronneby | Nashwauk | Keewatin | Greenwood |
| 8 | Sugar Hills-Mille Lacs Moraine Area | Menahga | Newson | Itasca | Ronneby | Hibbing | Dusler | Greenwood |
| 9 | Glacial Lake Duluth Area | Omega | Newson | Ahmeek | Ronneby | Ontonagon | Bergland | Mooselake |
| 10 | Barnum Clay Till Area | Omega | Newson | Ahmeek | Ronneby | Duluth | Dusler | Greenwood |
| 11 | Brainerd-Automba Drumlin Area | Menahga | Cormant | Brainerd | Nokay | Hibbing | Dusler | Greenwood |
| 12 | Anoka Sand Plain | Zimmerman | Isanti | Dorset | Paddock | Hayden | Hamel | Rifle |
| 13 | Eastern St. Croix Moraine | Mahtomedi | Isanti | Heyder | Paddock | Hayden | Hamel | Cathro |
| 14 | Western St. Croix Moraine | Menahga | Cormant | Brainerd | Nokay | Collegeville | Hamel | Mooselake |
| 15 | Bemidji Area | Menahga | Cormant | Itasca | Paddock | Beltrami | Shooker | Mooselake |
| 16 | Itasca Moraine | Menahga | Cormant | Rockwood | Paddock | Warba | Shooker | Mooselake |
| 17 | Wadena Drumlin Area | Menahga | Cormant | Rockwood | Paddock | Beltrami | Shooker | Mooselake |
| 18 | Alexandria Moraine Area | Marquette | Isanti | Dorset | Paddock | Waukon | Shooker | Cathro |
| 19 | Owatonna Moraine Area | Mahtomedi | Isanti | Heyder | Paddock | Lester | Minnetonka | Cathro |
| 25 | Beltrami Arm of Lake Agassiz | Hiwood | Cormant | Baudette | Spooner | Taylor | Indus | Mooselake |
| 27 | Rochester Till Plain | Plainfield | Isanti | Timula | Paddock | Mt. Carroll | Skyberg | Cathro |

**Table 2.12.** Equations used to estimate soil cation content using data from Minnesota Cooperative Soil Survey data base. Equations of the form: exchangeable cation (meq/100g) = b0 + b1*LOI(%) + b2*clay(%) + b3*$pH_{CaCl2}$, where LOI is loss on ignition and $pH_{CaCl2}$ is pH determined in 0.01M $CaCl_2$.

| Cation | b0 | b1 | b2 | b3 | $R^2$ | n |
|---|---|---|---|---|---|---|
| Ca | -15.378 | 0.885 | 0.237 | 3.226 | 0.49 | 430 |
| Mg | - 3.552 | 0.070 | 0.171 | 0.681 | 0.67 | 430 |
| K | 0.008 | 0.023 | 0.006 | 0.015 | 0.25 | 410 |
| Na | 0.002 | -0.002 | 0.002 | 0.011 | 0.08 | 404 |
| Sum of bases | -20.025 | 1.026 | 0.374 | 4.181 | 0.83 | 497 |
| CEC[a] | -16.761 | 0.791 | 0.321 | 3.865 | 0.82 | 169 |

[a] Unbuffered

*Organic Soils.* Because of the limited data available for organic soils within the Cooperative Soil Survey database, available nutrients for the two major taxonomic classes (suborders) of organic soils that support commercial forests, Hemists and Saprists, were determined from two published reports that contained data for a number of such soils (Kernik 1981, Grigal et al. 1974).

## Nutrient Availability

### *Rooting Depth*

All nutrients in a soil are not equally available. The fact that some nutrients are immobilized within soil minerals and are released to a form available to plants by weathering has already been discussed. Nutrient availability is also related to their spatial distribution in the soil. Tree roots do not occur uniformly in soil. Growth of fine roots is closely related to temperature, oxygen, nutrients, and resistance of the soil to penetration (Perry 1978). All these factors are most suitable for root growth near the soil surface; roots are abundant near the surface and decline exponentially with depth (figure 2.2). Gale and Grigal (1987) reviewed the available reports of root distributions of forest trees in the north temperate region. Based on the results of 123 excavations, they found that rooting distribution was influenced by tree successional status or shade tolerance (figure 2.2). Even the deepest rooting trees, however, those considered to be early successional, had 95 percent of the fine roots within the upper 40 inches of soil, with 53 percent within the upper 10 inches. Shade tolerant, or late successional species, had virtually all roots within the upper 40 inches of soil (99.9 percent) and 88 percent were in the upper 10 inches.

The concentration of roots near the surface has profound implications for nutrient use as a function of soil depth. Alban (1982) examined soil properties under the adjacent stands of aspen, spruce, and pine at two previously discussed sites in north central Minnesota. Alban found that after 40 years of occupancy, the effects of differential species on soil properties did not extend deeper than 10 inches (25 cm) on one site and no deeper than 14 inches (36 cm) at the second site. Based on the relationships developed by Gale and Grigal (1987), slightly more than half of the aspen roots occur within the upper 10 inches of soil, and two-thirds occur within the upper 14 inches. For white spruce, the respective fractions of roots are two-thirds and over three-fourths.

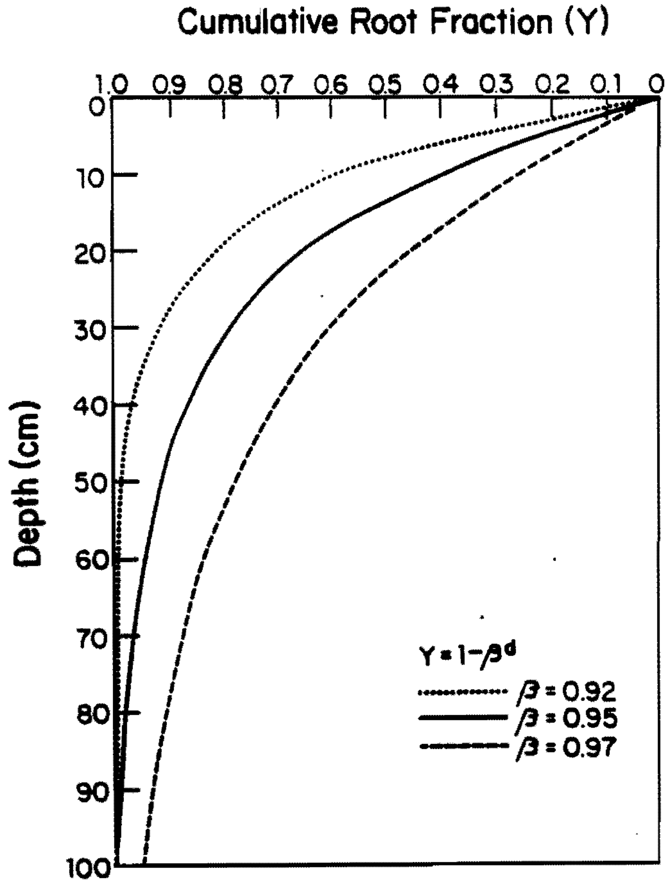

**Figure 2.2** Vertical root distribution for forest trees. Early successional or intolerant species tend to be more deeply rooted (higher $\beta$) than do late successional or tolerant species (lower $\beta$) (from Gale and Grigal 1987).

Based on the preponderance of roots in the upper horizons of the soil, and Alban's (1982) evidence of elemental depletion in those upper horizons, an estimation of the nutrient capital on a site that is available to trees can be carried out weighting soil properties by depth. In this way, upper horizons will have much greater influence on estimated capital than will deep horizons that have few roots.

Mycorrhizae are an important fungi-higher plant symbiotic system in forests, and interact by uptake of nutrients by the fungi and supply of fixed carbon from the host. Root tissue age and longevity affect nutrient uptake. In nonmycorrhizal roots, uptake occurs mostly near the root tip, but uptake by mycorrhizae extends back from the tip (Harley and Smith 1983). Mycorrhizae also maintain high absorbing rates for several months, and are able to sustain absorption in one location rather than transiently through the soil as do uninfected roots (Bowen 1973). This affects the volume of exploitation of nutrients. Although root distribution is important in assessing availability of nutrients, spatial distribution of mycorrhizae is also very important. Most tree roots are near the surface, but the majority of mycorrhizae are even closer to the surface and primarily occur in the forest floor (Harvey et al. 1986). Because data on mycorrhizae distribution in soils of Great Lakes' forests are limited, and because mycorrhizae are associated with fine roots (Fogel 1980), root distributions will be used as a surrogate for distribution of all nutrient-absorbing structures.

### *Chemical Extraction*

Although the spatial availability of nutrients is a complex question to consider, even more complex is the availability of nutrients within any unit volume of soil. Scientific literature dealing with forest soils and requirements of trees for nutrients contains many discussions concerning the way in which chemical extractants of soils mirror the mechanisms by which trees satisfy their requirements for nutrients (e.g., McColl 1984).

The mechanisms of nutrient uptake by trees have recently been discussed (Grigal 1990). Concentration profiles of important nutrient ions near absorbing roots and their rates of uptake by plants can be satisfactorily explained by mechanistic models in which ions move to roots by two processes, mass flow and diffusion (Barber 1984, Nye 1984). The rate of diffusion is described by the diffusion coefficient and by the diffusion gradient. The length of the diffusion path is a function of root distribution and growth rate, and the gradient is defined by the soil supplying power and by root uptake. The flow of water moving toward the root in response to transpirational gradients, and the soil solution concentration, determine the nutrient supply via mass flow. The importance of the process of mass flow varies among system (Prenzel 1979, Oliver and Barber 1966a,b). Although differences in species' requirements may provide part of the explanation for these differences, differences in soil solution concentrations are a more likely explanation. For example, soil solution concentrations in agricultural systems are commonly an order of magnitude higher than in forest systems, especially for Ca. Hence in some systems Ca can be supplied by mass flow (e.g., Oliver and Barber 1966a,b), while in other systems diffusion is more important (Prenzel 1979). In most forest systems, the relative difference in importance between diffusion and mass flow is of little significance; ions move by both processes.

Although these relationships are complex, the amount of cations on soil exchange sites can be used as a measure of the buffer power of mineral soils to supply nutrients to trees, either by diffusion or by mass flow. Adams and Boyle (1982) concluded that in Michigan Spodosols, exchangeable nutrient pools probably provided most of the cations necessary for growth. Exchangeable cations are therefore a reasonable indicator of nutrient quantity or capital available for tree growth.

Phosphorus availability is more problematic. A number of chemical extractants have been used in agricultural soils to *estimate* P availability. In forest systems, mycorrhizae play a very important role in nutrient uptake, especially that of P. As a result, P may be more available to forest trees than is indicated by many agronomic extractants. For example, although water-soluble P fertilizers are usually used in agricultural applications, rock phosphate, the relatively insoluble P ore, is a very suitable P fertilizer in forestry (Allen 1987). For a precise characterization of P availability, the concentration in soil solution and that on the soil matrix in equilibrium with the solution are the best measures of availability (*sensu* Neary et al. 1990). In the absence of such precise measures, levels of P extractable with weak acid are widely available and provide an approximate measure of P availability in forest soils.

Nitrogen availability opens up an entirely different set of processes and questions. Although measurement of quantity of N in forest floor and mineral soil is a relatively simple analytical procedure, the amount that is actually available to plants depends on the dynamics of the system. Nitrogen is nearly wholly present in soil organic matter, and is made available as the organic matter is broken down, or mineralized, by biological activity. Considerable research has been carried out on rates of N release, or mineralization, in forests (Edmonds and McColl 1983). The amount so released has been found to be related to tree growth (Pastor et al. 1984).

*In situ* techniques provide the best estimates of the amount of N that is annually released from organic matter and is therefore available for tree growth. In the Great Lakes region, such methods have been used by Pastor et al. (1984), Plymale et al. (1987), Zak and Pregitzer (1990), Zak and Grigal (1991), and Zak et al. (1991). Most of these studies were carried out in upland hardwood forests (table 2.13). Interestingly, the mean N that was mineralized in both conifer and hardwood forests was an identical proportion of the total soil N capital; 9.3 percent (table 2.13).

**Table 2.13.** Soil total N content and annual N mineralization rates for hardwood and coniferous forests in the Great Lakes region.

| Forest Type and Source | Total N | N Mineralization | Annual Proportion |
|---|---|---|---|
| Pastor et al. (1984) | (mg N $g^{-1}$) | (mg N $g^{-1}$ $yr^{-1}$) | (%) |
| Conifer - Wisconsin<br>red pine | 46 | 3.0 | 6.5 |
| white pine | 14 | 2.1 | 15.0 |
| eastern hemlock | 20 | 1.3 | 6.5 |
| mean | | | 9.3 |
| Hardwood - Wisconsin<br>red oak | 27 | 2.2 | 8.2 |
| red oak | 30 | 3.3 | 11.0 |
| white oak | 24 | 2.7 | 11.2 |
| sugar maple | 32 | 2.5 | 7.8 |
| sugar maple | 31 | 3.5 | 11.3 |
| mean | | | 9.9 |
| Zak and Pregitzer(1990) | (µg N $g^{-1}$) | (µ N $g^{-1}$ $yr^{-1}$) | |
| Hardwood - Michigan<br>sugar maple | 3040 | 426 | 14.0 |
| sugar maple | 1835 | 382 | 20.0 |
| white and black oak | 1913 | 313 | 16.4 |
| mean | | | 11.4 |
| Zak et al. (1991) | (g N $m^{-2}$) | (g N $m^{-2}$ $yr^{-1}$) | |
| Hardwood - Minnesota<br>upland pin oak | 69 | 2.9 | 4.2 |
| upland pin oak | 73 | 3.7 | 5.1 |
| upland pin oak | 87 | 6.3 | 7.2 |
| upland pin oak | 91 | 6.7 | 7.4 |
| mean | | | 6.0 |
| Zak and Grigal (1991) | (g N $m^{-2}$) | (g N $m^{-2}$ $yr^{-1}$) | |
| Hardwood - Minnesota<br>upland pin oak | 146 | 8.6 | 5.9 |
| bur oak savanna | 125 | 4.2 | 3.4 |
| mean | | | 4.6 |
| Plymale et al. (1987) | (mg N $g^{-1}$) | (mg N $g^{-1}$ $yr^{-1}$) | |
| Hardwood - Ohio<br>mixed oak | 1442 | 125 | 8.7 |
| mixed mesophytic | 2618 | 208 | 7.9 |
| mean | | | 8.3 |
| Grand means | | | |
| Conifer | | | 9.3 |
| Hardwood | | | 9.3 |

Just as N is released by mineralization, other nutrients within organic matter are also made available. Although considerable research has been carried out to quantify N mineralization, little has been done to examine release of other nutrients except S (Kowalenko and Lowe 1975) by mineralization. This process can be an important source of nutrients to trees.

For example, careful and long-term work by Jorgensen et al. (1980) indicated that as pine plantations in North Carolina matured, an increasing proportion of their demand for nutrients could be met by mineralization of the forest floor (86 percent of the N, 104 percent of P, and about 70 percent of K, Ca, and Mg). They consider that as forests develop following establishment, the source of nutrients for growth shifts from the mineral soil to the forest floor. Rates of mineralization of N, which have been thoroughly studied, can probably be used as the basis for estimating the availability of the other elements within the soil organic fraction, especially the forest floor.

Mycorrhizae are important in uptake of nutrients by their spatial exploitation, and also because their uptake characteristics and potential role in solubilizing nutrients or otherwise making them more available for uptake (Reid 1984) add further uncertainty to the assessment of nutrient capital.

## Computation of Nutrient Capital

### *Mineral Soils*

Data from all the pedons that were of the representative soil series within the Cooperative Soil Survey database were used to compute the nutrient capital for that series. To represent the mineral soils considered here (table 2.11), 181 pedons, representing 46 soil series and including data from 1,144 soil horizons, were used. Using the basic properties of particle-size distribution, organic carbon, and pH, and the relationships in table 2.12 and equations [1] and [2], nutrient concentration by horizon was estimated. In a few cases, organic C was only available for the upper two or three horizons; it was estimated for lower horizons as an exponential decline with depth, based on the soil data from across the Lake States (Ohmann and Grigal 1992) and data from special soil investigations such as the soil survey of Cedar Creek Natural History Area (Grigal et al. 1974). Extractable P is poorly related to readily available soil properties; it is primarily a function of soil mineralogy and texture. The weak relationship with texture ($R^2 = 0.11$), and summary data from a number of sources (e.g., Pluth et al. 1970, Silkworth 1980, Kernik 1981, Balogh 1983) were used to arrive at estimates of extractable P.

Concentrations of nutrients were converted to mass per unit area using horizon depth and bulk density (Grigal et al. 1989). Nutrient mass was summed to 40-inch depth, but a weighted average nutrient mass, based on tree rooting depth (*the rooting zone*), was also computed. The latter computation assumed that nutrients are available to trees in proportion to the distribution of fine roots in the soil. An exponential weighting function, as developed by Gale and Grigal (1987), was used

$$R = 1 - B^d \tag{3}$$

where R is proportion of fine roots occurring above depth d (in cm). The value of the coefficient B, 0.955, was based on the extensive literature review by Gale and Grigal (1987) and represents a rooting distribution that is somewhat deeper than the average of midtolerant species, and much deeper than that of late successional species. Computationally, this coefficient also yields an R that indicates that 99 percent of fine roots occur above 40 in. depth. The survey by Gale and Grigal (1987) indicates that 100 percent of the roots of late successional species occur above this depth, 98 percent of roots of midsuccessional species, and 87 percent of roots of early successional species.

Use of this weighting is consistent with nutrient depletion near the soil surface, and results in a lower estimate of nutrient capital than does assumption of a uniform root distribution with depth. Data for all nutrients except N are expressed as *available* (exchangeable Ca, Mg, and K and extractable P); N data are for total quantity in the rooting zone. The regional average rate of N mineralization for soils, 9.3 percent (table 2.13), can be used to assess N availability for upland soils. Rates of N mineralization in poorly drained soils are lower than upland rates because of periodic anaerobic conditions. Rates of N mineralization in those soils was estimated to be 5.4 percent, the mean of rates in upland soils and in organic (peatland) soils. That latter rate will be discussed below.

### *Forest Floor*

The amount of nutrients stored in forest floor of Great Lakes forests can be estimated from the data collected by Ohmann et al. (1989) from 169 forest stands representing five forest types across the Great Lakes states (table 2.14). As discussed earlier, most of the nutrients within the organic fraction of the soil are not available to plants until the organic matter has been mineralized. Rates of organic matter mineralization are important for determining availability of N from mineral soils, and of all nutrients from the forest floor. Major attention has been focused on N release from organic matter; other nutrients are released at differing rates (Grigal and McColl 1977, Jorgensen et al. 1980). Based on detailed, multiyear work, Ca and P are released from the forest floor at about twice the rate of N, Mg at three times the rate, and K at about six times the rate of N release (Jorgensen et al. 1980). If the regional average rate of N release from soil organic matter, 9.3 percent (table 2.13), is considered to be representative of the forest floor, then release of other nutrients can be computed from that value.

**Table 2.14.** Nutrient storage in forest floor of upland forests in Great Lakes states.

| Species Group | Nutrient | | | | | |
|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | Na |
| | (lb/ac) | | | | | |
| Aspen-birch | 295 | 25.5 | 33.8 | 348 | 61.1 | 2.8 |
| Pine | 255 | 18.3 | 22.7 | 151 | 28.0 | 1.8 |
| Spruce-Fir | 319 | 23.1 | 28.5 | 267 | 47.4 | 2.9 |
| Upland Hdwds | 281 | 23.5 | 29.3 | 298 | 42.5 | 2.6 |

### *Organic Soils*

Organic soils contain an acrotelm, or surface layer, that is not continuously saturated and is therefore periodically aerobic, and a catotelm, or subsurface layer, that is nearly continuously saturated because it lies beneath the surface of the water table and is therefore anaerobic (Ingram 1978). The acrotelm is the *active zone*; it contains plant roots and is the site of active nutrient cycling. After organic materials reach the depth of the catotelm, the nutrients therein are virtually eliminated from cycling processes through anaerobiosis. As a results of this distinctive layering, exponential weighting was not used for organic soils. Instead, the thickness of the acrotelm, usually about 10 in., was considered to be fully exploitable by roots and thus all exchangeable nutrients in that zone were considered to be available. As with mineral soils, exchangeable Ca, Mg, and K in the acrotelm were considered to be available. Total N and P in the acrotelm are not available; only that fraction that is mineralized from the organic matter is available. Work in peatlands in Minnesota indicates that about 1.5 percent of the N and P in the acrotelm become available per year (Grigal 1991), and this proportion was used to determine availability of those nutrients. This proportion is much less than the 9.3 percent mineralization rate for upland soils that was discussed earlier. The lower rate is due to the periodic saturation of the acrotelm.

## Results

### *Mineral Soils*

The results of the computation led to marked differences in interpretation depending on use of an unweighted total nutrient mass to 40 in., or the nutrient mass weighted by rooting distribution. For example, the Indus soil, a very fine, Typic Ochraqualf formed in calcium-rich lacustrine clays contained about 23 T ac$^{-1}$ of exchangeable soil Ca to 40 in., but only about 3.5 T ac$^{-1}$ of Ca within the rooting zone. The proportion of nutrients within the rooting zone varied with the soil and the distribution of nutrients by horizon. In general, sandy soils tended to have a greater proportion of nutrients near the surface, so that the ratio of nutrients within the rooting zone to total nutrients to 40 in. ranged from about 25 to 30 percent. The

Cloquet soil, a coarse-loamy over sandy Typic Dystrochrept, only contained 2.5 T $ac^{-1}$ exchangeable Ca to 40 in., but 0.7 T $ac^{-1}$, or nearly 30 percent, occurred within the rooting zone. In contrast, soils developed in calcium-rich till but with a leached surface, such as the Keewatin soil, a fine-loamy Aeric Glossaqualf, had relatively small proportions of nutrients in the rooting zone (only 0.8 T $ac^{-1}$ within the rooting zone, about 10 percent of the 7.9 T $ac^{-1}$ Ca to 40 in.).

Data from the Cloquet and Keewatin soils also demonstrate another feature of the data. Although the Cloquet soil only contains about 30 percent as much available Ca to 40 inches as does the Keewatin soil, the soils have nearly equal amounts of available Ca in the rooting zone. These kinds of relationships were also true for the other nutrients.

Because use of the rooting zone to compute available nutrients tended to reduce some of the variance in the data, and to eliminate differences between soils formed in Ca-rich materials compared to those formed in materials that were low in Ca (because differential deposition at the surface and pedogenesis had reduced differences in material within the rooting zone), mean nutrient capital was computed for each class of mineral soil, irrespective of physiographic unit. Thus one estimate for nutrient capital was developed for poorly-drained coarse (sandy) soils, well-drained coarse soils, poorly- and well-drained medium-textured soils, and poorly- and well-drained fine-textured soils (table 2.15). In the case of P, similar estimates were used for both the well- and poorly-drained member of each texture class.

**Table 2.15. Nutrient capital within tree rooting zone (Gale and Grigal 1987) of representative soils of Minnesota.**

| Soil | | Nutrient | | | | |
|---|---|---|---|---|---|---|
| Texture | Drainage | Ca[a] | Mg[a] | K[a] | N[b] | P[c] |
| | | (lb/ac) | | | | |
| **Coarse** | Well | 1300 | 165 | 120 | 70 | 25 |
| | Poor | 2040 | 185 | 120 | 90 | 25 |
| **Medium** | Well | 3085 | 625 | 195 | 120 | 15 |
| | Poor | 3460 | 730 | 225 | 100 | 15 |
| **Fine** | Well | 3935 | 1145 | 235 | 90 | 8 |
| | Poor | 4680 | 1340 | 265 | 80 | 8 |
| **Hemist** | Poor | 2700 | 445 | 24 | 80 | 2 |
| **Saprist** | Poor | 3850 | 295 | 72 | 120 | 8 |

[a] Amounts exchangeable with 1 M salt.

[b] Based on total quantities and annual mineralization rates.

[c] Based on amounts extractable with weak acids for mineral soils, and on annual mineralization rates for organic soils.

The results of the analysis demonstrate that for the cations, Ca, Mg, and K, nutrient capital varies as a function of the soil texture and drainage class; poorly-drained soils tend to have higher nutrient capital than do well-drained soils, and fine-textured soils tend to have higher nutrients than do coarse-textured soils (table 2.15). In the case of all three cations, differences among texture and drainage groups are significant. Nitrogen capital also varies with texture and drainage as do the cations, with greater amounts in poorly-drained and fine-textured soils. There was no statistically significant difference in quantity of N among drainage and texture groups, primarily because of the high variability within each group. The group means show the expected trends. When mineralization rates are used to estimate availability, medium-textured soils have highest available N (table 2.15). Based on agricultural criteria (Rehm 1987), levels of P range from *low* in fine-textured soils to ***medium-high*** in coarse-textured soils. These levels of extractable P must be assessed with consideration of the ability of forest trees and their mycorrhizal symbionts to obtain P from less soluble forms than are usually considered to be available to agronomic crops.

### *Forest Floor*

Based on the rate of release of N from soil organic matter (table 2.13), on the relative rate of release of other nutrients compared to N, and on the amount of nutrients stored in forest floor (table 2.14), nutrient availability to trees from forest floor can be estimated (table 2.16).

**Table 2.16. Nutrient availability (released) from forest floor of upland forests in Great Lakes states.**

| Species Group | Nutrient | | | | |
|---|---|---|---|---|---|
| | N | P | K | Ca | Mg |
| | (lb/ac/yr) | | | | |
| Aspen-birch | 28 | 5 | 20 | 69 | 18 |
| Pine | 24 | 4 | 13 | 30 | 8 |
| Spruce-Fir | 30 | 5 | 17 | 53 | 14 |
| Upland Hdwds | 26 | 5 | 17 | 59 | 13 |

Although amounts of Ca, Mg, and even K that are annually made available from the forest floor (table 2.16) are relatively small compared to that available from the mineral soil (table 2.15), 20 to 30 percent of the available N is in the forest floor.

### *Organic Soils*

The results of the calculation of nutrient quantities within the organic soils (table 2.15) fell within the same range as that for mineral soils. A major difference from the results with mineral soils was the low level of K in the organic soils (table 2.15). Potassium is commonly recognized as occurring at low levels in organic soils (e.g., Waughman and Bellamy 1984). The dynamics of the formation of peatlands tends to differentially deplete K from the soils. Although total quantity of N is high in peatland soils because the soils themselves are composed almost wholly of organic matter with a significant fraction of N (ca. 1 to 2 percent), the low mineralization rate leads to a similar availability as with mineral soils (table 2.15).

## 2.1.6
## Other Nutrient Manipulations

### Fertilization

The addition of nutrients (fertilization) to soils used for production of agronomic crops has been carried out for centuries. In early times, materials such as manure and wood ashes were used to increase fertility. Fertilization was necessary because of the inherently low nutritional status of a soil, or because of the depletion of nutrients due to multiple crop harvests. Use of fertilizers for improving growth of forest stands is a more recent concept, but it has been carried out for well over 100 years (Baule and Fricker 1970). In agronomic practice, the major nutrients whose depletion necessitated fertilization were N, P, and K, as indicated by the fact that their relative amounts are routinely listed on fertilizer bags (e.g., 10-10-10 means that 10 percent of the fertilizer is N, 10 percent is $P_2O_5$ or an equivalent amount of P, and 10 percent is $K_2O$, or an equivalent amount of K.

Similarly, the major nutrients to which attention has been focussed in forest fertilization are also N, P, and K. Their relative deficiency affects the response of forest stands to fertilization; growth response will be greatest where deficiency is greatest. Response of forest stands to fertilizers depends on a myriad of factors, including climate, soil, tree species, age, size, vigor, availability of water, etc. (Binkley 1986). In general, however, N is most commonly deficient for tree growth. Stated another way, positive response to fertilization is most common following addition of N. Nitrogen is operationally applied to Douglas-fir and other forest stands in the Pacific Northwest at rates near 200 lb $ac^{-1}$ (Allen 1987, Bengston 1979), and in the southeast on loblolly and slash pine at about 100 lb $ac^{-1}$ (Binkley 1986). Numerous research trials have indicated positive responses of jack pine to N fertilization (with effects diminishing beyond about 100 lb $ac^{-1}$) in Ontario (Morrison and Foster 1990).

Although present in adequate amounts at stand establishment, N may become deficient as a stand matures and the available N is sequestered in standing volume and in the forest floor. Hence a common time for N application is within about 10 years of harvest, so that the investment cost of the fertilizer is carried for a short time and the increased growth is added to larger and hence more valuable trees (Bengston 1979). As a general rule, best response as measured by either economic or biologic criteria is most often on intermediate rather than good sites (Fight and Dutrow 1981, Morrison and Foster 1990). Weetman and Fournier (1984) estimate that about 50 lb of N fertilizer are required to produce an additional cord of wood in jack pine. As with all nutrient additions via fertilization, those additions do not compensate on a 1:1 basis for those removed by harvest or other disturbance. For example, Bengston (1978) estimates that N applications must be at least twice as great as losses in order to *stay even*.

In North America, most reports and positive results of P fertilization have occurred in the southeastern U.S.. In that region, addition of P to some clayey soils with high P-fixing capabilities, and especially to coastal sands and peats with very low P reserves, leads to increased tree growth (Pritchett 1979). Growth responses are most uniform for applications of about 80 lb $ac^{-1}$ to young stands and 50 lb $ac^{-1}$ to semimature stands (Kushla and Fisher 1980), although rates of about 50 lb $ac^{-1}$ are most common (McKee 1989).

Potassium deficiency, and hence response to K fertilization, is relatively uncommon in North America. There is no operational K fertilization, but research has found K deficiencies in conifer plantations that have been established on abandoned cropland on outwash stands in the northern U.S. (Stone and Leaf 1969). Apparently tree demands for K, and supplies from soil, weathering, and the atmosphere, are sufficiently balanced in most forest stands.

Although N, P, and K are the macronutrients that are most commonly added to agricultural soils as fertilizers, two other macronutrients, Ca and Mg, are also added to agricultural soils. The practice by which they are added is usually not referred to as fertilization, but as liming. Acidic agronomic soils are limed; acid soils are both low in pH and usually low in Ca and Mg. Liming of forest stands is relatively rare, but has recently gained impetus as a possible ameliorative technique for soils affected by acidic deposition (Andersson and Persson 1988). Based on European and primarily Scandinavian experience to this point, liming does not seem to markedly increase tree growth and may even decrease growth (Popovic et al. 1988). This is apparently due to the complex interaction of liming as it affects pH, rates of N mineralization, and changes in availability of other nutrients. To summarize, "the growth response of liming may give a reduction or increase corresponding to +/- 10%" (Popovic et al. 1988)—scarcely a strong response.

The complexity of forest fertilization is well-summarized in the conclusions of a paper by Dippon and Shelton, examining the economic return associated with fertilization of semimature slash pine plantations (Dippon and Shelton 1982). They state that the rate of return varies with the "soil group, level of fertilization and the product mix at harvest," and that decisions on fertilization should be "based on the stumpage diameter distributions which are desired, the price differentials prevailing, costs of treatment and the expected growth responses" (Dippon and Shelton 1982). Obviously, such decisions should not be made lightly.

### Site Preparation

#### *Mechanical*

Site preparation prior to stand establishment, including such practices as windrowing, bedding, chopping, and harrowing (Pritchett 1979), has the potential to affect the nutrient status of a site. As might be expected, those techniques that either move material off the site (as in rock raking) or concentrate it on the site (in slash piles or in windrows) have a more significant effect on nutrients than do practices that simply mix surface materials but do not move them laterally, such as chopping or harrowing. However, Pritchett (1979) suggests that enhanced decomposition and reduced uptake may lead to increased leaching losses of nutrients even following techniques that simply incorporate and do not move material.

There is no question, however, that windrowing displaces nutrients. For example, Burger and Pritchett (1988) found that after two growing seasons the soil of a intensively prepared flatwoods site in Florida had about 450 lb $ac^{-1}$ less N than did an adjacent control site and 225 lb $ac^{-1}$ less than a site that had only been chopped as a preparation technique. The intensive site preparation included windrowing, harrowing, and bedding. A more intensive study by Morris et al. (1983) in a similar forest system found that windrows, occupying about 6 percent of the harvested area, contained about 325 lb $ac^{-1}$ of N, 16 lb $ac^{-1}$ of P, and 24 lb $ac^{-1}$ of K. These amounts were equivalent to the amount of nutrients removed in six merchantable bole harvests, and were about 10 percent of total site nutrients.

In spite of the removal of nutrients associated with many site preparation practices, clear evidence of declines in productivity associated with such losses are rare. There are few data for forests in the Great Lakes region; most of the research has been carried out in the southeastern U.S. For example, although Burger and Pritchett (1988) found less N in the chopped site compared to the site with intensive preparation, they also found that after two years the stem volume of the seedlings on the intensively prepared site was almost three times greater than on the chopped site. Similarly, Stransky et al. (1985) found that although blading significantly decreased soil nutrients on a loblolly pine site, after eight years cubic foot volume on the bladed site was nearly three times that on a control site, and was statistically equal, though somewhat less, than on a site that had been chopped. Finally, removal of three inches of surface soil followed by planting to loblolly pine significantly decreased soil nutrient levels three years after treatment, but led to significantly higher seedling volumes (Tuttle et al. 1985).

Both the reduction in competition (Tuttle et al. 1985, Stransky et al. 1985), and the increase in N mineralization due to disturbance (Burger and Pritchett 1988) were cited as the reasons for increased growth of seedlings on the most intensively prepared sites. The problem in assessing the impact of nutrient depletion due to intensive site preparation is the separation of short-term (reduction in competition) from long-term (reduction in nutrient capital) effects. Most studies have not been conducted for sufficient time to assess the latter effect. There are some exceptions. Nineteen years after establishment, Haines et al. (1975), found reductions in site index of loblolly pine of about 20 percent associated with windrowing; stem volume was only about half as great in the windrowed site as in an adjacent area that was only burned. In the southern hemisphere, decreased productivity in the second as compared to the first rotation of radiata pine has been identified in both Australia (Keeves 1966) and New Zealand (Dyck and Skinner 1990). Although on some sites the decline has been associated with harvest removals of nutrients (Dyck and Skinner 1990), displacement of soil organic matter and nutrients through inappropriate site preparation practices is considered to be the major cause of the problem (Dyck and Skinner 1990). For example, Ballard (1978) found greater stem volumes in the vicinity of windrows, and significantly smaller stem volumes far from windrows, in a radiata pine plantation in New Zealand. The overall growth of the windrowed site was less than in a similar site without windrows. The situation is well summarized by Dyck and Skinner (1990), "there is increasing evidence that inappropriate site treatments have reduced site quality and radiata pine productivity on several sites throughout New Zealand and that the cost of restoring productivity may be high." In conclusion, available information indicates that over the long-term, nutrient depletion due to site preparation will have a negative effect on tree growth.

### *Fire*

Prescribed burning is used as a technique for preparing a site for planting or for making it more suitable for natural regeneration. The goal of the burning is to inhibit competition, reduce slash, and/or to expose bare mineral soil. Although fires have occurred since time immemorial in North American forests (White 1972), including forests in Minnesota (Wright 1974), concern has been expressed about the nutrient losses associated with use of fire for site preparation. Fire rapidly oxidizes organic matter, releasing $CO_2$ and $H_2O$ as volatile products of combustion. Of more concern, however, is the fate of the other macronutrients within the organic matter. If combustion of organic matter is nearly complete, then N and organic P (but not inorganic P) are volatilized, while oxides of Ca, Mg, and K remain in the ash. Three questions must be addressed when considering the impact of prescribed burning on forest nutrient cycles: (1) the amount of complete combustion of organic matter, (2) the fate of the nutrients within the organic matter, and (3) the rate of replenishment of the lost nutrients.

Complete combustion is rare. Fires are most intense if accumulated, dry fuels are burned. Slash resulting from harvesting activities increases the fuel load at the surface; this is especially true if the slash is windrowed or piled (Wells et al. 1979). Depending on the season of the year, and hence the degree of fuel dryness, temperatures at the soil surface under such piles can reach 1,000°F (Raison 1979). In general, however, significant temperature increases are confined to the upper few inches of soil (Raison 1979). The increase is moderated because of the insulating effects of the litter layer (even if it is partially or wholly consumed), and because temperatures of moist soil do not exceed 200°F until the soil water has evaporated (Wells et al. 1979). Except under extreme conditions, most fires do not totally consume the forest floor. Although some proportion of the upper part of the forest floor can be lost, complete consumption is restricted to scattered *hot* spots (Wells et al. 1979). Estimates of forest floor loss ranged around 35 percent (Richter et al. 1982). The proportion of nutrients volatilized or oxidized is seldom as great as the proportion of forest floor that is consumed. Through decomposition processes, nutrients are concentrated in the basal layers of forest floor, the layers least likely to burn (Richter et al. 1982). Unless fires are very severe, organic matter in mineral soil is unlikely to be lost and may even increase due to movement of volatiles from the forest floor (Raison 1979, Wells 1971).

The fate of the combustion products varies with the nutrient. When effects of fire on nutrients are considered, nitrogen usually receives most emphasis because of its importance to ecosystem processes (Woodmansee and Wallach 1981). If the organic matter of which it is a part is totally consumed, then it is lost from the system by volatilization as $N_2$ or N oxides (Raison 1979). Based on data from Minnesota, volatilization of half the N within the forest floor (an unlikely occurrence) would decrease soil N by 150 lb $ac^{-1}$, about ten percent of that present in the rooting zone. Although some loss occurs, enhanced microbial activity following fire often makes N more available to plants following fire than before (Richter et al. 1982). Inorganic P, and Ca, Mg, and K are converted to oxides that are water soluble (Raison 1979). Although susceptible to leaching, a combination of factors, including soil immobilization (Raison 1979, Wood et al. 1984) and plant uptake (Woodmansee and Wallach 1981), prevent loss from the system.

Replenishment of nutrients lost by fire occurs by the same processes as in undisturbed systems, by atmospheric deposition, weathering, and, in the case of N, by biological fixation. While the rates of addition for most nutrients do not differ between burned and unburned systems, N is an important exception. There is extensive documentation of increases in rates of biological N fixation following fire (Raison 1979, Wells et al. 1979, Woodmansee and Wallach 1981). This is associated with better growing conditions for N-fixers, including greater availability of substrate for nonsymbiotic fixers, and increased light, water, and nutrients for symbiotic fixers. As a result, ecosystem N has most often been found to have changed negligibly within a few years after fire (Raison 1979). Referring to Minnesota conditions, if rates of biological inputs of N were to double following fire, a conservative increase, then the N loss of 150 lb $ac^{-1}$ suggested above would be replenished in about 12 to 15 years.

Unless prescribed burns are carried out under extremely dry conditions, and are associated with piling and windrowing of slash, they are of little long-term consequence to the nutrient economy of Minnesota's forests.

## 2.2
## Soil Compaction

The following section provides a broad overview of how forest management activities influence soil physical properties and how this might affect site quality and future yields. Readers are referred to publications in the literature cited section for more detailed discussions of selected topics. An attempt was made to focus this information on local conditions by presenting data from Minnesota where available. However, a considerable portion of the work summarized here was performed outside the region.

Soil compaction is one of several types of closely related physical soil disturbance that can occur during timber harvesting and forest management activities. The other types of physical soil disturbance include puddling, rutting, and scarification. These disturbances often occur simultaneously and are almost exclusively caused by (1) trafficking by heavy equipment during felling, forwarding, skidding, and site preparation operations, (2) the dragging action of logs as they are moved from the stump to the landing, and (3) slash disposal and the creation of planting or seeding sites during site preparation. It is difficult to distinguish between each type of disturbance in terms of their effect on site properties, and all of these disturbances are often referred to generically as soil compaction. In some cases this can lead to confusion and misrepresentation of forest management impacts on future forest growth, particularly when true compaction occurs without the other types of disturbance or vice-versa. Each of these disturbance types and their specific impacts on site properties are discussed below.

### 2.2.1
### Physical Soil Disturbances

**1 Soil Compaction**

Soil compaction is the increase in soil density resulting from loads applied to the soil surface, and is assessed by one of several techniques designed to measure soil density. During the compaction process, soil volume is decreased primarily through the elimination of macropores (pores $\geq$0.002 inches in diameter). Pore volume and pore size distribution are key properties that govern gas and water relations in the soil. Because of their relatively large diameter, macropores are particularly important in regulating the rates of water and gas movement.

Water is held more tightly and moves more slowly through smaller diameter pores (Baver et al. 1972). Compacted soils take longer to drain after they are saturated. This may be beneficial to plant growth in some droughty soils (Rosenburg 1964). However, compaction detrimentally reduces aeration in most other soils. This is attributed to both the disruption of continuous pathways for gas exchange and the increased proportion of water-filled pores which also block gas exchange routes (Ruark et al. 1982).

Soil compaction affects site quality and tree growth through its effect on the rooting environment. In well aerated soils, gaseous diffusion through air-filled pores maintains a near equilibrium between soil air and the atmosphere (Baver et al. 1972). When this continuum is interrupted, the major mechanism for gas exchange becomes molecular diffusion through water-filled pores, with a gas exchange rate that is 5 orders of magnitude slower than between air-filled pores (Meet and Stolzy 1978). Reduced aeration significantly decreases the respiratory activity of plant roots and their capacity to supply the plant with adequate moisture and nutrients.

Compaction also increases soil strength, which reduces root growth by increasing soil resistance to root penetration. Roots are generally only able to penetrate pores that have a diameter larger that of the root (Ruark et al. 1982). Once inside a pore, roots can expand laterally to a diameter larger than the pore only if they can exert a force great enough to expand the pore size. The agricultural literature contains many reports of crop roots unable to penetrate below a compacted plow pan (see for example Hopkins and Patrick 1969). In dense soils, root growth is often concentrated between ped faces (Foil and Rolston 1967). Studies have identified soil densities that are limiting to some tree root growth. Minore et al. (1969) reported that the roots of seven northwestern species could not penetrate a sandy loam compacted to 1.59 g/cm$^3$. Loblolly pine seedling roots were limited by densities of 1.33 g/cm$^3$ in loamy sands and 1.20 g/cm$^3$ in fine sands (Ruark et al. 1982). Daddow and Warrington (1983) summarized the results of many investigations and estimated growth limiting bulk densities for different soil textures (figure 2.3).

The decrease in porosity associated with compaction also reduces soil infiltration capacity or the rate of water movement into the soil. Hatchell et al. (1970) reported that infiltration capacity decreased from 25.2 in./hr in undisturbed soils (bulk density of 0.75 g/cm$^3$) to 2.6 in./hr when the soil was compacted to 1.14 g/cm$^3$. In addition to reducing the amount of soil water available for plant growth, slower infiltration capacities result in increased amounts of overland flow, which can lead to increased erosion rates.

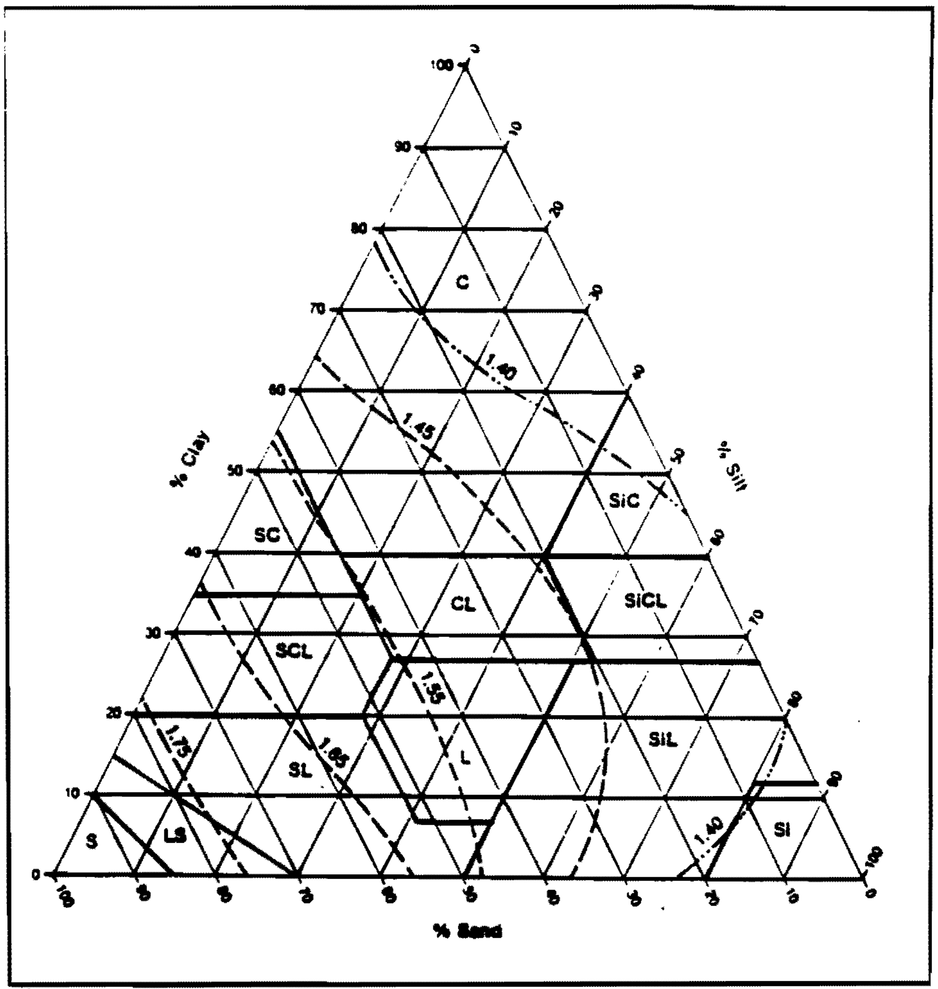

**Figure 2.3.** Growth limiting bulk densities for different soil textures (Daddow and Warrington 1983).

### 2 Puddling

Puddling is the reorientation of soil particles in response to an applied load. Puddling generally occurs in fine-textured soils at high soil water contents and may or may not result in an increase in soil density. During puddling, flat, clay-sized particles are forced into a parallel orientation that effectively seals the soil surface. In puddled soils, gas exchange between the soil and the atmosphere is greatly reduced. As with compaction this creates a poorer environment for root growth, as well as a potential for increased erosion due to more overland flow.

### 3 Rutting

Rutting occurs when wheels or tracks break through the surface litter or root mat and create depressions in the mineral soil. Rutting generally occurs at high soil water contents and is often accompanied by some compaction and puddling. Rutting channels surface runoff, which can lead to erosion. This may be compounded by compaction or puddling in the base of the rut. Dickerson (1976) reported that percolation rates decreased from 4.5 in./hr in undisturbed soils to 1.6 inches/hr in rutted soils. Ruts can also disrupt surface drainage patterns, increasing water ponding on level sites.

Another major concern of rutting is the physical injury to existing root systems that can harm residual trees left on a site. It can also be detrimental for species such as aspen that regenerate by root suckering. Aspen root injury was observed in rutted portions of harvested areas in Minnesota. This root injury may be responsible for the poor aspen regeneration reported in these areas (Bates 1990, Zasada and Tappeiner 1969a).

#### 4 Scarification

Scarification is the displacement of the forest floor or surface litter layer. This can occur inadvertently during skidding or other operations, or it can be the objective of some site preparation activities.

The forest floor (litter layer) and the upper part of the mineral soil contain a high concentration of soil nutrients. The forest floor also insulates the soil surface from temperature extremes and desiccation. While scarification can set back competing vegetation and improve seedling survival, studies have demonstrated that excessive displacement of the forest floor can significantly reduce regeneration quality (Morris et al. 1983, Tuttle et al. 1985, Weingartner 1980).

### 2.2.2
### Soil Strength

Soil strength is the resistance of soil particles to movement and is a function of the frictional and cohesive forces present in the soil. Soil strength determines the amount of compaction, puddling, and rutting that occur under a given load. Frictional forces occur at interparticle contacts, which occur primarily between coarser-sized particles (sand-sized or greater). The strength of these contacts are largely unaffected by soil water content, although they will be reduced at extremely wet or dry conditions. Cohesive forces arise from electrochemical forces of attraction between colloidal (clay-sized) particles. Cohesive forces are greatly affected by soil water content. At low water contents, soil colloids are held tightly together and are highly resistant to movement. As soil water content increases, water films develop between individual particles causing them to separate and decreasing the attractive forces between them. The result is a lessening of particle resistance to movement and a decrease in soil strength.

Consequently, soil strength is largely controlled by soil water content and particle size distribution. Coarse-textured soils and soils containing a large amount of coarse fragments (rocks and gravel) exhibit the greatest amount of strength across the widest range of moisture conditions. Soils that are high in clay exhibit a high amount of strength when they are dry, but their strength decreases rapidly as soil water content increases. Humic compounds in soil organic matter contribute to soil strength by cementing soil particles together, though the amount of strength contributed by organic matter decreases as soil water content increases (Byrnes et al. 1981).

The soil water content at which the maximum density will be achieved varies with the applied load (Weaver and Jamison 1951). As the load increases, the optimum water content decreases, and the maximum obtainable density increases. Under the load conditions typically imposed during forest harvesting and management activities, maximum compaction occurs when the soil water content is near field capacity. This is defined as the amount of water remaining in a soil that was saturated after it had drained freely for two days. As the soil water content increases above field capacity, pore water pressure supports the load and inhibits against any further increase in density. However, it is important to recognize that soil strength will continue to decrease as water content increases above field capacity to saturation; and while pore water pressure will prevent a further increase in soil density, these soils are increasingly sensitive to puddling and rutting.

There have been reports that surface residues, such as litter or slash, can protect the underlying mineral soil from the compactive forces of forestry equipment. These organic residues will compress, absorbing the compactive forces, and then rebound when the force is removed. In some cases an intact forest floor layer 2 to 4 inches thick can protect the soil for one or two equipment passes (Miles 1978). Mace (1970) reported a twofold increase in density for full-tree versus tree-length skidding, which was attributed to the greater amount of slash protecting the soil on the tree-length site.

Season has a major influence on soil strength, particularly in areas that experience cold winters. Snow cover can protect the underlying soil from compactive forces, and frozen soils are extremely resistant to particle movement. Alm (1971) reported that following winter tree-length and full-tree logging in northern Minnesota, much of the duff layer and lesser vegetation were practically undisturbed. Mace (1971) compared summer to winter harvesting on two sites in Minnesota when there was 12 to 16 inches of snow and the soil was frozen to between 4 and 6 inches. Mace reported that medium and heavy disturbance occurred on an average of 47 percent of the summer logged sites versus only 9 percent of the winter logged sites. Only 1 percent of the winter logged area was heavily disturbed.

Because of the importance of soil water content, soil strength also varies greatly with seasonal hydrologic cycles. Under a continental climate regime, such as exists in Minnesota, soil water content is generally greatest during the spring following snowmelt. Water content decreases during the summer due to high rates of evapotranspiration associated with warm temperatures and rapid plant growth. Soil water content increases again in the fall as plants become dormant. This pattern is demonstrated for an agricultural field near Lamberton, MN (figure 2.4). The same pattern has also been documented in forested areas in northern Minnesota (Verry 1972). Thus under average or typical climatic conditions, soil strength in medium- and fine-textured soils will be lowest in the late spring and early summer. Soil strength will increase during the summer as soils dry, then drop off again in the fall. However, it is important to recognize that in any given year, soil water content, and thus soil strength, can deviate significantly from this pattern.

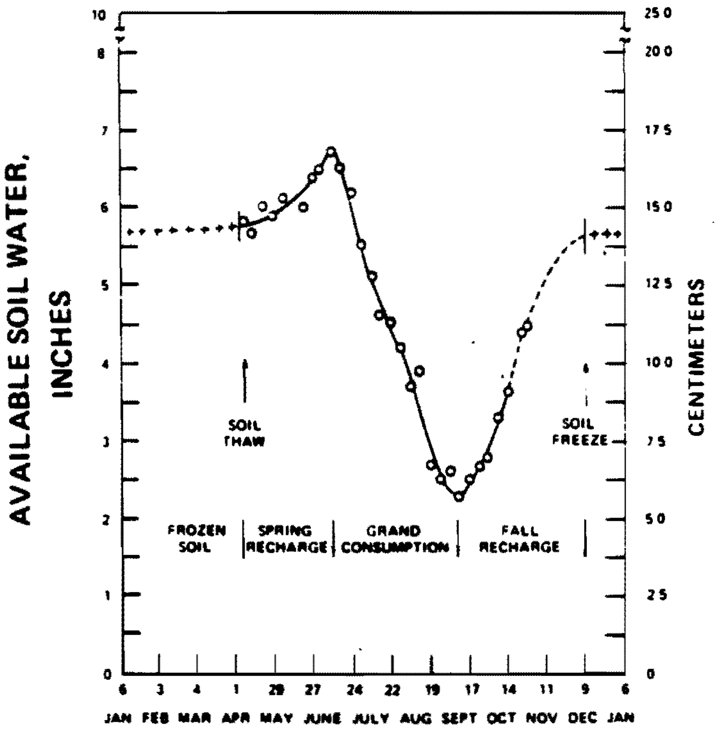

**Figure 2.4. The average total plant available water to a depth of 5 feet under continuous corn during the course of a year at Lamberton, MN, for 1960-76 (Baker et al. 1979).**

### 2.2.3
### Equipment Considerations

Most of the physical soil disturbance caused during forest management activities is directly attributable to trafficking by heavy equipment. Consequently, equipment type can influence the amount of disturbance that occurs. Many studies compare equipment impacts based on ground contact pressure of the vehicles in question. For track-type vehicles, this is commonly arrived at by dividing the total load by the area of the track in contact with the ground. For rubber-tired vehicles, ground contact pressure is often approximated by the inflation pressures of the tires.

Based on these calculations, rubber-tired vehicles were considered to have greater contact pressures, and early reports suggested that they caused greater amounts of disturbance than track vehicles (Lull 1959). However, subsequent research has not identified a consistent trend regarding relative amounts of disturbance caused track versus rubber-tired vehicles (see table 2.17 for results from a number of soil compaction studies conducted in North America). For example, in a California study, Froehlich et al. (1980) reported that crawler tractors caused greater increases in soil density than rubber-tired vehicles. Bates (1981), also reported that track vehicles caused the same or more compaction than rubber-tired vehicles. However, Burger et al. (1984) reported no significant differences between tracked and rubber-tired vehicles in terms of increased soil density or decreased soil porosity. This lack of a clear trend is attributable to the difficulty in accurately measuring ground contact pressures for different equipment types, and the fact that there are factors that contribute to compaction and related disturbances. Inflation pressure can give misleading results of the ground-contact pressure exerted by rubber-tired vehicles. Pressures along stiff sidewalls can be two to three times as great as the inflation pressure (Larson and Gill 1973). Also, wheel slippage can cause significant compaction and rutting regardless of inflation pressure (Raghaven et al. 1978). In addition, the ground pressure under track vehicles is not constant. In undulating topography or when pulling heavy loads, pressures can be shifted to the rear one-half or one-third of the track (Byrnes et al. 1981). Equipment vibration and slower travel speeds also increase the amount of disturbance that occurs.

Equipment specifically designed to reduce ground pressures has been shown to reduce but not eliminate compaction. In a study where different equipment types made 20 passes over the same area, soil density increased 9 percent for a torsion suspension vehicle (these are track vehicles where the track is flexible and thus able to conform to the ground surface), 11 percent for a rubber-tired vehicle, and 16 percent for a tracked vehicle (Froehlich et al. 1980). Other studies have also demonstrated significantly less compaction on sites harvested with torsion suspension vehicles than traditional track or rubber-tired vehicles (Albright 1980, Sidle and Drlica 1981).

**Table 2.17.** Results of studies evaluating forestry equipment impacts on soil compaction.

| Source | Equipment type | Sample depth cm | Soil H2O content % | Control density g/cc | Trafficking level/Soil density —# of passes-g/cc— | | | |
|---|---|---|---|---|---|---|---|---|
| Bates 1981 | Tractor | 0-8 | 15 | 1.06 | 1-1.05 | 2-1.11 | 8-1.19 | |
| | RT skidder | 0-8 | 15 | 1.06 | 1-1.03 | 2-1.08 | 8-1.16 | |
| Burger et al. 1984 | Tractor | 0-8 | 21 | 1.30 | 1-1.47 | 3-1.53 | 9-1.62 | |
| | RT skidder | 0-8 | 21 | 1.30 | 1-1.47 | 3-1.53 | 9-1.62 | |
| Campbell et al. 1973 | RT skidder | 0-8 | ?[a] | 1.37 | 1-1.38 | 3-1.40 | 10-1.45 | 15-1.46 |
| Greene 1983 | RT skidder | 0-6 | 19 | 1.20 | 1-1.20 | 3-1.28 | 10-1.26 | |
| | RT skidder | 0-6 | 34 | 1.05 | 1-1.13 | 3-1.09 | 10-1.16 | |
| Gent et al. 1983 | RT skidder | 0-8 | 22 | 1.04 | | | | 15-1.43 |
| | RT skidder | 0-8 | 22 | 1.07 | | | 8-1.19 | |
| | RT skidder | 0-8 | 22 | 1.00 | | | 8-1.20 | |
| Gent & Morris 1986 | Fell-bunch | 0-8 | fc[b] | 1.25 | | | ?-1.50 | |
| | RT skidder | 0-8 | fc | 1.25 | | | ?-1.47 | |
| Rachel & Karr 1989 | RT skidder | 0-8 | >10 | 1.20 | | >4-1.35 | ?-1.40 | ?-1.48 |
| | RT skidder | 0-8 | <10 | 1.19 | | ?-1.24 | ?-1.32 | ?-1.40 |
| Hatchell et al. 1970 | RT skidder | ? | ? | 0.75 | | ?-0.92 | ?-1.08 | ?-1.14 |
| Lockaby & Vidrine 1984 | RT skidder | 0-5 | ? | 1.03 | | ?-1.01 | ?-1.17 | ?-1.13 |
| Guo and Karr 1989 | RT skidder | 0-8 | 3 | 1.18 | 1-1.35 | 3-1.40 | 6-1.41 | 12-1.43 |
| | RT skidder | 0-8 | 14 | 1.18 | 1-1.52 | 3-1.55 | 6-1.59 | 12-1.57 |
| | RT skidder | 0-8 | 16 | 1.18 | 1-1.53 | 3-1.61 | 6-1.62 | 12-1.60 |

[a] ? indicates that data were not available.
[b] fc indicates field capacity.

Wide or high flotation tires have also been promoted as a means of reducing disturbance, with several studies reporting less soil compaction for wide tires than traditional tires (Sauder 1985, Murphy and Hassan 1988). However, as with torsion-suspension vehicles, wide tires do not eliminate compaction. Green and Stuart (1985) reported that wide tires and narrow tires compacted soils to the same maximum densities, but that more passes were required to achieve this density for the wide tires. Rummer and Sirois (1984) found that wide tires increased traction and reduced overall disturbance on wet soils. However, the amount of compaction was not significantly less in areas trafficked by wide tires than in areas trafficked by narrow tires. They suggest that these results may be partially attributable to the heavier loads afforded the wide-tire vehicles due to their greater traction. An additional concern of wide tires is that for a given axle load, they transmit greater stresses into the subsoil, and thus cause deeper disturbance than narrow tires (Swan et al. 1987).

There is almost universal agreement that, regardless of the equipment used, a majority of any compaction that occurs, occurs during the first several passes (Jamison et al. 1950, Reaves and Nichols 1955) (figure 2.5). This is attributed to the initial compression of the large macropores and the fact that soil strength increases with density. As discussed above, the major exception to this rule is when surface residues are able to protect the soil for one or two passes. Generally, the maximum density increase occurs near the soil surface with the magnitude of change decreasing with depth. Compaction in forested soils seldom occurs deeper than 12 inches (Lull 1959).

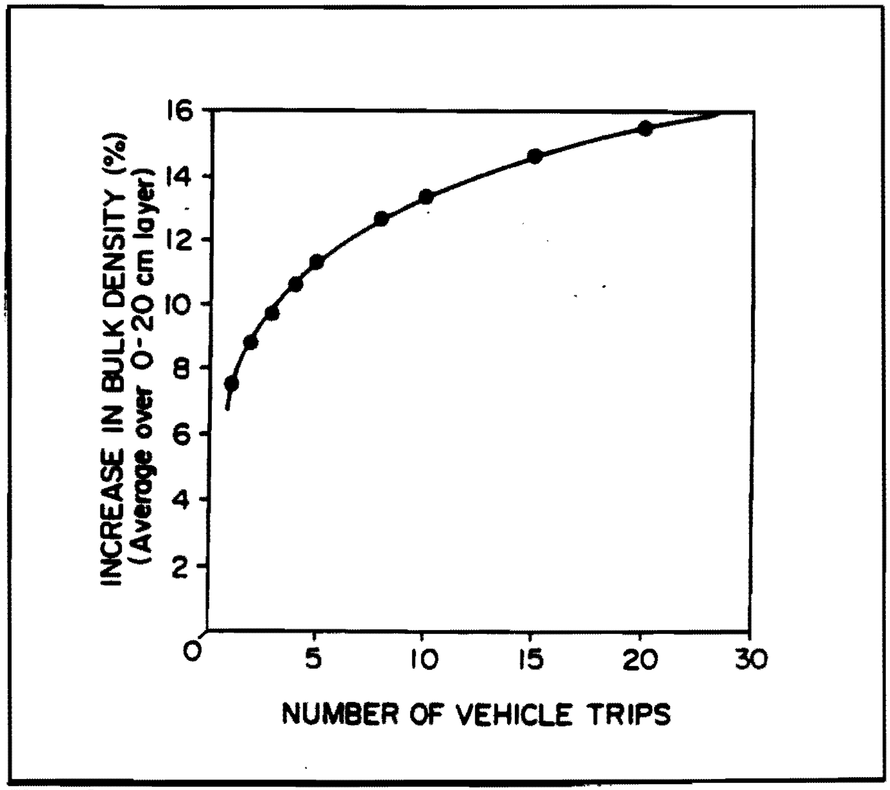

**Figure 2.5. Relationship between increases in bulk density and the number of machine trips (Froehlich et al. 1980).**

While the above studies discussed equipment related disturbance in terms of increases in soil density, it must be restated that important site disturbance can and does occur without significant increases in density being observed. As discussed above, puddling and rutting can occur without increasing soil density. Equipment operations can mix low-density organic material into the top of the mineral soil and actually decrease bulk density in some disturbed areas. In some cases, increases in soil density may be difficult to identify because of the natural spatial variability in many soil properties, including soil density.

Most of the equipment used in Minnesota are traditional track-type vehicles or rubber-tired vehicles (Jaakko Pöyry Consulting, Inc. 1992b). Essentially all of this equipment exert forces capable of causing compaction related disturbances. There have been some recent trials in Minnesota with wide, high-flotation tires (Schmit, per. comm. 1992), though this equipment will not eliminate physical site disturbances. Aerial yarding systems, such as helicopters or cables, which do eliminate many physical disturbances are not used in Minnesota.

### 2.2.4
### Areal Extent of Site Disturbance

In addition to the magnitude of the disturbance, a critical factor in evaluating forest management impacts on site properties is the areal extent of the disturbance. The areal extent of site disturbance is a function of the soil strength at the time of the operation and the intensity of equipment trafficking (both areal distribution and number of passes). The factors influencing soil strength were discussed above (section 2.2.2). The intensity of equipment trafficking is largely determined by the type of operation (i.e., clearcutting, partial cutting, or site preparation) and the equipment used.

Burger et al. (1984) found less area disturbed on steep topography. This was attributed to steeper topography restricting trafficking patterns, thereby reducing overall disturbance. However, other studies from a wide range of sites indicated that there is not a clear relationship between slope steepness and soil disturbance caused by ground based harvesting systems (Smith and Wass 1976).

Thinnings or other partial harvests may result in less areal disturbance than clearcuts (Dickerson 1968, Nyland et al. 1977). However, these differences are negligible over the entire rotation of a stand where multiple entry into the nonclearcut stands may actually cause more disturbance than a single clearcutting operation. Others have reported that the area disturbed is similar for both clearcutting and selection cutting (Cromach et al. 1979, Froehlich and Berglund 1976).

It is difficult to estimate the amount of the site that is actually trafficked by heavy equipment. There are few, if any, studies that monitored equipment trafficking throughout the duration of an operation. Consequently, most studies quantify trafficking patterns based on post-treatment site disturbance. Table 2.18 presents the areal disturbance reported for a number of studies in North America. There was some disparity in definitions and methodology used in these studies. For the purpose of creating this table, undisturbed areas had no visible disturbance, light disturbance consisted of shallow scarification, moderate disturbance generally referred to secondary skid trails or compaction and/or rutting up to 2 or 3 inches deep, and heavy disturbance consisted of primary skid trails, landings, or soil disturbances at least 4 to 6 inches deep. The amount of moderate and heavy disturbance in these studies ranged from 15 to 81 percent of the site. At the other end of the spectrum, between 8 and 77 percent of these sites were undisturbed.

Attention was focused on disturbance caused by operations that are typical of Minnesota conditions. The construction of bladed skid trails in the steep topography of the Pacific Northwest contributed greatly to the large areas of heavy disturbance in that region. This type of activity is not typical in Minnesota. The results of those studies presented in table 2.18 that are most representative of Minnesota operations are summarized in table 2.19. Seven of these studies were hand-felled clearcuts from Minnesota. An average of 34 percent of these sites were in the moderate and heavy disturbance categories. Many operations in Minnesota also employ mechanical felling, which can increase site disturbance because of the additional trafficking by the felling machine. In four mechanically-felled sites in Louisiana, an average of 12 percent of each site was occupied by primary skid trails, 20 percent was occupied by secondary skid trails, and fellers tracks were visible on an additional 33 percent of each site (Shoulders and Terry 1978). No data were available from mechanically-felled operations in Minnesota. In a New England study of mechanically harvested sites, nearly twice as much area was moderately and heavily disturbed as in the hand felling operations in Minnesota. Not all of this disturbance was attributable to heavy equipment. As with many harvesting operations, some site disturbance is caused by the dragging action of logs. However, in the New England sites, Martin (1988) estimated that 48 to 81 percent of the soil received some soil compaction, and that the areal extent of serious compaction ranged from 23 to 31 percent.

Forest haul roads contribute significantly to soil physical disturbances. Several investigators have reported on haul road area (Campbell et al. 1973, Krag et al. 1986, Martin 1988, Wooldridge 1960, Smith and Wass 1976). Their estimates of haul road area range from 3 to 8 percent of timberland area, with an overall average of 5.5 percent. For the purposes of this review, haul roads are defined as any roads used by logging trucks to transport forest products. It is difficult to estimate the area of haul roads created during forest management operation in Minnesota because no detailed records are available. There are many classes of haul roads representing different levels of use. They range from temporary, unimproved roads that are only utilized while a timber sale is active to constructed, heavy-duty roads that may be used for many years. Part of the difficulty in monitoring haul roads is due to the fact that they are built by a number of entities ranging from individual loggers to state agencies.

**Table 2.18.** Summary of areal extent of site disturbance for some ground skidding operations in North America.

| Source | | | Disturbance Level | | | | |
|---|---|---|---|---|---|---|---|
| | Location[1], Treatment[2] | n[3] | Undist | Light | Mod | Heavy | Mod + Heavy |
| | | | % of site | | | | |
| Krag et al. 1986 | BC | 10 | | | 10 | 35 | 45 |
| Bockheim et al. 1975 | BC slopes < 25% | 3 | | 18 | 11 | 33 | 44 |
| | BC slopes < 55% | 6 | | 32 | 14 | 7 | 21 |
| Garrison & Rummell 1951 | WA, OR | 18 | | 6 | 15 | | 15 |
| Wooldridge 1960 | WA | 1 | | 7 | 6 | 16 | 22 |
| Smith & Wass 1976 | BC | 1 | | | 6 | 36 | 42 |
| Harr et al. 1979 | OR shelterwood | 1 | 52 | | | | |
| | OR | 2 | 8 | | | | |
| Zasada & Tappeiner 1969a | MN handfell | 3 | 43 | 32 | 15 | 9 | 24 |
| | MN 30% sheared | 1 | 39 | 32 | 18 | 11 | 29 |
| Mace et al. 1971 | MN | 2 | 30 | 23 | 31 | 16 | 47 |
| Martin 1988 | NE Drott | 1 | 29 | 20 | | | 51 |
| | NE RT feller | 1 | 7 | 13 | | | 81 |
| | NE Drott | 1 | 8 | 31 | | | 62 |
| Zasada 1971 | MN shortwood | 1 | 51 | 26 | 15 | 8 | 23 |
| | MN treelength | 1 | 34 | 28 | 29 | 9 | 38 |
| | MN fulltree | 1 | 24 | 30 | 35 | 11 | 46 |
| Steinbrenner & Gessell 1955 | WA | 9 | | | | | |
| Dyrness 1965 | OR | 1 | 36 | 26 | | | 36 |
| Sidle & Drlica 1981 | OR 1/3 vol cut | 1 | | | 3 | 12 | 15 |
| Hatchell et al. 1970 | SC, VA | 9 | | | 12 | 20 | 32 |
| Nyland et al. 1977 | NY | 2 | | | | | 34 |
| Campbell et al. 1973 | GA | 1 | 77 | | | | 17 |
| Geist et al. 1989 | OR, WA | 11 | | | | 29 | 29 |
| Miller & Sirois, 1986 | MS | 4 | | | 13 | 31 | 44 |

[1] BC=British Columbia, WA=Washington, OR=Oregon, MN=Minnesota, NE-New England, SC=South Carolina, VA=Virginia, NY=New York, MS=Mississippi.

[2] All clearcuts unless otherwise indicated.

[3] n=number of harvest units evaluated.

**Table 2.19.** Summaries of data presented in table 2.18 that are most representative of Minnesota conditions.

| System | Undist. | Light | Mod. | Heavy | Mod. + Heavy |
|---|---|---|---|---|---|
| Overall average from table 2.18 | 34 | 23 | 16 | 19 | 33 |
| Clearcut, mechanically felled | 15 | 21 | | | 64 |
| Minnesota studies, clearcut, hand-felled | 37 | 28 | 23 | 11 | 34 |

Although detailed records were not available, silviculturists within the MNDNR provided rough estimates of the haul road area in different regions of the state. They estimate that about 0.5 to 3 percent of the total harvest area is impacted by forest haul roads. There is some local variation that may be due to surrounding land use patterns. For example, timber road area may be less in agricultural areas where existing farm and field roads can serve as timber haul roads.

Mechanical site preparation is the final source of physical site disturbance associated with forest management. The objective of mechanical site preparation is to facilitate regeneration by creating planting sites, disposing of slash, and/or controlling plant competition. Consequently, mechanical site preparation can impact a large percentage of a site by design. The amount of compaction and related disturbance caused during mechanical site preparation are a function of the type of operation and the site conditions at the time of the operation. Because most site preparation goals can be achieved with a single pass, minimal impacts will occur when equipment operates on top of slash or when soils are dry or frozen. Disk trenching and patch scarification are two operations commonly practiced in Minnesota where equipment can operate on slash and the forest floor.

Maximum disturbance can occur during operations, such as windrowing and rock raking, that are designed to remove or pile slash. During these operations equipment can be in direct contact with mineral soil material. Under some conditions, windrowing can impact up to 90 percent of a site (Utzig and Walmsley 1988). Disking designed to sever the roots of competing vegetation can also impact a large percentage of a site.

### 2.2.5
### Disturbance Effects on Tree Growth

As stated above, soil disturbance has traditionally been evaluated in terms of soil compaction or increases in soil density. Consequently, most studies tried to evaluate the effects of equipment-related disturbances on site quality by comparing tree growth to soil density. These studies have demonstrated that as soil density increases, tree growth decreases (figure 2.6). Froehlich (1974) reported a 1.3 percent decrease in Douglas-fir height growth for 1 percent increase in soil density. The loss in volume growth may be 2 to 3 times the reduction in height growth (Froehlich 1979). This growth reduction is attributed to reduced aeration and increased resistance to root growth in soils of high density. However, it is difficult to determine whether these growth reductions are a function of increased density alone, or may be attributed to puddling, rutting, and/or scarification.

There are few studies that have identified the long-term impact of soil physical disturbances on productivity. Wert and Thomas (1981) evaluated

Douglas-fir growth in compacted skid trails 32 years after logging. Both stocking and tree size were reduced in the compacted skid trails. They estimated that tree volume in skid trails was about 75 percent less than in noncompacted areas. This represents an overall volume loss of about 12 percent, based on 25 percent of the area being occupied by skid trails. Utzig and Walmsley (1988) summarized a number of studies from the Pacific Northwest and found that volume reductions in compacted areas ranged from 26 to 95 percent, and when this was prorated over the entire cutting unit, losses ranged from 2 to 15 percent. Similar findings have also been reported in the south where Perry (1964) observed loblolly pine volume was 45 percent lower in skid roads than in uncompacted areas.

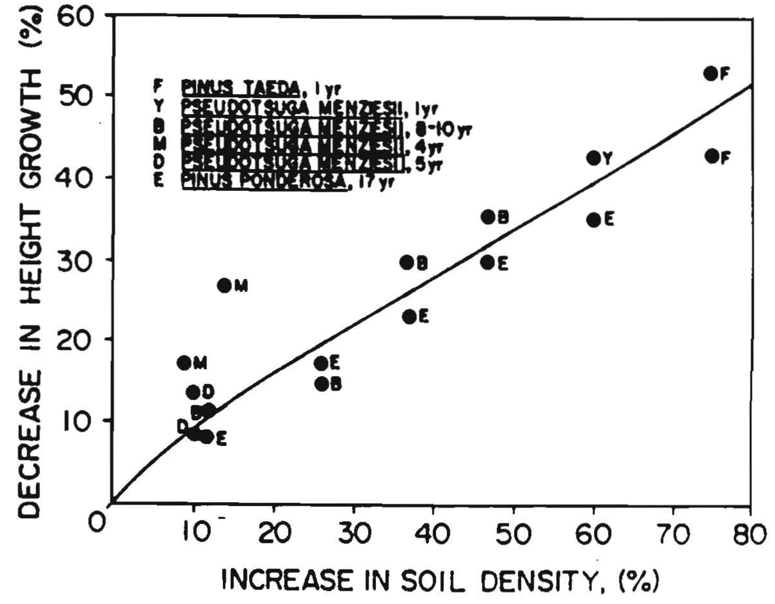

**Figure 2.6. Relationship between the increase in bulk density and the decrease in seedling height growth (Froehlich and McNabb 1984).**

Studies have identified reduced forest growth on soils that were rutted and scarified, with and without measured increases in soil density. In Oregon, Youngberg (1959) reported chlorotic and significantly shorter Douglas-fir seedlings in skid trails. In addition to higher densities, skid trail soils had lower organic matter content than other areas. Several investigators have reported poor aspen regeneration in heavily trafficked areas. Low aspen stocking and height growth has been found in skid trails up to ten years after harvest (Bates et al. 1990, Zasada and Tappeiner 1969b). In Arizona, aspen were lacking in skid trails and landings 23 years after logging (Schier et al. 1985).

### 2.2.6
### Disturbance Duration

The recovery rate for compacted forest soils ranges from a few years (Holman et al. 1978, Thorud and Frissell 1969) to several decades (Dickerson 1976, Hatchell et al. 1970). In general, the time required for recovery in a given soil is proportional to the amount of compaction that occurred. The primary mechanisms that restore porosity and decrease density include shrinking and swelling of the soil (caused by either wetting and drying or freezing and thawing cycles), root growth, and soil mixing by soil organisms. Recovery rates are greater nearer the soil surface because of the greater frequency and completeness of wetting, drying, freezing and thawing that occurs there (Alexander and Poff 1985). Root growth and biological activity are also concentrated near the surface.

In one of the most complete studies, Froehlich et al. (1985) evaluated recovery rates for 23 years in soils formed in granitic and volcanic materials in Idaho (figure 2.7). The recovery rate was greatest in the surface 2 inches for both soils. Complete recovery occurred after about 20 years in the surface of the granitic soil. After 23 years, complete recovery did not occur at greater depths in the granitic soil or at any depth in the volcanic soil.

In the Pacific Northwest, Froehlich (1974) reported no significant decrease in the density of compacted surface soils on one site after 6 years and on another site after 17 years. Also in the Pacific Northwest, Wert and Thomas (1981) found that while compaction in the upper inch of skid roads had recovered after 32 years, compaction was still present at the 8- to 12-inch depth. Hatchell and Rolston (1971) reported that log deck densities in the Virginia Coastal Plain returned to normal after 18 years. However, they did not find a significant recovery in primary skid trails after the same period. In the North Carolina Piedmont, Perry (1964) observed that skid trails were still compacted 26 years after harvest, and projected their recovery would require about 40 years.

It is often proposed that the most rapid recovery occurs in areas that experience cold winters because of the freeze/thaw cycles. Holman et al. (1978) reported that in Maine, some lightly trafficked areas returned to preharvest densities after one winter. In Minnesota, Mace (1971) reported surface layers of some soils recovered after as few as two years. Thorud and Frissell (1969, 1976) also estimated that surface soils in Minnesota returned to their pretreatment densities after about eight years. However, winter conditions do not always lead to complete and rapid recovery. Winter snowpacks can insulate the soil, greatly reducing the number of freeze/thaw cycles (Froehlich and McNabb 1984). Also, winter conditions do not lead to rapid recovery of subsurface compaction. In the study reported above, Thorud and Frissel (1976) did not detect any recovery in the 6- to 9-inch layer. Similarly, in a cultivated field in southern Minnesota, compacted subsoil density did not change after nine years (Blake et al. 1976).

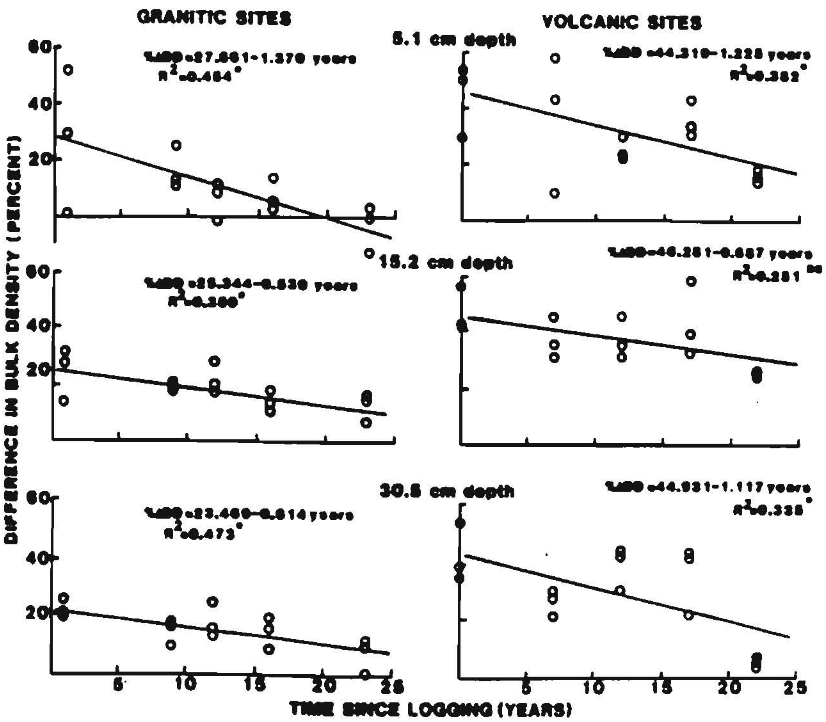

**Figure 2.7.** The percentage difference in bulk density of soils (% BD) in skid trails and in undisturbed areas related to the number of years since logging on granitic and volcanic sites (Froehlich et al. 1985).

## 2.3 Soil Erosion

Soil erosion is the movement of soil material by wind, water, and gravity. Erosion can lead to severe environmental problems both on- and offsite. The soil conservation movement was largely born out of man's recognition of the dire consequences of unchecked soil erosion. However, a majority of this concern, and the focus of most research, is the erosion of agricultural lands. While the physical processes that control erosion are universal, forests in general, and Minnesota's forests in particular, represent environments that rarely mimic agricultural conditions. Agricultural practices alter surface soil properties and vegetative cover to a degree that is unmatched by forest management as it is currently practiced in Minnesota. This section provides a broad overview of how timber harvesting and forest management activities influence soil erosion rates. Readers are referred to publications in the literature cited section for more detailed discussions of selected topics.

There are two types of erosion that predominate in forested areas—surface erosion and mass wasting.

*Surface erosion* is the movement of individual soil particles along the ground surface. Although some surface erosion is triggered by the splashing action of individual raindrops, a majority of surface erosion occurs when particles are suspended in overland flow or surface runoff. Many of the factors that control surface erosion rates have been identified and quantified in agricultural settings. Wischmeier and Smith (1968) integrated these concepts in the process of developing the Universal Soil Loss Equation which remains one of the most commonly used tools for estimating and predicting surface erosion rates throughout the world. These same concepts are generally used to describe surface erosion rates and processes in forested environments, though their applicability for this purpose has not been fully documented (Warrington et al. 1980).

Surface erosion rates are determined by the ease with which individual particles can be detached and transported, and the amount and flow rate of the transporting water. Ease of particle movement or inherent soil erodibility is a function of particle size distribution, aggregate stability, and soil permeability (Wischmeier et al. 1971). Soil organic matter and clay-sized particles add cohesiveness to the soil which generally improve aggregate stability and permeability. Soils high in coarser sand-sized particles often lack cohesion, but these soils are highly permeable and the large particles are more resistant to movement. Soils with the highest inherent erodibility contain high proportions of fine sand and silt, low amounts of soil organic matter, massive structure and slow permeability.

The water energy available for soil transport is determined by the amount and intensity of rainfall events and topographic factors including slope steepness and slope length. When all other factors are held constant, surface erosion rates increase with increasing rainfall intensity, increasing slope steepness, and increasing slope length.

Perhaps the greatest factor controlling surface erosion rates is the amount of vegetative cover and forest litter protecting the soil surface (Megahan 1990).

Low vegetative cover and surface litter absorb the forces of raindrop impact. Tree canopy cover only a negligibly reduces raindrop impact since raindrops reach close to their terminal velocity after falling between 4 and 6 m (Laws 1941). Surface mulches provide the greatest protection against erosion because, in addition intercepting raindrops, these residues interrupt and reduce the velocity of overland flow, limiting its ability to detach and transport soil particles (Warrington et al 1980).

*Mass movements* or mass flows are the movement of soil volumes rather than individual particles. Mass flows occur as continuous downslope movements (soil creep) or as discrete failures (such as slumps or debris avalanches). Mass flows are triggered when downslope, gravitational forces exceed the internal strength (shear strength) within the soil resisting the movement. Many factors contribute to the frequency of mass flow events, though they are predominantly restricted to areas with steep topography. Dyrness (1967) reported that mass movements were rare on slopes less than 45 percent, and other suggest that mass flow events are most frequent on slopes greater than 60 percent (Megahan 1990, Rice and Kammes 1971, Rice et al. 1972).

In addition to topography, mass flows are a function of climate, soils, and geology. Mass movements occur primarily during periods of heavy rain which increase soil weight and decrease soil strength. Failures are also more common when a distinct boundary exists between loose, noncohesive, surface materials and dense, impermeable subsoil or bedrock layers.

### 2.3.1
### Geologic Erosion Rates

Soil erosion is a natural, continuous geologic process. Estimates of the regional erosion rate for the eastern United States since World War II range from about 0.18 to about 0.30 ton/ac/yr (Patric 1976). However, these rates consider more than just forest land, they also include erosion that might be caused by other activities such as agriculture, urbanization, and highway construction.

Most research suggests that natural or geologic erosion rates in undisturbed forests are quite low because there is minimal overland flow. Forest soils are generally highly permeable and virtually all rainfall on forested land is absorbed into the soil (Hewlett and Hibbert 1967, Rice et al. 1972). Davis (1970) predicted the prehistoric erosion rate in forested southern Michigan at 0.05 ton/ac/yr. Patric (1976) set the average erosion rate from undisturbed and *well-managed* forest lands in the eastern United States at 0.05 to 0.1 ton/ac/yr. These rates translate to a soil loss of about 0.5 inches per 1000 yr (McColl and Grigal 1979).

## 2.3.2
## Accelerated Erosion Due to Forest Management Activities

Any increase in erosion above the geologic erosion rate is accelerated erosion. A number of studies have reported accelerated erosion rates associated with forest management activities. It is often difficult to compare the results between studies or to interpret them in terms of harvesting impacts because of the methodology used. For example, erosion is commonly estimated indirectly by measuring stream sedimentation. In these cases it is difficult to separate increased sedimentation due to overland flow from increased stream channel scour caused by increased water yield in the harvested watershed. Also, the soil loss is often averaged across the entire treatment or watershed area which may underestimate or overestimate local erosion rates. Finally, these studies do not account for soil material that moved but did not reach a stream.

Virtually all accelerated erosion on forested lands follows major disturbances that increase the exposure of soil to water (Patric and Brink 1977). Road construction is probably the single greatest activity causing erosion. Patric (1976) states that logging roads are unquestionably the source of most of the soil lost from nonchannel portions of managed forest land in the East. Road construction is also cited as the major factor contributing to erosion in the South (Vowell 1985) and the West where it plays a major role in triggering mass movements (Dyrness 1967).

Swift (1985) estimated that about 300 ton/ac eroded from a forest road during the first year after construction in North Carolina. Vowell (1985) estimated soil losses from four two-year-old road segments in Oklahoma ranged from 8 to 77 ton/ac/yr, with an overall average of 41 ton/ac/yr. These are many times greater than the geologic erosion rates reported above.

The accelerated erosion caused by roads is attributed to (1) the removal of vegetation and litter which exposes mineral soil to rain and water, (2) soil compaction which decreases the rate of water infiltration into the soil, and (3) the concentration of surface runoff (Rice et al. 1972). Accelerated erosion is greatest during road construction when ditchbanks and cutbanks are unprotected and oversteepened.

Skid trails and landings are also implicated as sites of increased erosion (Klock 1982, McColl and Grigal 1979, USDA 1984), as are mechanical site preparation and burning (Beasley and Granillo 1985, Debano 1969, Debyle and Packer 1972, Ursic 1970). Again, increased erosion is primarily attributed to increased exposure of mineral soil.

Fire can create a water repellent barrier that retards water infiltration into the soil and increases overland flow. The severity of this condition is positively correlated with the burning temperature (Debano 1969). DeByle and Packer (1972) reported maximum erosion rates of 0.08 ton/ac/yr on plots with slopes ranging from 9 to 35 percent that had been logged and burned in western Montana.

Forest management and associated activities can also increase erosion through mass movements. Although some argue that mass movements occur in areas that are inherently unstable and that management activities only set in motion an earth mass that was already on the verge of failure (Sowers and Sowers 1951). Because of the difficulty in quantifying the amount of soil involved and the questionable value of direct comparisons between individual events, it is more useful to evaluate forest management activities based on the frequency of events they may trigger.

Road construction has been implicated as a major cause of increased mass movements. Roads can disrupt slope equilibrium, particularly in geologically unstable areas (Swanston and Swanson 1976). Dyrness (1967) observed that following a 50-year storm that triggered numerous mass movements in an Oregon forest, 72 percent of the mass movements were associated with roads, yet only 1.8 percent of the forest was roaded. Only 11 percent of the mass movements occurred in undisturbed areas.

Timber harvesting can also decrease slope stability by increasing water content in the soil mass through reduced rainfall interception and transpiration (Gray and Megahan 1981, Rice et al. 1972). Higher water contents increase downslope stresses and reduce internal strength. Living tree roots also bind soils together and contribute to slope stability (Burroughs and Thomas 1977, Swanston and Walkotten 1970). Landslides in Idaho were most frequent four to ten years following clearcutting which was attributed to the lag time required for root decay (Megahan et al. 1978).

Swanston and Swanson (1976) summarized several studies of timber harvesting and forest management effects on the acceleration of mass movements in the coastal mountain ranges of western North America. These studies monitored mass movement events for periods ranging from 15 to 32 years. On average, clearcutting increased the frequency of mass movements 2 to 4 times over nonharvested areas, and road construction increased the frequency from 25 to 340 times. Much of the range in road construction was attributed to differences design and construction practices.

### 2.3.3
### Magnitude of Accelerated Erosion

While it is generally accepted that forest management activities contribute to accelerated erosion, most reports suggest that, except for some forest roads, forestry related erosion in North America is of minor importance (Rice et al.

1972). North American forests represent diverse ecosystems that quickly revegetate. Because of this revegetation, accelerated erosion caused by roads and harvesting activities decrease exponentially with time so that within three to five years it is back to a low rate (McColl and Grigal 1979, Megahan 1974).

In the study from western Montana where the maximum erosion rate was 0.08 ton/ac second year following logging and burning, no erosion was detected the fourth year after harvest (DeByle and Packer 1972). On 1 to 3 percent slopes in the Gulf Coastal Plain of Arkansas, clearcutting followed by windrowing significantly increased sediment losses over uncut control areas for only two years (Beasley and Granillo 1985). However, the losses were only slightly different from the control areas. Clearcutting on slopes ranging from 15 to 30 percent in Arkansas significantly increased sediment yields over control areas (0.13 ton/ac/yr versus 0.01 ton/ac/yr) the first year after treatment, however, no significant differences were detected the second or third year following harvest (Miller et al. 1988). Similar results were also reported for clearcutting followed by shearing and windrowing on slopes between 8 and 15 percent in Arkansas (Beasley and Granillo 1985). Soil loss in treated areas never exceeded 0.5 ton/ac/yr, and no significant soil losses were reported by the third year following treatment. Even on the steep slopes of Idaho (slopes > 60 percent), a site that was clearcut, lopped, and broadcast burned had a maximum erosion rate of about 7 ton/ac/yr the first year after treatment which decreased to about 2 ton/ac/yr after the second year when the study ended (Clayton and Kennedy 1985).

The same trend is also evident on forest roads where most of the soil loss occurs during the construction and early life of the road (Megahan 1990). In a North Carolina study, 75 percent of the soil lost by a forest road that drained directly into a stream occurred during the first 2 months, and soil loss essentially ended after three years (Swift 1985).

### 2.3.4
### Erosion Impacts on Site Quality

Erosion can increase sedimentation of surface waters (see Water Quality and Fisheries Technical Paper), and reduce site productivity. The primary mechanism of reduced site productivity are the loss of soil nutrients and water holding capacity which are concentrated in surface soil horizons (Klock 1979). For example, 50 percent of the nutrients in a granitic soil in Idaho are contained in the upper 0.75 in. (Megahan 1990). Also, during erosion and sediment transport, there is a selective removal of finer soil particles and humus together with soluble nutrients (Logan 1982). Severe erosion reduces the total rooting volume and exposes subsoil material which has physical and chemical properties that are less amenable to root growth (Hall et al. 1982, Shrader 1980). Runoff is also greater in eroded versus uneroded soils meaning less water infiltrates the soil and is available for plant growth (McCormack et al. 1982).

It is difficult to evaluate the effects of erosion on plant growth because its impacts are often confounded with other physical disturbances such as compaction. Also, in many cases soil is moved only a few inches or feet and not totally removed from the site (McColl and Grigal 1979). Using a greenhouse bioassay technique, Klock (1982) estimated that severe erosion can cause productivity losses of up to 85 percent. He reported that site reductions are directly, but not linearly proportional to the depth of soil removal.

## 3
## METHODS FOR ASSESSMENT OF IMPACTS

This section discusses the methodology used for assessing current and future timber harvesting and forest management impacts on soil properties. These analyses were conducted based on the timber harvesting scenarios described in the *Initial Harvesting Scenarios for a Generic Environmental Impact Statement* (Jaakko Pöyry Consulting, Inc. 1991b) and in the Maintaining Productivity and the Forest Resources Base Technical Paper (Jaakko Pöyry Consulting, Inc. 1992_).

### 3.1
### Data Organization

The soil and timber data for the state of Minnesota were reorganized to more efficiently evaluate the effects of timber harvesting on soil properties. The forested soils were aggregated into seven groups based on soil texture and drainage. These groups included well- and poorly-drained fine-textured soils (WDF and PDF), well- and poorly-drained medium-textured soils (WDM and PDM), well- and poorly-drained coarse-textured soils (WDC and PDC), and very-poorly-drained organic soils (O). Similarly, Minnesota's forest covertypes were aggregated into seven major types. These types included aspen-birch, black spruce, lowland conifers, lowland hardwoods, pine, spruce-fir, and upland hardwoods.

The extent and distribution of soil types were estimated using the Soil Atlas database maintained by the Minnesota Land Management Information Center. The distribution of forest covertypes was derived from the Forest Inventory and Analysis (FIA) data. The output from the initial harvesting scenarios were combined with these data to estimate how many acres of each soil type would be harvested under each harvesting scenario.

Harvesting impacts were evaluated at the ecoregion level (the three prairie ecoregions were grouped for the analyses). Impacts within each ecoregion were summed to arrive at statewide assessments.

## 3.2
## Nutrients

### 3.2.1
### Nutrient Budgets

The assessment of the impacts of timber harvesting and forest management on forest nutrient cycles considered five macronutrients, defined as nutrients that are required in relatively large amounts by plants and whose deficiency has been associated with impaired growth of some kind of plant (not necessarily trees). These five nutrients were nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg).

**Soil Groups**
As described above, forested soils were aggregated into seven groups based on soil texture and drainage. The available nutrient content or capital of each of these soil groups was estimated, based on chemical availability and tree rooting depth. Some forms of each nutrient are chemically more available to plants than are other forms, and nutrients that are located in proximity to tree roots (the rooting zone) are more available than are nutrients that occur where roots are rare or absent. The distribution of soils in each of these groups in Minnesota can be determined from the map of soil landscape units, based on the Soil Atlas Series (Minnesota Soil Atlas Project 1969–81), and implemented into the EPPL7 Standard Data Set from the Minnesota Land Management Information Center (LMIC). These data are sufficiently accurate for regional assessments, but cannot be considered suitable for site-specific assessments.

**Forest Covertype Groups**
The amounts of the five nutrients that are accumulated in stands of each of the seven covertype groups were compiled from research reports from Minnesota and similar climatic and geologic areas. These data were segregated by plant parts, including wood, bark, branches, and leaves (or needles), and were associated with specific levels of stand volume and biomass.

**Budgets**
Nutrient budgets were also developed for Minnesota forests. These budgets included estimates of nutrient inputs by atmospheric deposition, by soil mineral weathering, and in the case of nitrogen, by biological fixation. Losses of nutrients by leaching of soil solution to surface or groundwater were also estimated. Volume of leaching was based on a modified

Thornthwaite model (Grigal and Bloom 1985). These budgets were developed for each of the five nutrients, on each of the seven soil groups, for each ecoregion (49 ecoregion/soil combinations). In addition, an average *statewide* budget was also developed for each nutrient and soil combination. That budget was based on average values for the state.

### 3.2.2
### Application of Model Results

The location of each FIA plot was related to the soil at that location as determined from the LMIC data set. The management activities on each FIA plot, for each of the model runs (base, medium, and high scenarios), were summarized by soil group and forest covertype group within each ecoregion. This summary included all modeled activities within the 50-year planning horizon. The nutrient loss associated with the volume removed was computed for each harvest. Unless otherwise stated, harvest was assumed to consist of removal of the merchantable bole (woody bole plus bark).

**Harvesting Removals**
*All* forest harvests remove the nutrients within the product being harvested and transported from the site. From the data described above, harvest-related removals of each of the nutrients can be estimated. This estimate is based on the forest type being harvested and on the volume removed by the harvest. Estimates of nutrient removal associated with each of the three harvesting scenarios within the 50-year planning horizon were computed. The FIA data were used to associate the nutrient removal for each forest type to each of the seven soil groups within each of the seven ecoregions. Nutrient removal was then evaluated in the context of the overall nutrient cycle for each ecoregion.

The primary analysis assumed that the harvest removed the merchantable bole (including bark). To assess differences in nutrient removal with different levels of utilization, computations were also based on assumptions of full-tree or bole-only (without bark) harvest. For full-tree harvest, all nutrients within the tree were assumed to be removed from the site. For bole-only harvesting (tree length or bolt), nutrient removal *without* bark was also estimated. These assessments of nutrient removal with differing degrees of utilization were only carried out using the statewide data for nutrient cycles.

The planning model does not explicitly provide information on other activities that can remove nutrients from sites. The model does not consider season of harvest. In the case of full-tree harvest of deciduous trees, the lack of seasonality has limited impact on assessment of nutrient removal. The Review of the Existing Environment indicates that deciduous leaves do not contain a major proportion of nutrients compared to the remainder of the tree. For conifers, nutrient removal associated with full-tree harvest is not affected by season. The model does not include other activities that may displace nutrients from sites where trees are growing and concentrate them at a single site (e.g., delimbing and topping, or removing branches and tops at landings rather than at the stump, has the same effect on nutrient depletion as a full-tree harvest). In addition, some activities associated with preparing a site for subsequent regeneration may also displace and concentrate nutrients (e.g., windrowing as a site preparation technique). The impacts of site preparation and of the location of delimbing and topping (whether at the stump or at a landing) could only be qualitatively assessed. This assessment was based on the survey of forestry operations that was carried out as part of the GEIS.

## 3.3
## Soil Compaction and Related Disturbances

Compaction and related disturbances were assessed based on the harvesting systems and harvest seasons described in the Silvicultural Systems and Harvesting Systems background papers (Jaakko Pöyry Consulting, Inc. 1992a,b). Analyses were only conducted for harvesting related activities and for the mineral soil types. Organic soils exhibit very little strength when they are not frozen and are virtually unable to support heavy equipment. Equipment operation on organic soils are limited to periods when they are frozen. Mechanical site preparation was evaluated qualitatively. The Silvicultural Systems background paper indicated that only about 10,000 ac are mechanically site prepared annually. Insufficient data was available to perform a quantitative assessment.

As discussed in the literature review, soil compaction and related disturbances are almost entirely a function of the level of equipment trafficking and soil strength. The methods used to define these conditions are as follows:

### 3.3.1
### Equipment Trafficking

The following four categories of equipment trafficking were defined:

*Untrafficked.*—Areas that are untrafficked or are lightly scarified by dragging logs.

*Light.*—Areas trafficked by 1 to 3 equipment passes.

*Moderate.*—Areas trafficked by 4 to 12 equipment passes. Secondary skid trails would be typical of this level of trafficking.

*Heavy.*—Areas trafficked by more than 12 equipment passes. Primary skid trails and landings would fall into this category.

Analyses were based on the assumption that equipment configuration is the primary factor influencing the percent of a site that falls into each of these trafficking categories. The evidence regarding reduced amounts of site disturbance associated with partial cutting is inconclusive. In addition, the initial harvesting scenarios indicated that virtually all stands that were harvested were clearcut at some point during the 50-year planning period.

The equipment configurations used in Minnesota were defined in the Silvicultural and Harvesting Systems background papers. The equipment configurations were separated into two broad categories— those that are fully mechanized versus those that employ hand-felling. The estimated percentage of a harvest unit within each trafficking category for each equipment configuration is presented in table 3.1.

**Table 3.1.** Estimated percentage of harvest units in trafficking categories.

| | Untrafficked | Lightly trafficked | Moderately trafficked | Heavily trafficked |
|---|---|---|---|---|
| Mechanical-fell | 45 | 30 | 17 | 8 |
| Hand-fell | 70 | 5 | 17 | 8 |

These values indicate that similar amounts of a site are occupied by skid trails and landings for all operations, and that mechanical felling results in a major increase in the area that is lightly trafficked. Actual values can vary with specific pieces of equipment, site conditions, or skidding strategies; however, the information is not available to consider all of these variables on a site-by-site basis. These values have been chosen as representative of the trafficking levels that are possible during typical Minnesota operations.

Haul roads were considered independently. It was estimated that haul roads comprised a constant 1 percent of the total area harvested under each scenario.

### 3.3.2
### Soil Strength

Soil strength is largely controlled by soil texture (the proportion of sand, silt, and clay) and soil water content. In general, soil strength decreases as soil water content increases and as soil textures become finer. Soils with low strength are more susceptible to compaction and related disturbances.

A soil sensitivity rating was developed for each of the six mineral soil types. These sensitivity ratings were based on the soil texture, drainage class, and soil water content. Thus the sensitivity rating for each soil varied with season. Soils were considered to be wettest during the spring, driest during the summer, frozen during the winter and moist in the fall. Highly sensitive soils would compact or puddle under light trafficking as defined above. Moderately sensitive soils would compact or puddle under moderate trafficking, and soils with low sensitivity would compact or puddle only under heavy trafficking. The sensitivity ratings for each soil type for each season are given in table 3.2.

**Table 3.2. Seasonal changes in sensitivity ratings for soil types.**

| SOIL | Winter | Spring | Summer | Fall |
|---|---|---|---|---|
| WDF | LOW | HIGH | LOW | MOD |
| PDF | LOW | HIGH | MOD | HIGH |
| WDM | LOW | HIGH | LOW | LOW |
| PDM | LOW | HIGH | LOW | MOD |
| WDC | LOW | LOW | LOW | LOW |
| PDC | LOW | MOD | LOW | LOW |

### 3.3.3
### Assessment Matrix

Soil compaction and related disturbances were estimated by applying the above information to timber harvesting and forest management activities using a spreadsheet analysis. The area of each soil type harvested in each ecoregion under each harvesting level were derived from the expansion factors of harvested FIA plots (Jaakko Pöyry Consulting, Inc. 1991b). The equipment configurations and seasonal distribution of harvesting activities in each ecoregion were summarized from information presented in the Silviculture and Harvesting System background papers (Jaakko Pöyry Consulting, Inc. 1992a,b).

No data were available suggesting that either equipment configurations or seasonal distribution of harvesting activities would change for the medium or high scenarios. Thus all three harvesting scenarios were evaluated using the data as presented in the background papers. As a result, the area impacted for each soil type in each ecoregion would be directly proportional to the area harvested under each scenario.

## 3.4
## Soil Erosion

The objective of this analysis was to evaluate where accelerated soil erosion associated with the harvesting levels outlined in the three harvesting scenarios (Jaakko Pöyry Consulting, Inc. 1991b) exceeded a significant threshold value. Primary emphasis was placed on surface erosion. Although mass movements do occur in Minnesota, little information is available linking their occurrence to timber harvesting or management activities, thus only a qualitative assessment was made.

Surface erosion is largely a function of rainfall intensity, the amount of exposed mineral soil, and slope steepness and length. Surface erosion was evaluated using a modified version of the Universal Soil Loss Equation that was developed by the U.S. Environmental Protection Agency (EPA 1980) for use in conjunction with forest management activities. The form of the equation is

$$A = R \times K \times LS \times VM \qquad [1]$$

where A=the average annual soil loss (tons/ac)
R=the rainfall intensity factor
K=the soil erodibility factor
LS=the topographic factor
VM=the vegetative management factor

Erosion rates were estimated for each soil type in each ecoregion. A single R value was assigned to each ecoregion based on published values, and the VM factor was estimated for varying management practices using procedures outlined by the EPA (1980). K values for each soil series in Minnesota were published by the Soil Conservation Service.

A threshold soil loss value was determined for each soil type based on the soil loss tolerance value, or T-value, developed by the Soil Conservation Service. As discussed in the technical review, accelerated erosion rates associated with timber harvesting return to preharvest levels within 3 to 5 years. This is due to rapid revegetation of the site by grasses, forbs, and shrubs. The T-value was multiplied by 2.5 to estimate the maximum soil that could be lost if the initial accelerated erosion rate (T-value) decreased to premanagement conditions after 4 years, and this decrease was linear. This is a relatively conservative estimate since the literature suggests that this is usually an exponential rather than linear decrease. For each management practice (VM level), equation 1 was rearranged to solve for LS as follows:

$$LS = \frac{2.5 \times A}{R \times K \times VM} \qquad [2]$$

The calculated LS value, which is a function of both slope steepness and slope length, was used to determine the slope steepness above which the soil loss threshold would be exceeded. This was determined assuming a constant slope length of 100 ft which was chosen because analysis of the FIA data indicated that a majority of the slopes in the state were this length or shorter. The expansion factor for each FIA plot was then used to estimate the areas where threshold erosion rates were exceeded.

# 4
# SIGNIFICANT IMPACTS

## 4.1
## Significance Criteria

Impacts identified in the course of this study will vary in their significance and therefore in the need to develop a specific mitigation response. This is a critical stage of the study process, as these tests of significance will ultimately define the scope of policy recommendations developed by the GEIS.

Assessment of an impact as being significant does not automatically prescribe a specific mitigation response. The significance criteria have been developed to be inclusive rather than exclusive. Their purpose is to identify the issues and circumstances where policy initiatives will be required. The range of possible policy responses, the factors used to choose between them, and the implications of selecting a particular response are all evaluated by subsequent criteria.

Criteria have been developed for each of the issues of concern in the FSD and are identified in the second section of this document. Therefore, because the criteria underpin the impact assessments to be undertaken in subsequent stages of the study, this aspect of the study will be made as clear as possible for interested readers.

The categories of impacts to be considered are set out in the FSD within the Issues of Concern (section viii, page 8). Eighteen *categories* of impacts have been identified based on the ten issue areas in the FSD. The categories are as follows:

1. The sustainability of harvesting forest resources;
2. Size and composition of Minnesota's forest land base;
3. Abundance, composition, spatial distribution, age class structure, genetic variability and tree species mixture of Minnesota's forests;
4. Risk of disease and insect infestation;
5. Biological diversity at a genetic, species or ecosystem level;
6. Patterns of forest cover;

7. Federal or state listed species of special concern, threatened, or endangered species or their habitats;
8. Old growth forests;
9. Populations of (10 groups) of forest dependent wildlife and fish and their habitats;
10. Level of sedimentation, nutrient loading, and runoff in lakes, rivers, streams and wetlands;
11. Water quality of ground and surface waters;
12. Aquatic ecosystems, wetlands and peatlands;
13. Soil erosion;
14. Forest soil productivity;
15. Recreational use;
16. Regional and state economies;
17. Historical and cultural resources; and
18. Visual quality.

For each significance criterion developed, several background factors were used to determine levels or thresholds when impacts are likely to be considered significant. They include:

- severity and spatial extent of impact;
- certainty of impacts;
- duration of impact (irreversibility);
- consideration of existing guidelines and standards; and
- biological and economic implications.

The first factor identifies the likely extent and severity of an impact. Impact extent varies considerably, ranging from very localized site specific impacts to those impacting a watershed, physiographic region, soil type, covertype, ecoregion or the entire state. The second factor identifies the degree of certainty that a predicted impact will occur. The key factors influencing certainty are identified for each criterion. The third factor incorporates the anticipated duration of the impact, and whether or not it is reversible. Duration is defined as very short-term—less than 2 years; short-term—2 to 10 years; medium-term—10 to 50 years; long-term—greater than 50 years; and irreversible. The fourth factor incorporates those existing standards and guidelines that are applicable to the respective issue areas. The fifth factor identifies the key biological and economic implications of the impact. These are particularly important in those circumstances where impacts are indirect. For example, loss of mast (e.g., acorns) producing trees is the impact criterion and what makes this loss significant is its effect on populations of animals dependent on these trees for food.

## 4.2
## Nutrients

### 4.2.1
### Significance Criteria

> An impact is considered significant if nutrients removed and/or redistributed during harvest and followup activities are not replaced over the term of the projected rotation.

**Severity and/or extent.** This criterion will be applied to seven soil categories, seven covertypes and will be assessed by ecoregion. Changes to five nutrients will be assessed for each possible combination of the above factors. The nutrients assessed are: nitrogen, phosphorus, potassium, calcium and magnesium. Removals and redistribution of nutrients will be interpreted based on volumes of biomass removed/redistributed during and following harvest. Typical yields per acre and the harvesting and site preparation systems used will be drawn from the Harvesting Systems and Silvicultural Systems background papers.

All forest harvests remove nutrients that are contained within the product being removed. Some harvesting activities may also displace nutrients from sites where trees are growing and concentrate them at a single site (e.g., removing branches and tops at landing rather than at the stump). Finally, some activities associated with preparing a site for subsequent regeneration may also displace and concentrate nutrients (e.g., windrowing as a site preparation technique).

Nutrients are continuously being added to forests by atmospheric deposition and by geological weathering, and being lost by leaching. Over the long-term, rates of removal that exceed rates of replenishment can be considered to be *mining* the nutrient capital of a site. The criterion for a significant impact was established to identify circumstances where such mining is likely to occur, allowing the opportunity for mitigations aimed at maintaining sites at their current nutrient status over many rotations. Although the initial nutrient capital of a site (i.e, the nutrients stored in the soil) affects current productivity, it does not influence the criterion for a significant impact. The size of the nutrient capital affects the degree of nutrient fluctuation at a site over a rotation. A site with high initial capital will experience proportionally smaller fluctuations (as nutrients are removed and then replenished) when compared to sites with low capital where proportional fluctuations will be much greater.

The initial nutrient capital of a site (i.e., the nutrients stored in the soil) should also be considered when nutrient removal is assessed. Although the criterion for a significant impact is not influenced by the initial nutrient capital of a site, that capital affects the degree of nutrient depletion at a site over a rotation. Although a site may irreversibly lose nutrients, the amount may be a small proportion of the nutrients that are present on a site with high initial capital. In that case, the mining may be considered to be relatively insignificant and to be economically and biologically justifiable. Sites with low capital will be more heavily impacted by equivalent amounts of nutrient removal without replenishment. Impacts will be increasingly severe as the nutrient capital of a site is depleted over many rotations.

*Spatial extent.*— Impacts will occur wherever forest activities are conducted. As described above, impacts will be most severe on sites with low nutrient capital. These sites can be broadly categorized as those on coarse-textured soils. Such soils occupy about one-fourth of the forested area of Minnesota, or about 4.5 million acres (based on LMIC Forest Cover Type and Soil maps). They are scattered throughout the forested parts of the state.

**Certainty of impact.** Data on nutrient removal by harvest and on nutrient additions by atmospheric deposition are comparatively good; it can be assumed that they are accurate with uncertainties of less than an order of magnitude. Similarly, nutrient capital of soils classified into general texture and drainage classes can be estimated with an uncertainty of less than an order of magnitude. There is, however, large uncertainty associated with rates of return of nutrients via geological weathering.

Another major source of uncertainty is the precise quantification of the relationship between quantity of nutrients and stand productivity. Using agricultural experience as an analog, it is known that depletion of nutrients leads to reductions in productivity. In some areas (e.g., upstate New York), soils that have been depleted of nutrients by agricultural activities cannot support normal forest growth without nutrient additions; even species with low requirements require added nutrients. The addition of some nutrients via fertilization (especially N and P) to some forests (in the Pacific Northwest and the southeast U.S., respectively) can increase productivity. Although there are suggestions of *second-rotation* productivity declines in pine plantations in the Southern Hemisphere, the cause of such declines has not been unequivocally determined. Part of the uncertainty is due to the characteristics of natural forest systems; systems that are low in nutrients are often also limited in available water and have other characteristics that make them less suitable for tree growth than high-nutrient sites. Experiments that demonstrate decreases in productivity with nutrient depletion have not been carried out. In summary, between productivity and nutrient quality, especially under conditions of nutrient depletion, quantification of the relationship is lacking.

**Duration of impact (irreversibility).** The duration of the impact of nutrient depletion is long-term. If natural processes continually replenish site nutrients, then with sufficient time between harvests or other disturbances, a site will regain its original nutrient capital. Where large quantities of nutrients have been removed from a site that has low rates of natural replenishment (meeting the criterion for adverse impacts), such restoration will require more than 50 years and is, therefore, considered to be long-term. Artificial nutrient addition via fertilization can shorten the duration of the impact.

**Biological implications.** The implications of application of this criterion depend on the techniques that are used to mitigate the impacts. If the criterion is ignored, and no mitigation is attempted, then productivity of Minnesota's forests will decline. This decline will be most obvious on sites currently low in nutrients (i.e., on coarse-textured soils) that are currently occupied by aspen-birch or upland hardwood forests. One of the most feasible mitigation measures is that trees on sites with low rates of nutrient replenishment will be harvested at longer rotations. Biologically, this may mean increased susceptibility of those trees to insect and disease attacks, especially in the aspen-birch type.

**Existing guidelines and standards.** None applicable

**Economic implications.** Reduced site productivity may impact yields and/or the rotation length for affected species/soil combinations.

**Caveat.** In this assessment, those impacts of timber harvesting and forest management that meet the criterion for significance to forest soil nutrient status will be identified. *All* timber harvesting and forest management activities create impacts on nutrient status. Those impacts range from nearly none (likely where the management activity is minimal) to very great. That continuum of impacts is impossible to treat in any quantitative sense; a threshold must be developed to aid in communication. Impacts that are greater than that threshold merit attention; impacts below the threshold are not large enough to justify further consideration. The size of that threshold may vary with the state of knowledge. The threshold in our analysis is the criterion for significant impacts.

**Summary.** The criterion for a significant impact was developed to be simple in concept and conservative with respect to the uncertainties regarding both nutrient replenishment and effects on productivity. To express the criterion in other words, mining soil nutrients without replenishment indicates a negative impact. If the criterion is never exceeded, assuming estimates of rates of replacement are accurate, then forest management activities will *never* deplete the nutrient capital of Minnesota forests.

Because of uncertainties in the data, in assessing impacts identification was made of the acreage of each forest type and soil where the nutrients removed by the harvest would not be replenished over the rotation *plus* 25 years. In other words, if a stand was harvested at age 50, and a specific nutrient that was removed could not be replenished within 75 years (50 + 25), then the area occupied by that stand was considered to be negatively impacted. If the nutrient could be replenished in less than 75 years, then the area occupied by the stand was not included in an impacted category. This can be summarized by:

IF [(atmo. input + weathering - leaching) * (rotation age + 25)
$\geq$ nutrient removal]

THEN = negative impact

## 4.2.2
## Results

### Levels of Harvest

***Base Scenario***

Based on our criterion, under the base scenario and harvesting of the merchantable bole, 1.8 million acres of forest land lost potassium, 5.0 million acres lost calcium, and 2.7 million acres lost magnesium in excess of their replenishment (figure 4.1). Both phosphorus and nitrogen were adequately replenished by natural processes. Almost one million acres associated with potassium loss are coarse-textured soils, and about 700 thousand acres are organic soils. About half the area (2.5 million acres) associated with calcium loss is medium-textured soils, and 1.7 million acres are coarse-textured soils. The large area of medium-textured soils associated with calcium loss is related to the predominance of aspen-birch on those soils, and to the high levels of calcium in the bark of aspen. About half the acreage associated with magnesium loss is coarse-textured soils, and an additional 800,000 acres are organic soils.

The loss of each of these nutrients should be evaluated with respect to the nutrient capital present on the sites. For example, potassium losses are the highest proportion of the capital of any of the three nutrients of concern. On coarse-textured soils, potassium losses are about half of the capital. Fortunately, potassium is quickly replenished so that the losses are replaced in about 40 years. On medium-textured soils, potassium losses are about a third of the capital, and are replaced within about 20 years. The relatively rapid rate of potassium replacement is one of the reasons that less area is associated with potassium depletion by harvest than areas associated with calcium and magnesium depletion (figure 4.1). Although the latter two nutrients have more area associated with depletion (figure 4.1), on most sites depletion is a smaller proportion of total capital. For example, on the

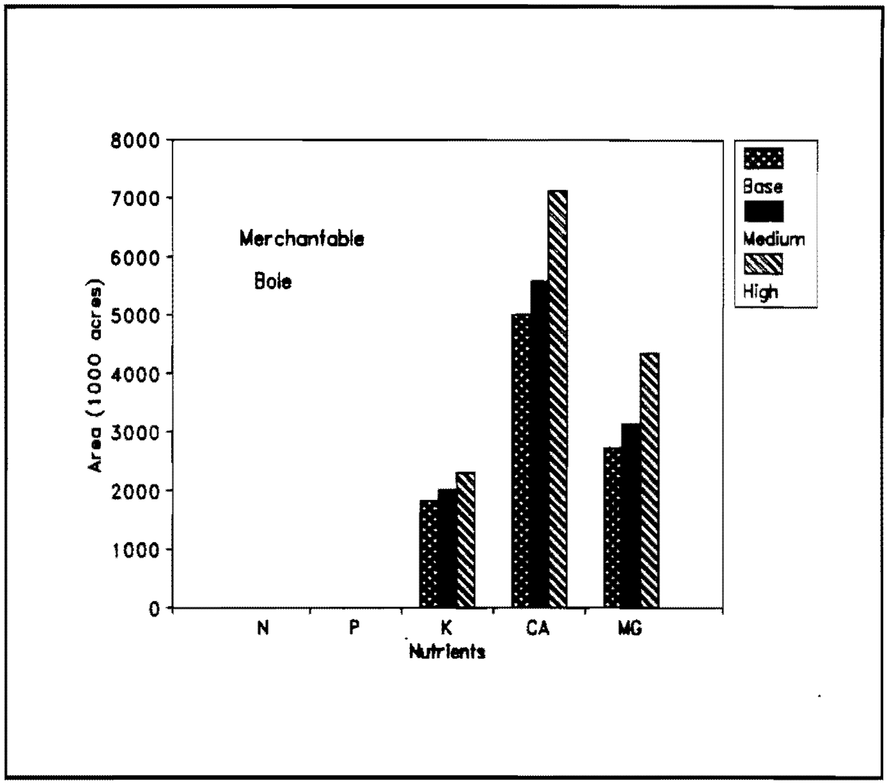

**Fig. 4.1.** Area of forest land for which nutrient losses exceed replenishment under three harvesting scenarios.

average coarse-textured soil, calcium losses associated with harvest are about 10 percent of the capital; harvest removes a smaller proportion on medium- and fine-textured soils (about 5 percent). In the case of magnesium, harvest also removes about 10 percent of the capital on coarse-textured soils but only about 2 percent on fine soils.

Organic soils are a special case because they do not have an input of mineral weathering to replenish nutrients; they depend on atmospheric deposition. Organic soils are commonly recognized to be low in potassium. Harvest removes most of the immediately available potassium on organic soils and rates of replenishment are low; about 100 years are required to rebuild potassium reserves to their original level. Conversely, only about 5 percent of the calcium and magnesium reserves on organic soils are lost by harvesting.

### Increased Harvesting

As described in the discussion of the Existing Environment, both the soil and the forest type interact to affect nutrient loss with harvest. The effect of harvest intensity on area of forest land for which the rate of nutrient removal exceeds the rate of nutrient replenishment over the rotation demonstrates that interaction.

Comparison of results of the base harvest scenario with results of the high scenario indicate that about one-half million additional acres of land will be *mined* for potassium (table 4.1). Most of this increase will occur with harvest of the aspen-birch type, primarily on coarse-textured and organic soils (table 4.1). Aspen harvesting on organic soils may seem surprising, but the spatial resolution of the data are not sufficient to precisely place every FIA plot with respect to each soil. The aspen stands that apparently *occur* on organic soils may actually occur on mineral islands within larger areas of organic soils, or on mineral soils that are intimately intermingled with organic soils. The resolution of the existing soil maps cannot make those distinctions for areas as small as the FIA plots (ca. 1 acre).

**Table 4.1.** Increase in area of forest land for which losses of potassium exceed replenishment when results of the base model scenario are compared to those of the high scenario.

| Forest Type[b] | Soil[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WDF | PDF | WDM | PDM | WDC | PDC | ORG | Sum |
| | (10³ acres) | | | | | | | |
| AB | 0 | 0 | 59 | -3 | 109 | 20 | 116 | 300 |
| BS | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 6 |
| LC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LH | 0 | 0 | 0 | 0 | 0 | 0 | 86 | 86 |
| P | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SF | 0 | 0 | 0 | 0 | 12 | 0 | 0 | 12 |
| UH | 0 | 0 | 23 | 0 | 2 | -7 | 61 | 79 |
| Sum | 0 | 0 | 82 | -3 | 128 | 13 | 264 | 483 |

[a] WDF = well-drained, fine-texture; PDF = poorly-drained, fine-texture; WDM = well-drained, medium-texture; PDM = poorly-drained, medium-texture; WDC = well-drained, coarse-texture; PDC = poorly-drained, coarse-texture; ORG = organic.

[b] AB = aspen-birch, BS = black spruce, LC = lowland conifers, LH = lowland hardwoods, P = pine, SF = spruce-fir, UH = upland hardwoods.

Increase in harvest intensity from the base to the high scenario also increases the area on which magnesium loss exceeds replenishment; about one and one-half million additional acres are affected (table 4.2). As with potassium, a significant portion of the increased area is associated with aspen-birch harvest on coarse-textured and organic soils (table 4.2). The results of these analyses are not additive. That is, the same soils affected by potassium loss may also be affected by magnesium loss. A comparison of the data for aspen-birch harvest on coarse-textured and organic soils shows that this is clearly the case (tables 4.1 and 4.2). Significant additional areas of magnesium loss are associated with increased harvest of spruce-fir, both as the black spruce and as the spruce-fir types (table 4.2). Although the harvest of spruce and aspen-birch types make the largest contributions to the increased area, increased harvest of all forest types has an impact (table 4.2).

**Table 4.2.** Increase in area of forest land for which losses of magnesium exceed replenishment when the results of the base scenario are compared to those of the high scenario.

| Forest Type[b] | Soil[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WDF | PDF | WDM | PDM | WDC | PDC | ORG | Sum |
| | (10$^3$ acres) | | | | | | | |
| AB | 18 | 2 | 59 | 1 | 109 | 20 | 116 | 323 |
| BS | 11 | 2 | 18 | 0 | 110 | 24 | 312 | 478 |
| LC | 4 | 6 | 3 | 0 | 29 | 23 | 70 | 134 |
| LH | 22 | 6 | 15 | 0 | 45 | 14 | 24 | 125 |
| P | 0 | 1 | 0 | 0 | 115 | 6 | 14 | 126 |
| SF | 14 | 0 | 51 | 0 | 82 | 24 | 67 | 236 |
| UH | 19 | 9 | 23 | 1 | 68 | 17 | 57 | 193 |
| Sum | 86 | 26 | 169 | 2 | 557 | 127 | 659 | 1626 |

[a] WDF = well-drained, fine-texture; PDF = poorly-drained, fine-texture; WDM = well-drained, medium-texture; PDM = poorly-drained, medium-texture; WDC = well-drained, coarse-texture; PDC = poorly-drained, coarse-texture; ORG = organic.

[b] AB = aspen-birch, BS = black spruce, LC = lowland conifers, LH = lowland hardwoods, P = pine, SF = spruce-fir, UH = upland hardwoods.

When harvest intensity is increased from the base to high scenario, calcium loss exceeds replenishment on about two million additional acres (table 4.3). Aspen-birch harvest significantly contributes to this increase, as it does in the cases of the other nutrient elements (table 4.3). The increased harvest of upland hardwoods, and the high calcium content of their boles and bark, also significantly contributes to the impact of the increased harvest (table 4.3).

Because both aspen-birch and upland hardwoods are most common on well-drained medium-textured soils, over one million acres of that soil group is affected (table 4.3). With respect to their total area in the state, however, coarse-textured soils are disproportionally affected by nutrient removal. They also have the lowest nutrient capital of the soil groups (table 2.15), and productivity on those soils is therefore most likely to be negatively affected by nutrient depletion.

To repeat, the areas impacted by potassium, magnesium, and calcium loss are not additive. In many cases the same areas are affected by loss of more than one nutrient (tables 4.1, 4.2, and 4.3).

Table 4.3. Increase in area of forest land for which losses of calcium exceed replenishment when the results of the base scenario are compared to those of the high scenario.

| Forest Type[b] | Soil[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WDF | PDF | WDM | PDM | WDC | PDC | ORG | Sum |
| | (10³ acres) | | | | | | | |
| AB | 12 | 0 | 327 | 23 | 123 | 33 | 129 | 645 |
| BS | 2 | 0 | 78 | 0 | 110 | 24 | 0 | 215 |
| LC | 0 | 0 | 3 | 0 | 29 | 23 | 0 | 55 |
| LH | 7 | 0 | 153 | 25 | 45 | 11 | 0 | 240 |
| P | 0 | 0 | 25 | 0 | 115 | 6 | 0 | 146 |
| SF | 10 | 0 | 100 | 0 | 82 | 24 | 0 | 215 |
| UH | 4 | 0 | 330 | 40 | 112 | 53 | 61 | 600 |
| Sum | 34 | 0 | 1,017 | 88 | 615 | 174 | 190 | 2,117 |

[a] WDF = well-drained, fine-texture; PDF = poorly-drained, fine-texture; WDM = well-drained, medium-texture; PDM = poorly-drained, medium-texture; WDC = well-drained, coarse-texture; PDC = poorly-drained, coarse-texture; ORG = organic.

[b] AB = aspen-birch, BS = black spruce, LC = lowland conifers, LH = lowland hardwoods, P = pine, SF = spruce-fir, UH = upland hardwoods.

## Levels of Utilization

Another evaluation was based on different levels of removal or utilization with harvest. This evaluation was done using statewide data. Both phosphorus and nitrogen were naturally replenished at adequate rates irrespective of utilization levels. The other three nutrients, magnesium, potassium and calcium, differ in their biogeochemistry and therefore the impact of increased utilization on their loss also differs.

If harvest is restricted to the bole without bark (*bole-only*), then magnesium is not adequately replenished on about 1.4 million acres of harvested forest land under the base scenario (figure 4.2). About half of this area is fine-textured soils where magnesium is naturally being lost at a greater rate than it is being replaced; harvest does not affect that loss. For these soils, each rotation removes less than 2 percent of the total magnesium capital. The other large area of magnesium loss, about half of the 1.4 million acres, are organic soils. In this case, harvest removes about 5 percent of the magnesium capital. As the level of bole-only harvest increases, the area of land impacted by magnesium loss only increases by about 300,000 acres, to 1.7 million acres. Removing only the bole, without bark, has a relatively small impact on the magnesium capital of sites.

In contrast, full-tree harvest has significant impact on magnesium depletion, affecting 4.1 million acres of forest land under the base scenario and 7.1 million acres of land under the high scenario (figure 4.2). Major areas of magnesium loss associated with full-tree harvest under the base scenario are coarse-textured soils (about 1.8 million acres) and organic soils (about 1 million acres). Under the high harvest scenario about 2.7 million acres of coarse-textured soils and 2.1 million acres of organic soils are negatively impacted. The large increase in area affected by full-tree harvest from the base to high scenario (figure 4.2) is related to the greater volumes of aspen, spruce, and upland hardwoods harvested under the high scenario; both forest types contain considerable magnesium in their branches and leaves.

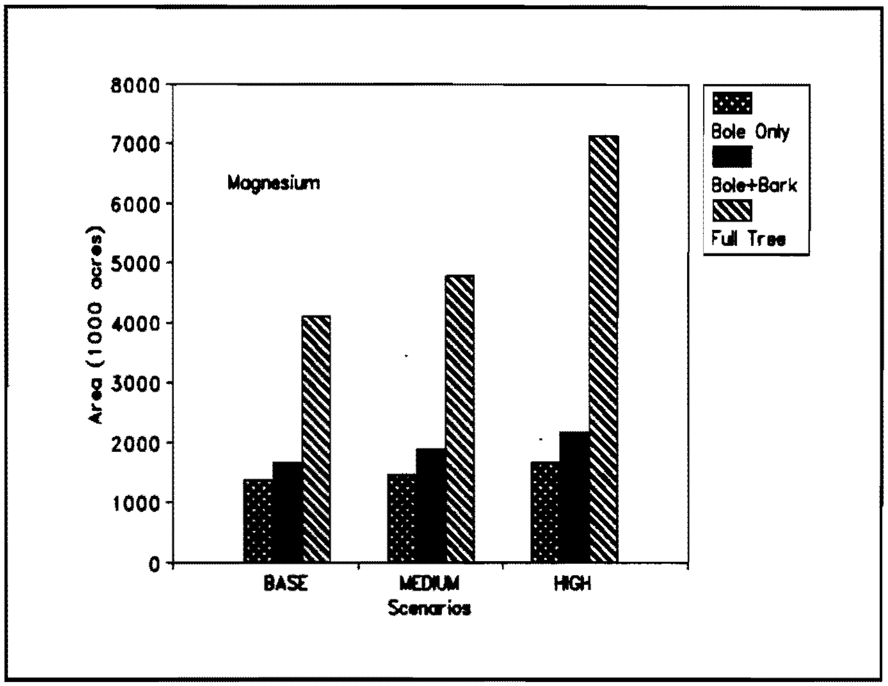

**Fig. 4.2. Area of forest land for which magnesium losses exceed replenishment under three harvesting scenarios and three levels of utilization.**

Potassium behaves similarly to magnesium, showing marked increases in the area of land affected as utilization increases from bole-only to full-tree (figure 4.3). Under the high scenario, the area affected by potassium loss increases from less than a million acres if only the bole without bark is removed, to 4.5 million acres with full-tree harvest. Potassium is primarily stored in the tree in the leaves and branches, both of which are retained on site in both bole-only and merchantable bole (bole and bark) harvests.

Because of its high levels in bark, but lower levels in branches and leaves, differences in area of calcium loss between bole-only and merchantable bole (with bark) removal are significant (figure 4.4). The increase in area with significant calcium loss when utilization shifts from merchantable bole to full-tree harvest is relatively smaller (figure 4.4).

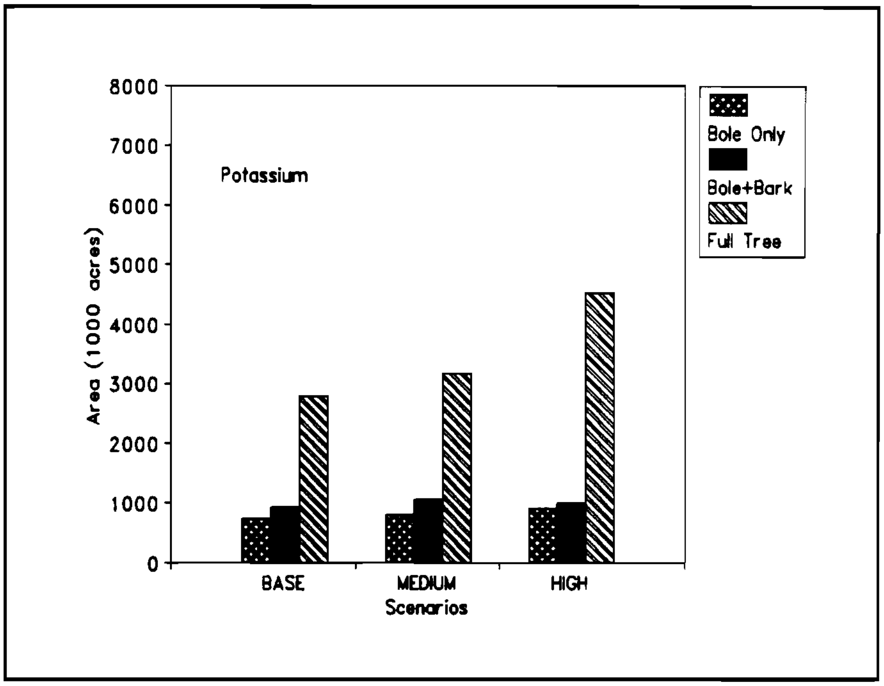

**Fig. 4.3.** Area of forest land for which potassium losses exceed replenishment under three harvesting scenarios and three levels of utilization.

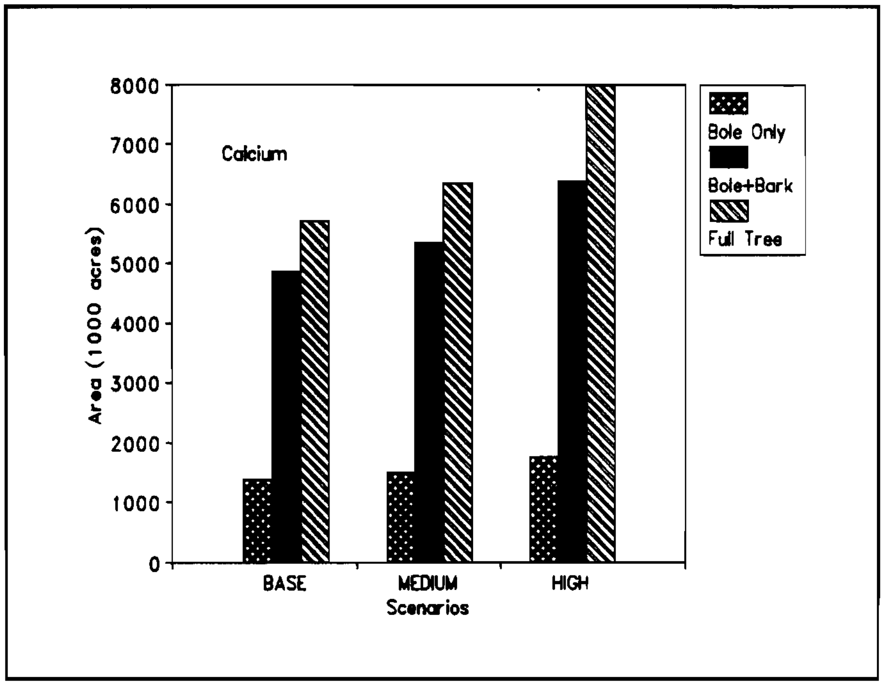

**Fig. 4.4.** Area of forest land for which calcium losses exceed replenishment under three harvesting scenarios and three levels of utilization.

The interaction of level of utilization, specific nutrient, and covertype can be further illustrated by the impact of change in utilization on change in areas of specific covertypes that are affected by nutrient depletion (table 4.4). As harvesting under the high scenario changes from the minimal depletion associated with bole-only removal to maximal depletion with full-tree removal, the largest change in area affected is related to calcium loss (over six million acres). This increase is especially associated with harvest of aspen-birch, but increase in area of upland hardwoods is also important (table 4.4). Bark of trees in both covertypes contain significant calcium. When utilization increases, the area affected by increased magnesium loss increases by about five and one-half million acres (table 4.4). Although aspen-birch and upland hardwood covertypes are significant in this increase, large areas of black spruce, pine, and spruce-fir types are also affected (table 4.4). Foliage of these conifers contains relatively high level of magnesium. As is the case with calcium, increased areas associated with potassium loss are primarily in the aspen-birch and upland hardwood covertypes (table 4.4).

**Table 4.4. Increase in area of forest land for which losses of specified nutrient exceeds replenishment when harvest removal is bole-only (without bark) compared to harvest of full-tree under the high model scenario.**

| Forest Type[a] | Nutrient | | | | |
|---|---|---|---|---|---|
| | N | P | K | Ca | Mg |
| | (10³ acres) | | | | |
| AB | 0 | 0 | 1328 | 3817 | 1328 |
| BS | 0 | 0 | 0 | 248 | 941 |
| LC | 0 | 0 | 259 | 79 | 357 |
| LH | 0 | 0 | 167 | 134 | 322 |
| P | 0 | 0 | 81 | 425 | 518 |
| SF | 0 | 0 | 190 | 222 | 455 |
| UH | 0 | 118 | 1608 | 1301 | 1539 |
| Sum | 0 | 118 | 3633 | 6225 | 5459 |

[a] AB = aspen-birch, BS = black spruce, LC = lowland conifers, LH = lowland hardwoods, P = pine, SF = spruce-fir, UH = upland hardwoods.

This comparison (figures 4.2, 4.3, and 4.4) clearly shows the dramatic difference in nutrient loss associated with different levels of utilization or removal of product from the forest. Removal of only the woody bole, leaving bark, branches, and leaves at the stump, retains maximum amounts of nutrients and results in minimal area of land being negatively impacted by harvest.

### Other Activities

#### *Delimbing and Topping*

Based on the summary of timber harvest operations carried out as part of the GEIS, delimbing and topping is carried out at a landing in about one-third of the harvests. This practice does not recycle or replenish the nutrients on the site, and is equivalent to a full-tree harvest in terms of nutrient depletion. The data developed for harvest of merchantable bole (figure 4.1) should be increased to take this practice into consideration. For any of the scenarios, the area affected by potassium loss should be multiplied by 2.25, for calcium loss by 1.5, and for magnesium loss by 2.0 to account for the present extent of delimbing and topping at landings.

#### *Mechanical Site Preparation*

Although not directly considered by the three harvesting scenarios, nutrient depletion related to site preparation techniques has also been evaluated. The GEIS survey indicates that about 10,000 acres are annually affected by mechanical site preparation. As discussed in the Technical Review, there is virtually no justification, from the standpoint of nutrient status, for any site preparation technique that displaces material. Mechanical techniques that create slash piles or windrows either remove nutrients from the site or localize them, depleting the remainder of the area; from the standpoint of nutrient conservation such techniques should be abandoned. Site preparation techniques that incorporate materials, or only displace materials a foot or two, do not have those negative impacts.

## 4.3
## Compaction and Related Disturbances

### 4.3.1
### Significance Criteria

An impact is considered significant if the proportion of the harvest unit projected to be moderately to severely compacted/puddled exceeds the following threshold proportions:
- 5 percent on highly sensitive sites;
- 10 percent on moderately sensitive sites; and
- 20 percent on sites with low sensitivity.

**Severity and/or extent.** This criterion addresses the problem of physical damage to soil structure that can occur in the course of harvesting. The significance threshold is expressed as a proportion of the site that experiences physical damage and uses a sliding scale that recognizes three classes of sensitivity to physical damage. Soil sensitivity is a function of soil strength. Soils with low strength are unable to support the heavy equipment used in forest management activities. Also, the amount of time for recovery is greater for soils exhibiting low strength. The most sensitive soils are wet soils with a high percentage of silt and clay, and organic soils. It is expected that one to three equipment passes would result in at least a moderate level of site disturbance (as defined previously) on these sites. Soil sensitivity decreases with either increased coarse fragment content or drier conditions. On moderately sensitive soils, four to twelve equipment passes would cause at least a moderate level of disturbance. Sites with the lowest sensitivity are the coarsest, driest sites. More than twelve equipment passes would be required to cause a moderate level of disturbance on these sites. The seven major soil types have been categorized according to sensitivity to physical damage. Soils that are more susceptible when wet have been placed under more than one category to account for seasonal differences. In addition, the criterion recognizes there is considerable variation in the degree of disturbance. The three categories of disturbance used are:

- slight: no disturbance to light scarification;
- moderate: depressions up to 2 inches deep in the mineral soil; and
- severe: depressions or ruts in the mineral soil greater than 2 inches deep.

Only moderate and severe damage categories are used in assessing significance. The thresholds do not consider area of haul roads. All of the area occupied by haul roads was considered to be significantly impacted.

The criterion will be applied to combinations of seven soil types, seven covertypes and seven ecoregions. The proportion of a harvesting unit affected will be estimated based on logging practices and equipment configurations described in the silviculture and harvesting background papers.

Seasonality is addressed implicitly by considering soil water status. Soils can be in one of three conditions—wet, dry, or frozen. Soil water status is highly correlated with season, though it is also a function of the texture and drainage class of the soil. Soil water status is a major factor in determining the sensitivity of a site to equipment impacts. The seasonal distribution of management activities is based on the information reported in the Silvicultural background paper. It is assumed that all equipment operation on organic soils is limited to frozen conditions.

**Certainty of impact.** The certainty of soil physical damage depends on many variables such as season of harvest, site condition, soil type, equipment used and harvest and related road planning.

**Duration of impact (irreversibility).** Short- to long-term impacts occur depending on the severity of damage and the rate of recovery of soil physical characteristics.

**Biological implications**. Reduced site productivity occurs due to a reduction in volumes of soil available for root development. In addition, site hydrological processes are altered, more overland flow of water is generated leading to increased potential for erosion and subsequently sedimentation.

**Existing guidelines and standards**. *BC Standards:* British Columbia has adopted guidelines that define limits of soil disturbance which cannot be surpassed during harvesting activities. These standards are based on considerable research and field experience and are designed to ensure continued forest productivity in BC. These guidelines are cited because they represent a situation where a public agency, operating in a major forest industry center, has completed the process of developing limits of site disturbance. They also comprise a useful framework for assessing site disturbance. However, their basic framework is not particularly new or unique, and while the significance criterion follows a similar framework, the definitions and limits have been modified to better reflect Minnesota conditions.

**Economic implications**. Soil compaction can cause a loss of productive capacity during subsequent rotations.

**Caveat**. In this assessment, timber harvesting and forest management impacts that meet the criterion for significance to forest soil compaction and puddling are identified. *All* timber harvesting and forest management activities create impacts on soil physical properties. Those impacts range from nearly none (likely where the management activity is minimal) to very great. That continuum of impacts is impossible to treat in any quantitative sense; a threshold must be developed to aid in communication. Impacts that are greater than that threshold merit attention; impacts below the threshold are not large enough to justify further consideration. The size of that threshold may vary with the state of knowledge. The threshold in our analysis is the criterion for significant impacts.

### 4.3.2
### Results

**Harvesting**

The following are the cumulative results for the 50-year planning period assuming the harvesting strategies outlined in the three harvesting scenarios (Jaakko Pöyry Consulting, Inc. 1991b) and the seasonal distribution of harvesting activities outlined in the Silvicultural Systems Background Paper (Jaakko Pöyry Consulting, Inc. 1992a). Under the base or current scenario, about 6 million acres would be harvested statewide (figure 4.5). The significance criteria would be exceeded in harvesting units representing about 840,000 ac (figure 4.6). If 1 percent of the area harvested were devoted to haul roads in order to extract the timber, an additional 60,000 ac would be significantly impacted under the base scenario (figure 4.7).

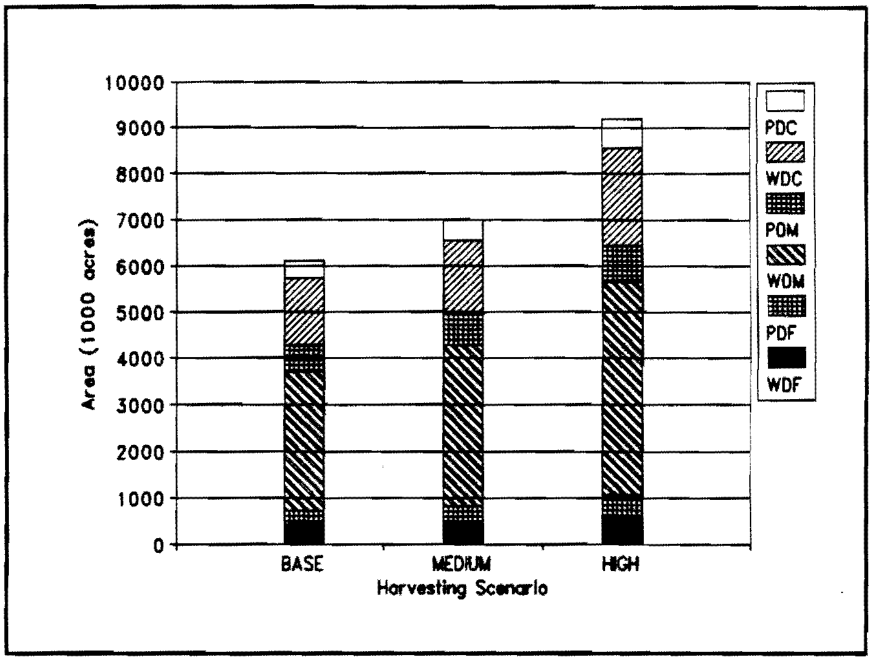

**Figure 4.5. Area of each mineral soil type harvested in the initial model run under the base, medium, and high scenarios. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.**

As the harvesting level increases in the medium and high scenarios, the area where significance criteria are exceeded also increases. Under the medium scenario, significance criteria would be exceeded in harvest units representing about 955,000 ac (figure 4.6). This area increases to about 1,240,000 ac under the high scenario. Under all three scenarios, the area of harvest units where significance criteria are exceeded is about 13.5 percent of the total area harvested. This is in addition to the area that would be would be occupied by haul roads.

The statewide results are not distributed evenly between soil types. Figure 4.5 represents the area of each soil type that would be harvested under each scenario, and reflects the relative predominance of each soil type throughout the state. Under all three scenarios most harvesting occurs on well-drained medium-textured soils followed by well-drained coarse textured soils. There are significant differences in the sensitivity of varying soil types to harvesting impacts. Figure 4.8 shows the percentage of harvest unit area where significance criteria were exceeded for each soil type, and demonstrates that the significance criteria were exceeded most frequently on the well-drained fine textured soils, poorly-drained fined textured soils, and the poorly-drained medium textured soils. These results reflect the lower soil strength

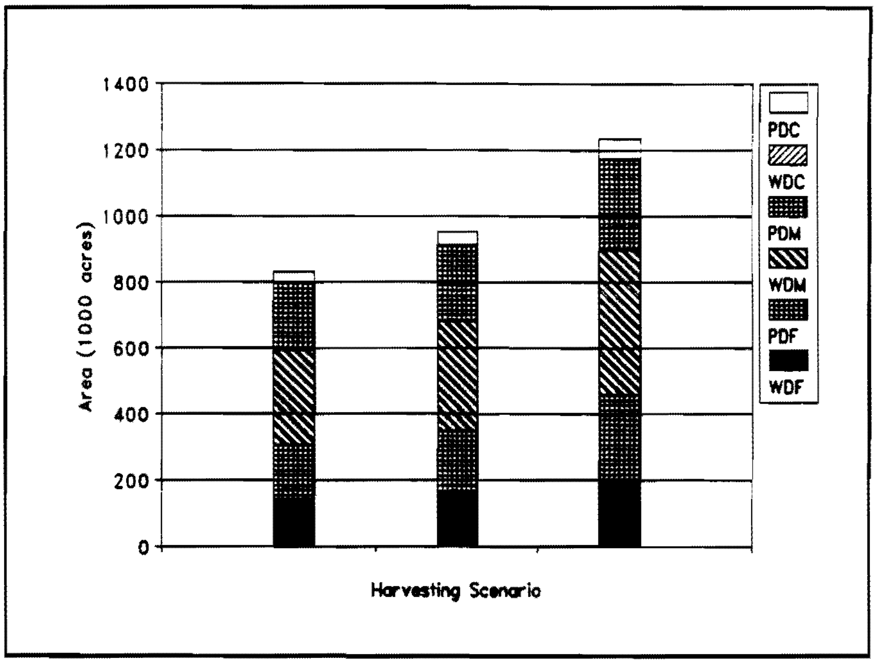

**Figure 4.6.** Harvest unit area where compaction significance criteria were exceeded during the initial model run. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

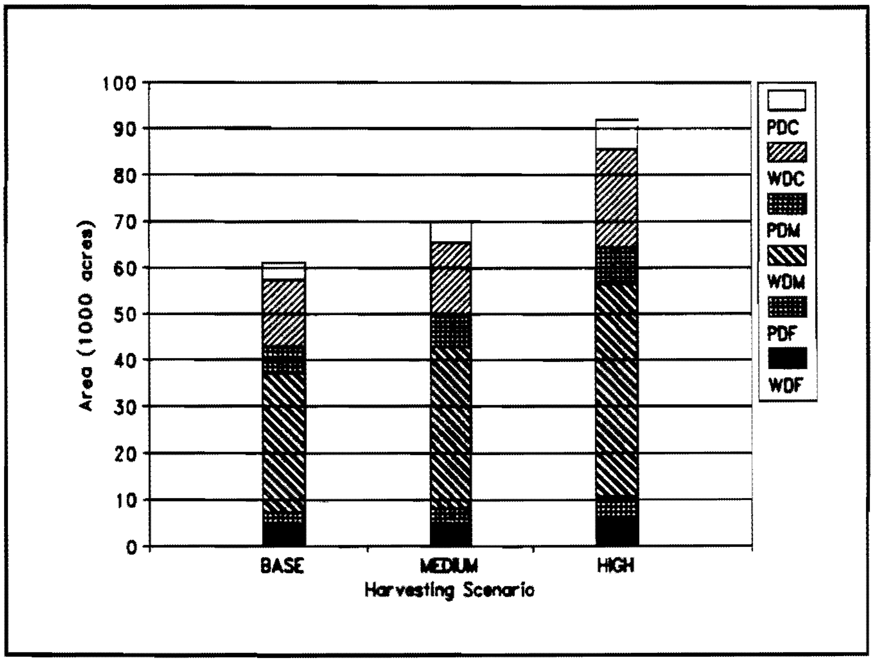

**Figure 4.7.** Area impacted by haul roads for each scenario of the initial model run if they occupied 1% of harvest unit area. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

associated with finer soil textures and wetter soil conditions. In fact, based on these analyses, significance criteria were exceeded on more than 50 percent of the poorly-drained fine textured soils. The significance criteria are never exceeded on well-drained, coarse-textured soils.

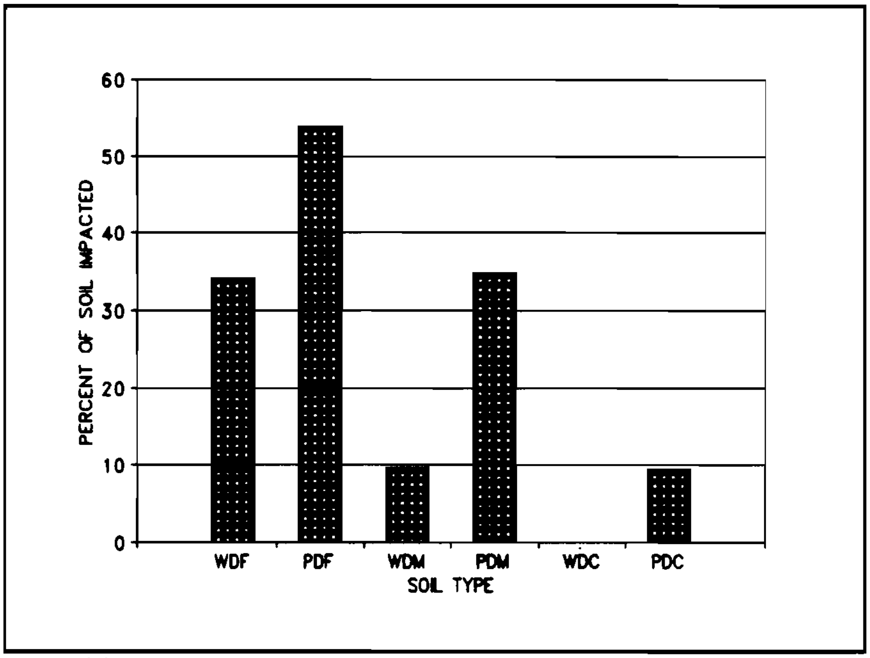

**Figure 4.8.** Percent of harvest area where significance criteria are exceeded for each soil type.PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

The disparities between soil types suggest that compaction impacts will be more widespread in ecoregions containing higher proportions of the more sensitive soils. This is demonstrated by comparing the area impacted under each harvesting scenario in each ecoregion (figures 4.9 to 4.11) with the area harvested (figures 4.12 to 4.14).

Ecoregion 1 is dominated by an old lake bed and thus contains a high percentage of poorly drained, fine-textured soils. Conversely, ecoregion 2 has a low percentage of the three most susceptible soils (PDF, WDF, and PDM). It was estimated that 27 percent of the area harvested in ecoregion 1 exceeded significance criteria while only 8 percent of the area harvested in ecoregion 2 exceeded the criteria. The sensitivity of the soils in ecoregion 1 is further seen by comparing it with ecoregion 4. Under each harvesting scenario, about four times as much area was harvested in ecoregion 4, yet only about 30 percent less area was impacted in ecoregion 1.

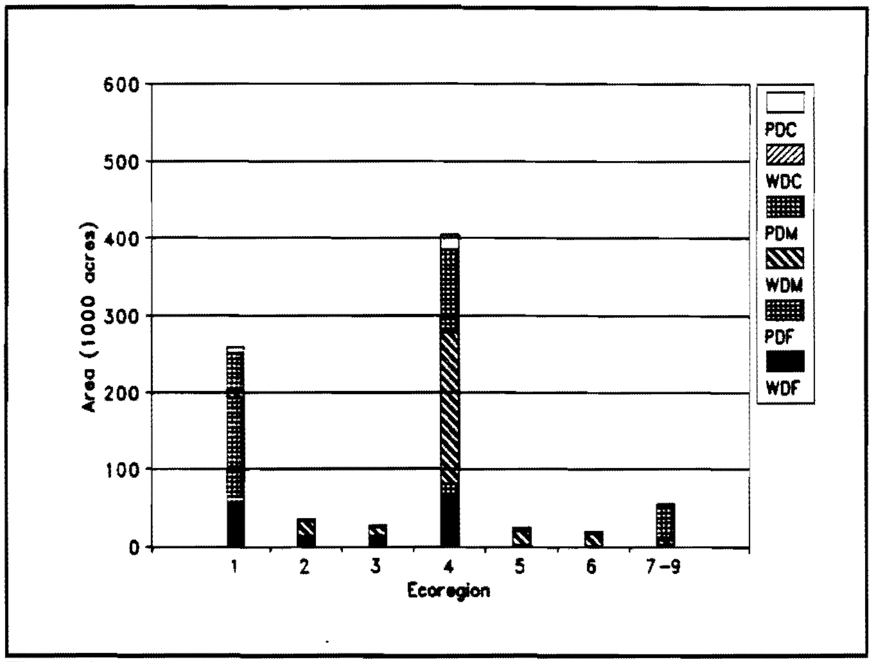

**Figure 4.9.** Harvest unit area where compaction significance criteria were exceeded in each ecoregion under the base scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

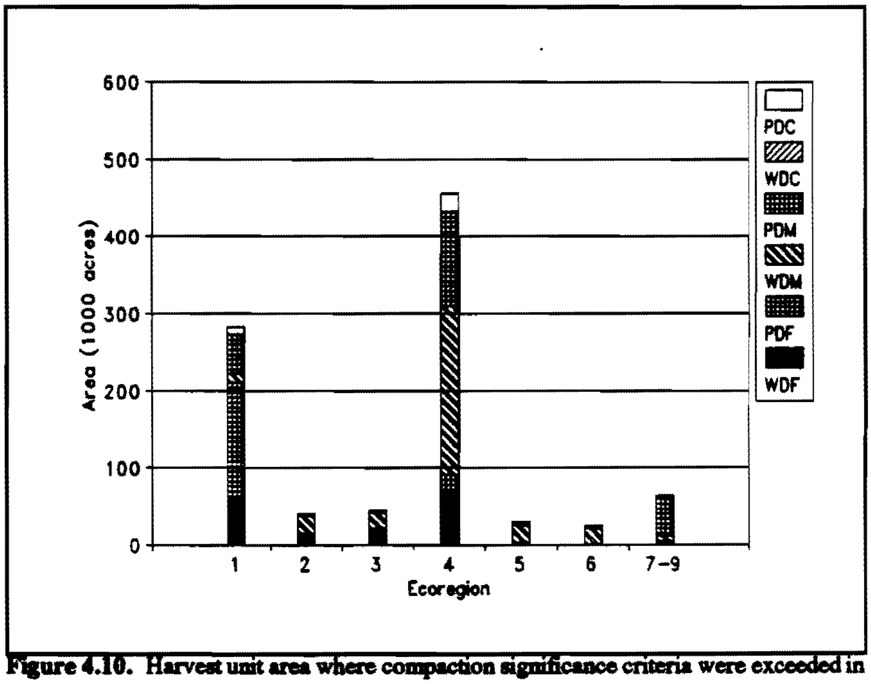

**Figure 4.10.** Harvest unit area where compaction significance criteria were exceeded in each ecoregion under the medium scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

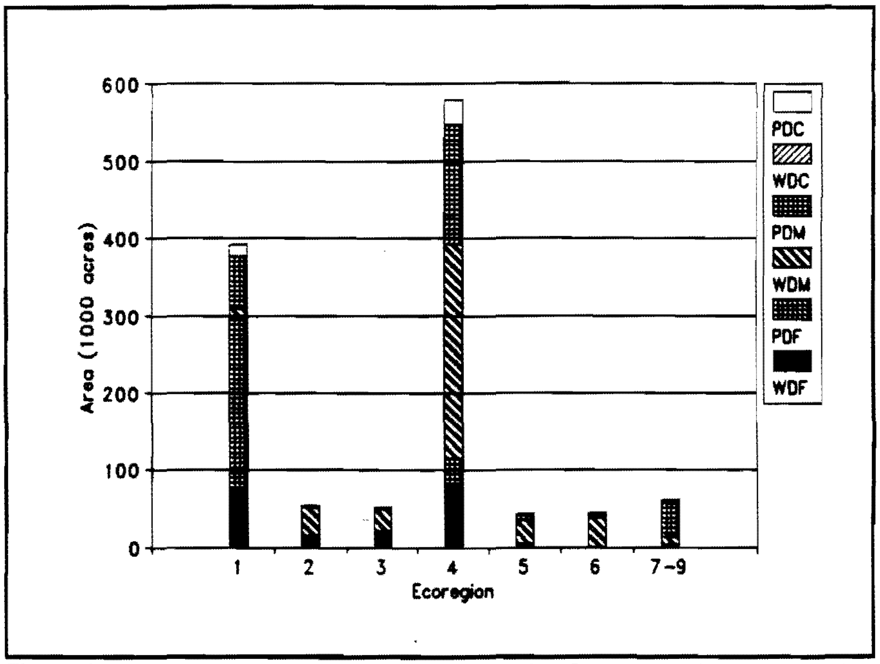

**Figure 4.11.** Harvest unit area where compaction significance criteria were exceeded under the high scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

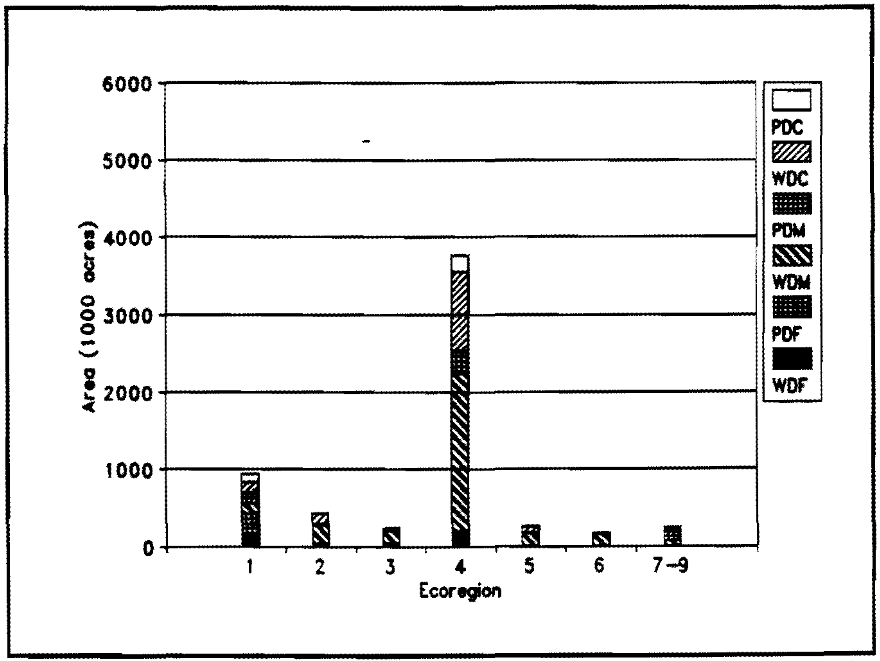

**Figure 4.12.** Area harvested in each ecoregion under the base scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

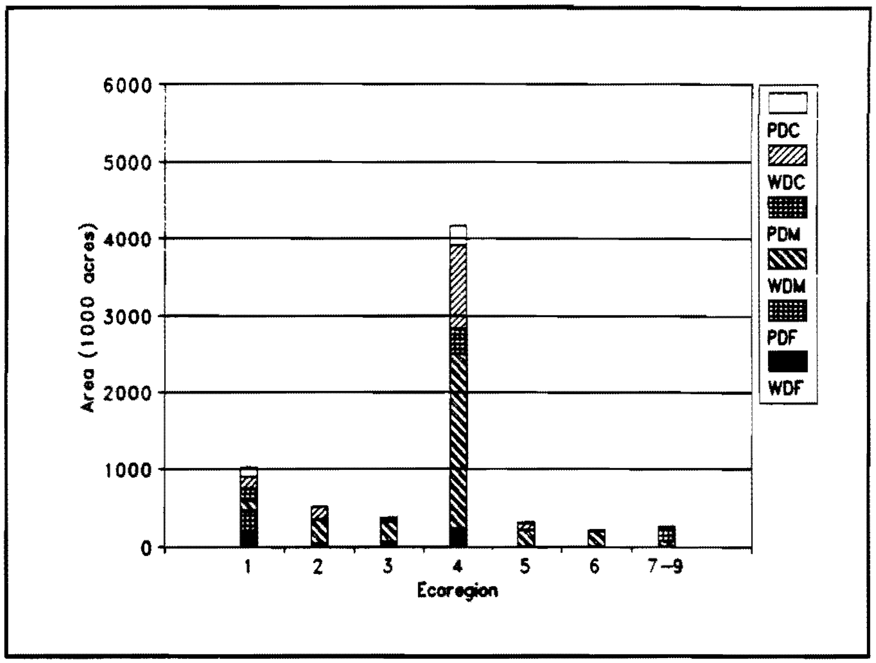

**Figure 4.13.** Area harvested in each ecoregion under the medium scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

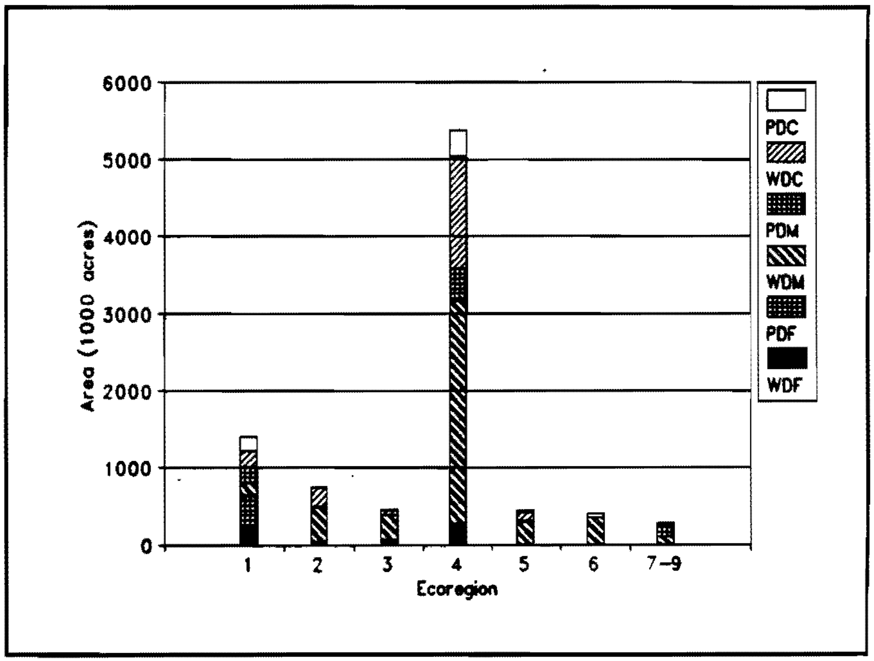

**Figure 4.14.** Area harvested in each ecoregion under the high scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

### Mechanical Site Preparation

It was not possible to qualitatively assess the additional impacts of mechanical site preparation on soil compaction. However, the Silvicultural Systems Background Paper suggested that only about 10,000 ac are mechanically site prepared in Minnesota annually. Thus any effects would be minor relative to timber harvesting impacts. Most mechanical site preparation falls into the light trafficking category (one to three passes) and, by design, covers most of the site. Based on the significance criteria, this would only have a significant impact when conducted on sensitive sites, although the type of site preparation would determine the extent of the impact.

Site preparation practices such as windrowing and root raking pose the greatest risk of negative impacts. These activities remove slash and other protective surface residues, maximizing compaction by allowing equipment to operate in direct contact with the ground. These practices can also remove the surface soil layer exposing naturally more dense subsoils.

Other common site preparation techniques, such as discing and scalping may cause less compaction, or may even reduce soil densities. In both of these cases the equipment can operate on top of slash and surface residues. Discing often loosens the soil surface and incorporates organic matter into the soil and can ameliorate compaction that occurred during the harvesting.

## 4.3.3
## Discussion

Sensitivity is largely controlled by season (table 3.2). It was estimated that all soils exhibit low sensitivity in the winter when they are frozen. Spring is the period of greatest sensitivity when the fine- and medium-textured soils are highly sensitive, although, the well- and poorly-drained, coarse-textured soils have low and moderate sensitivity, respectively. During the summer and fall, sensitivity varies with texture and drainage class, with poorer drainage and finer textures increasing site sensitivity.

The impact assessment indicated that increased levels of timber harvesting will invariably lead to increased amounts of compaction and related disturbance. The significance criteria were exceeded by both mechanical and hand-felling operations on moderately and highly sensitive sites. It was estimated that about 25 percent of the area within moderate sensitive sites would be negatively affected by equipment trafficking for both harvesting configurations. The portion of highly sensitive sites that are negatively impacted could increase to about 30 percent for hand-felling operations and 55 percent for mechanical felling operations.

These results are based on the seasonal harvesting distribution outlined in the Silvicultural Systems Background Paper, and reflect similar harvesting periods on all soil types within each ecoregion. Limiting timber harvesting to specific seasons on individual soils or sites could greatly affect the impact assessment. However, with the exception of organic soils, there is no evidence that this is currently being done on a regular or operational basis.

Additional research is required to fully quantify the effects of these disturbances on Minnesota's forest resource. Although, it has been clearly documented that compaction and related disturbance reduces forest growth, what is not certain is the magnitude and duration of the impact. Most research suggests that the effects are both significant and long-term. Based on these results, it is possible to calculate crude estimates of the potential impact of compaction and related disturbances on future productivity. It was estimated that over the 50-year planning period, the *actual* area impacted within harvest units where significance criteria were exceeded are about 330,000, 375,000, and 490,000 ac under the base, medium, and high scenarios, respectively. An additional 60,000, 70,000, and 90,000 would be impacted under the base, medium, and high scenarios if 1 percent of the area harvested is occupied by haul roads. Assuming that productivity is reduced by 25 percent in lightly trafficked areas, by 50 percent in heavily trafficked areas, and by 75 percent in haul roads, these impacts would translate to losing the wood-producing equivalent of as much as 170,000 ac under the base or current scenario. This area increases up to 195,000 ac under the medium scenario and 250,000 ac under the high scenario.

It should be emphasized that there is a great deal of uncertainty in these estimates. There is no definitive data available regarding how fast the impact declines. Also, for the purposes of growth, trees adjacent to forest openings may benefit from less canopy competition, thereby reducing the impact. In addition, these losses do not consider the possible benefits such as the increased access afforded by a forest road system or habitat improvement associated with semipermanent forest openings.

## 4.4
## Soil Erosion

### 4.4.1
### Significance Criteria

An impact is considered significant if the rate of soil loss is projected to exceed the limits prescribed by the U.S. Soil Conservation Service expressed as:

$$\text{rate} > T$$

where T varies between 1-5 (tons/ac/yr)

**Severity and/or extent.** A forest management activity will be considered to significantly affect site quality if it results in an erosion rate that is greater than the soil loss tolerance value (T value) as defined by the Soil Conservation Service. The T value is strongly based on the rate of soil formation. Soil formation processes vary considerably and this is reflected in the variation between one and five tons per acre used in the criterion. Variation in the rate of formation is due to several factors including: depth of loose materials above bedrock, climatic conditions (particularly temperature and precipitation), parent material, topography and vegetation. The T index has been developed for use in agricultural areas. An analogous index has not been developed for use in forests. Consequently, all erosion work in forests has been compared with established T values, resulting in a substantial body of literature from which to draw when assessing impacts.

The criterion will be applied to relevant combinations of seven soil categories and seven covertypes. The analysis will be reported at ecoregion level, and will assess impacts cumulatively over the 50-year study period. It will identify areas where management activities accelerate the rate of erosion above the rate of soil formation. Erosion rates will be estimated for areas representing different levels of disturbance within harvest units, and not averaged across the entire harvest unit.

**Certainty of impact.** The impact timber harvesting has on the rate of soil erosion depends on many variables including soil type, site conditions, season, application of BMPs, timber sale layout and design. Typically lower levels of erosion occur with care in the location, construction and maintenance of roads and use of soil conservation measures identified in BMPs.

**Duration of impact (irreversibility).** Erosion impacts vary from short- to long-term. Short-term impacts are associated with the soil loss that accompanies typical harvesting operations prior to revegetation. Longer term impacts occur where the quantity of soil eroded would require many decades to replace at the prevailing rate of soil formation.

**Biological implications.** Soil loss impacts site productivity by removing nutrients bonded to eroded particle and by reducing the volume of soil available on the site. Nutrient loss can be exacerbated by losses of the organically rich upper horizon due to surface erosion. Off-site impacts can occur via sedimentation, which reduces water quality and can adversely affect aquatic ecosystems.

**Existing guidelines and standards.** BMPs; U.S. Soil Conservation Service Guidelines soil loss tolerance guidelines; Upper Mississippi River Board Ordinances for relevant counties.

**Economic implications.** Potential reduction in site productivity due to a loss in soil volume and nutrients.

**Caveat.** In this assessment, timber harvesting and forest management impacts that meet the criterion for significance to forest soil erosion are identified. *All* timber harvesting and forest management activities create impacts on soil properties that can lead to erosion. Those impacts range from nearly none (likely where the management activity is minimal) to very great. That continuum of impacts is impossible to treat in any quantitative sense; a threshold must be developed to aid in communication. Impacts that are greater than that threshold merit attention; impacts below the threshold are not large enough to justify further consideration. The size of that threshold may vary with the state of knowledge. The threshold in our analysis is the criterion for significant impacts.

### 4.4.2
### Results

These results represent the total area impacted over the 50-year planning period. The analyses indicated that significance criteria would be exceeded only in moderately and heavily trafficked areas (skid trails) within harvest units and on haul roads. Also, significant impacts were concentrated in well-drained mineral soils which is to be expected since they are the soils with steepest slopes.

Under the base or current scenario, about 35,000 ac within harvest units would develop erosion rates that exceed T-values. This area would increase to about 30,000 ac under the medium scenario and about 45,000 ac under the high scenario (figure 4.15). Accelerated erosion caused by skidding and felling activities would exceed T-values on less than 1 percent of the total area harvested during the 50-year period.

The greatest erosion rates were estimated to occur in ecoregion 6 (figures 4.16 to 4.18). This ecoregion has the steepest slopes (averaging 45 percent in many areas). The southern portion of the state also has the highest rainfall intensity. It was estimated that initial erosion rates could exceed 14 ton/ac/yr in some areas in ecoregion 6. Initial rates rarely exceeded 5 ton/ac/yr in other ecoregions.

If an area equal to 1 percent of the harvest area were utilized for hall roads, T-values would be exceeded on an additional 6,000 ac under the base scenario, this would slightly increase under the medium scenario and reach about 10,000 ac under the base scenario (figure 4.19). These totals indicate that erosion rates would be exceeded on about 8 percent of the haul road area.

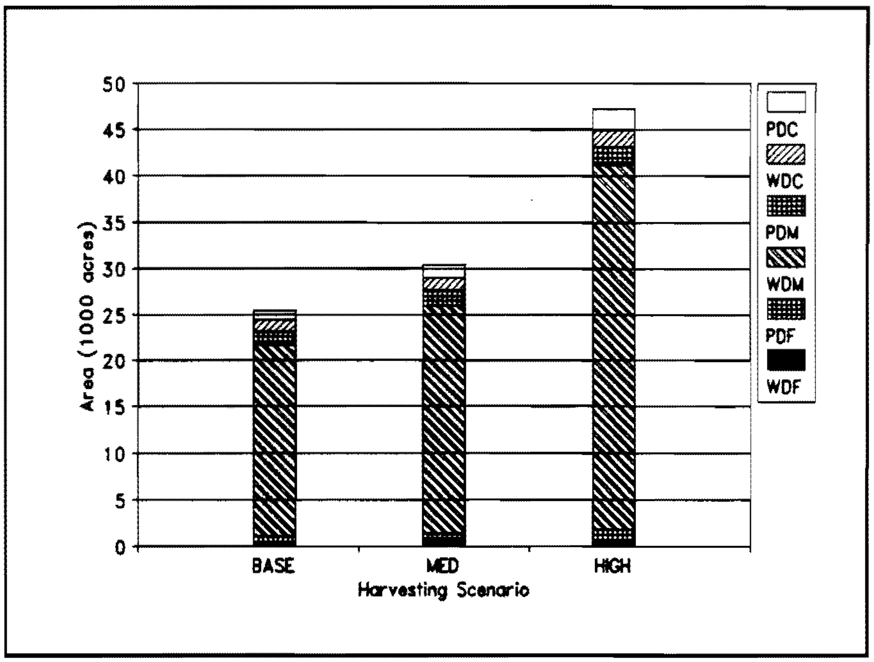

**Figure 4.15.** Area within harvest units where erosion exceeds T-values under each scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

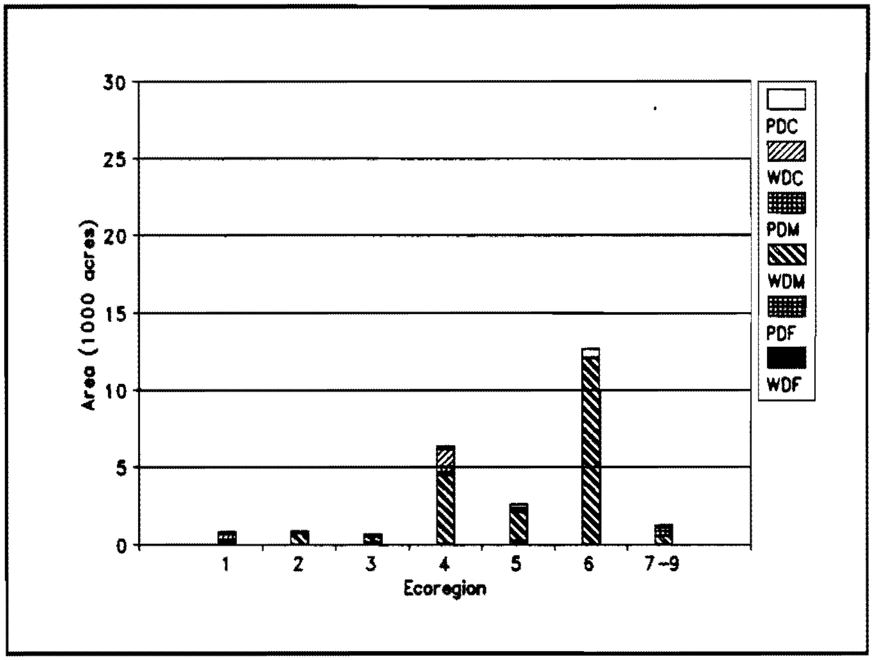

**Figure 4.16.** Area within harvest units where erosion exceeded T-values in each ecoregion under the base scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

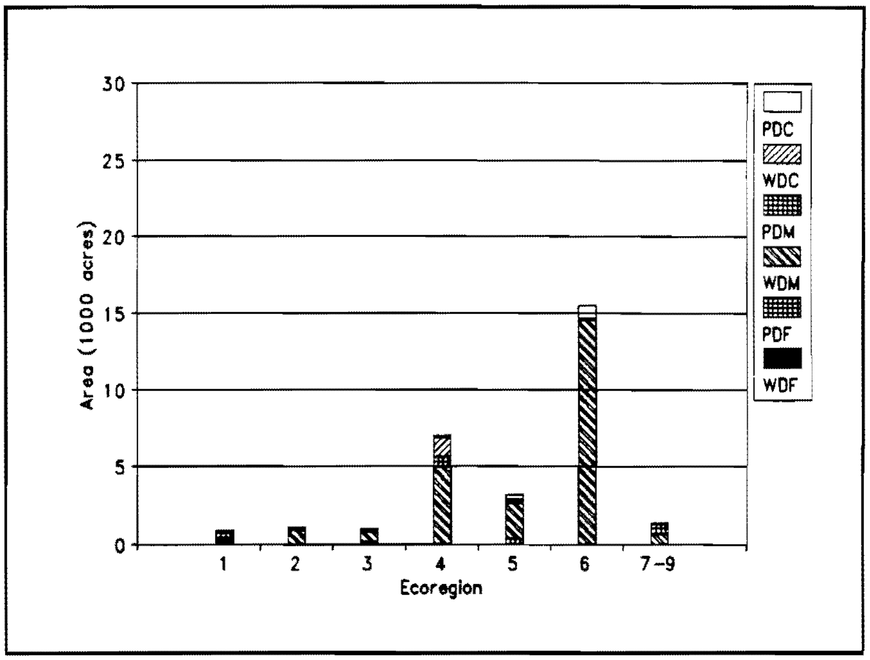

**Figure 4.17.** Area within harvest units where erosion exceeded T-value in each ecoregion under the medium scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

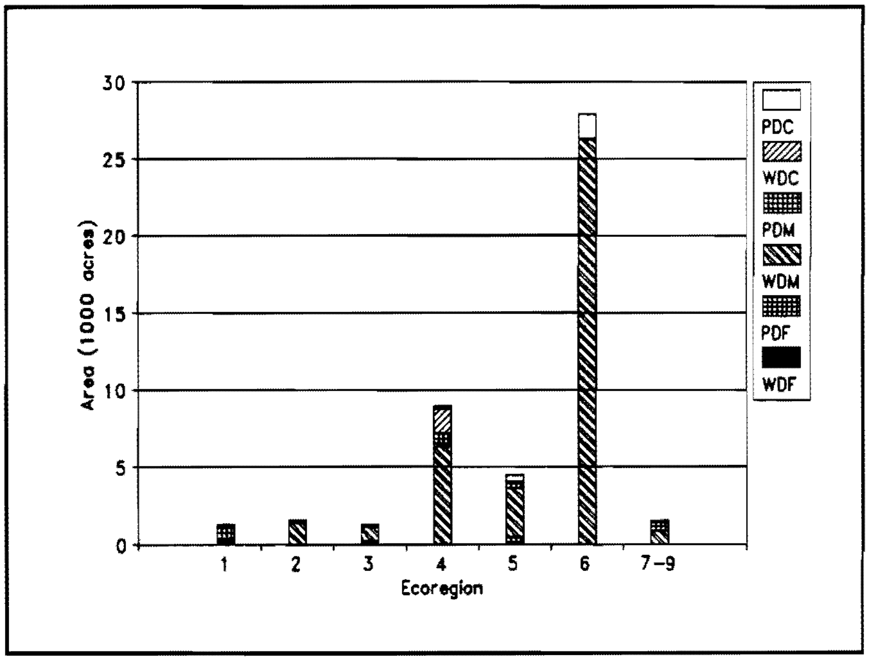

**Figure 4.18.** Area within harvest units where erosion exceeded T-value in each ecoregion under the high scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

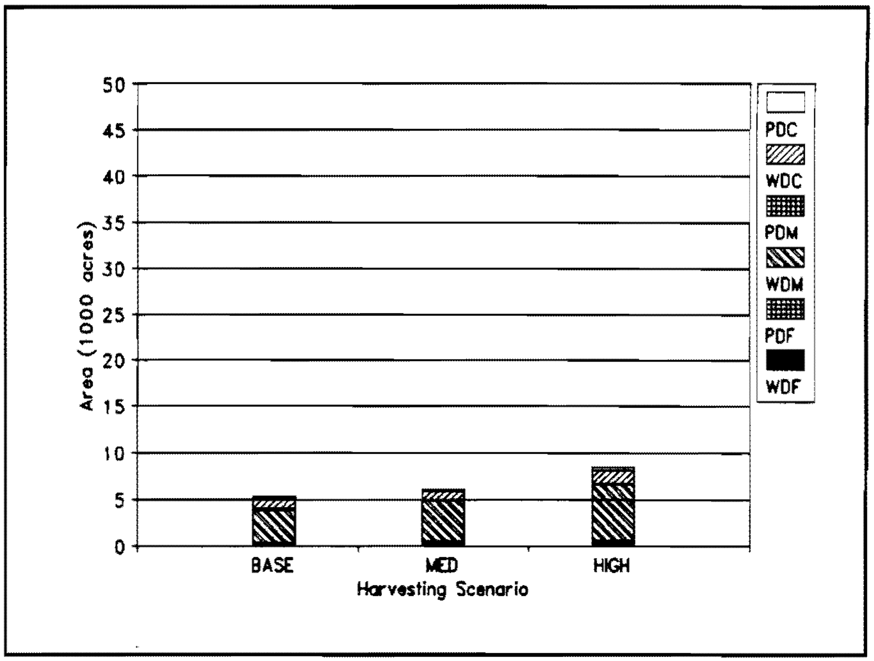

**Figure 4.19. Area of haul roads where erosion exceeded T-values under each scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.**

Erosion associated with haul roads would occur at faster rates than erosion within harvest units. This is a function of the more complete removal of surface protection and smoothing of the ground surface in haul roads. The analyses indicated that maximum initial erosion rates in haul roads could approach 100 ton/ac/yr in some areas. The distribution of significant haul road erosion within ecoregions are presented in figures 4.20 to 4.22.

The effects of timber harvesting and forest management activities on mass movements were not quantified. It is expected that these activities would increase the number of mass movements that occur. Poorly located roads pose the greatest risk for triggering mass movement events. This is particularly true when road construction activities disrupt marginally stable slopes. The greatest potential for mass movements would occur in areas with steep slopes such as the Coulee region of southeastern Minnesota (in ecoregion 6) and areas with shallow soils over bedrock (ecoregions 2 and 3). The literature suggests that mass movement events may at least double following timber harvesting and may increase by 25 or more times in response to road construction. However, there is currently no evidence suggesting that mass movements are currently a major problem in forested portions of Minnesota.

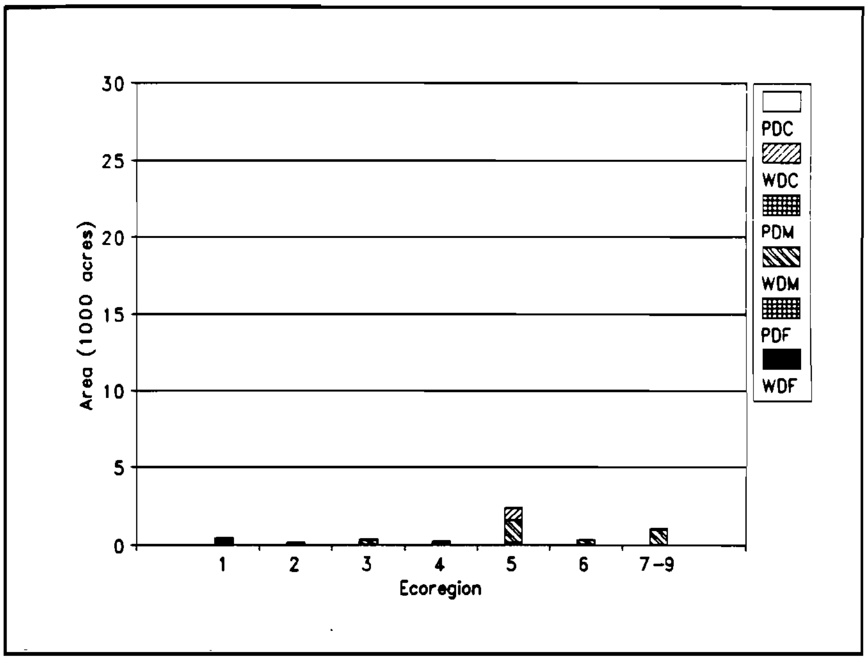

**Figure 4.20.** Area of haul roads where erosion exceeded T-values in each ecoregion under the base scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

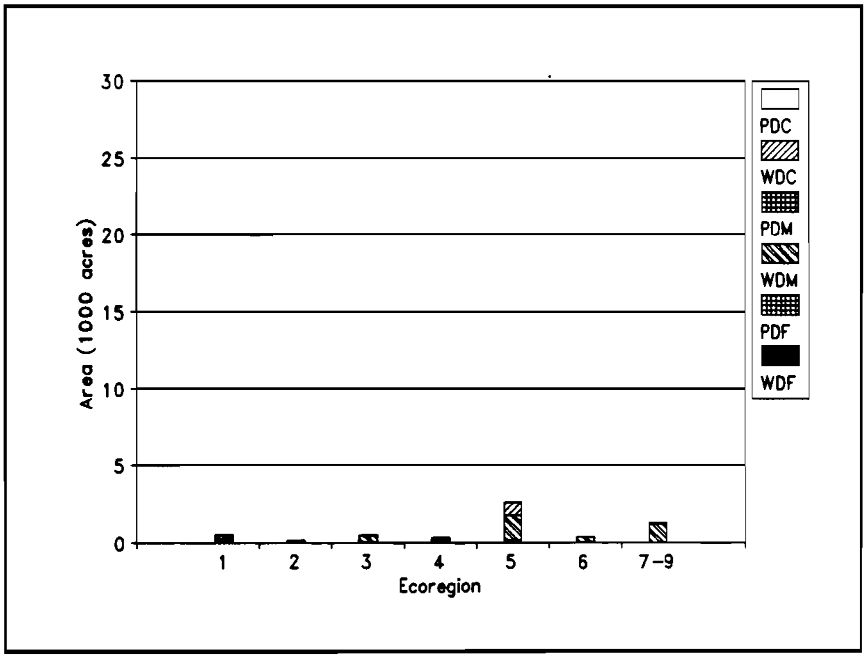

**Figure 4.21.** Area of haul roads where erosion exceeded T-value in each ecoregion under the medium scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

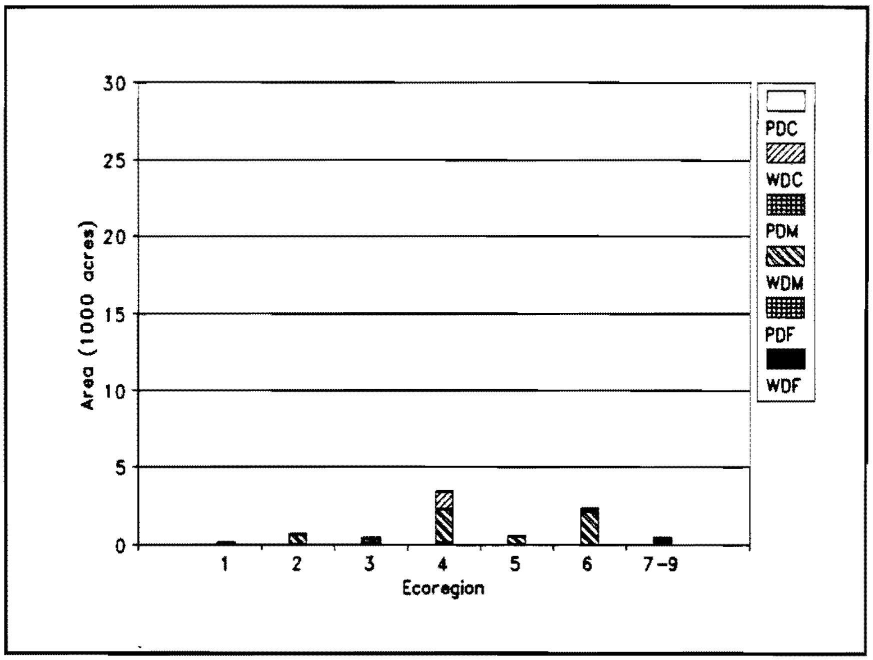

**Figure 4.22.** Area of haul roads where erosion exceeded T-values in each ecoregion under the high scenario. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

## 4.4.3 Discussion

The results of this study are consistent with what has been reported by others, namely that surface erosion would rarely exceed T-values within harvest units but can be a major concern in conjunction with skid trails and haul roads. These results are attributed to the fact that the rapid revegetation and surface roughness within harvest units greatly reduces the surface erosion that will occur there. The initial removal of vegetation and forest litter is much more complete in more heavily trafficked areas which leads to higher initial erosion rates.

It should be noted that accelerated erosion was evaluated as a short-term impact (i.e., recovery after four years). If the soil loss had been averaged over a longer period, such as the rotation length, then erosion rates would have exceeded T-values in fewer areas.

It appears that accelerated erosion within harvest units due to timber harvesting activities will have a minimal effect on forest productivity in Minnesota. This statement is based on the minimal area within harvest units (less than 1 percent of total harvest area) where the significance criteria were exceeded. Furthermore, in terms of productivity, T-values represent the annual amount of soil that can be lost indefinitely—not just over four years.

The higher erosion rates that would occur on haul roads may be more important in terms of water quality impacts. As discussed above, compaction and related disturbances on haul roads would greatly reduce the productivity of these areas. It would be difficult to evaluate the added effect of erosion on productivity. However, the large amount of soil that can be eroded from roads can contribute greatly to water sedimentation problems.

## 4.5
## Impacts of Second Harvesting Scenarios

### 4.5.1
### Background

Two model runs were made, creating two harvesting scenarios. The major differences between the model runs are based on the assumed availability of timberlands for harvest.

In the initial model runs, an important assumption was that all timberlands in the state were available for harvesting. The only exceptions were those within designated reserve areas and those designated as being unproductive. The initial model runs also assumed that management objectives for all available lands allowed timber production. These assumptions ignore some of the constraints imposed by the various ownerships.

The second model runs introduced ownership constraints that limited availability of certain categories of timberlands. These constraints reflect current management procedures and policies applied by the major forest land managers. Examples of availability constraints include protecting riparian lands and old growth forests. Other constraints include management on longer rotations for a proportion of stands in some covertypes. The second model runs also applied the USDA Forest Service allowable cut limits for yields from their timberlands. ***Inclusion of these constraints means that the second model runs are a reasonable depiction of availability and practices.***

The impacts of these second model run scenarios on soils were assessed by using the same approaches that were used to assess the initial scenarios. Briefly, the forested soils were aggregated into seven groups based on soil texture and drainage. Similarly, forest covertypes were aggregated into seven major types. The output from the second model run scenarios were combined with data on extent and distribution of soil types and on the distribution of forest types to estimate how many acres of each soil would be harvested under each level of harvesting.

Impacts of the second model run scenarios were evaluated by using the same tests of significance that were used to evaluate the initial harvesting scenarios.

The following presents the output of these analyses which highlight the marginal differences between the scenarios generated by the initial and second model runs.

## 4.5.2 Nutrients

### Base Scenario

Impacts of the base scenario of the second model run were similar to those of the base scenario of the initial model run. Because relative nutrient removals and replenishment by forest type and soil did not differ between the two model runs, impacts were assessed with reference to the area of each forest type that was cut on each soil. More area of aspen-birch was cut than of any of the other types (figure 4.23); aspen-birch is also the dominant

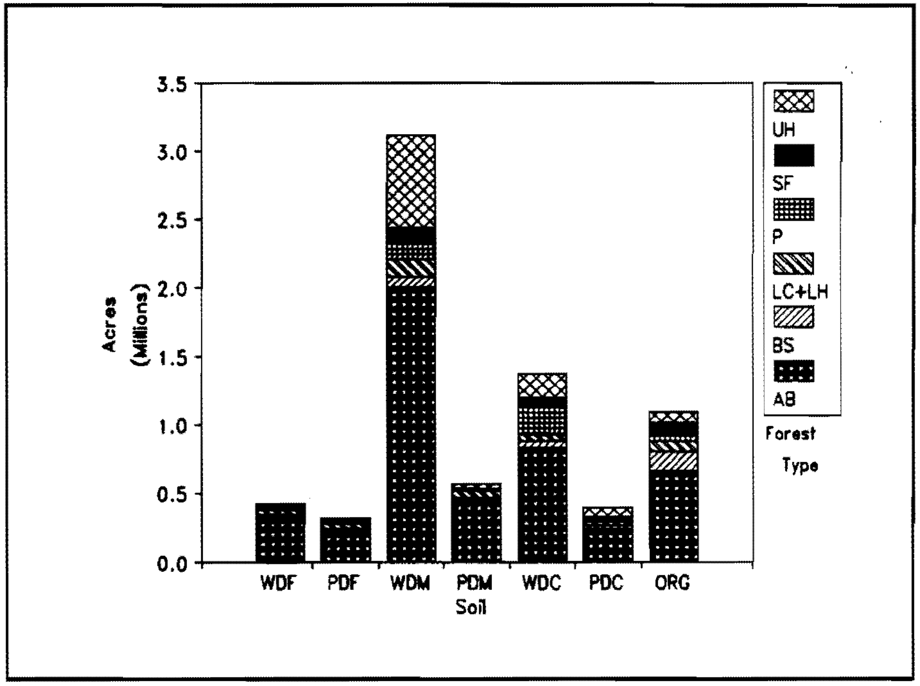

**Figure 4.23.** Area of forest types[a], on each of seven soil groups[b], that were clearcut over the planning horizon under the base harvest scenario of the second model run.

[a] Forest types; AB = aspen-birch, BS = black spruce, LC + LH = lowland conifers and lowland hardwoods, P = pine, SF = spruce-fir, UH = upland hardwoods.

[b] Soils; WDF = well-drained, fine-texture; PDF = poorly-drained, fine-texture; WDM = well-drained, medium-texture; PDM = poorly-drained, medium-texture; WDC = well-drained, coarse-texture; PDC = poorly-drained, coarse-texture; ORG = organic.

forest type in the state. Similarly, greatest area of harvest was on well-drained medium-textured soils; that is also the dominant soil type in the state.

As with the initial scenarios, harvest of merchantable bole did not remove either nitrogen nor phosphorus beyond their rates of replenishment. Areas at risk for loss of calcium are most closely associated with harvest of aspen-birch and upland hardwoods, on both medium- and especially on coarse-textured soils. Because of that, approximately 5 million acres are at risk for calcium loss. Loss of magnesium beyond rates of replenishment is especially associated with harvest on coarse-textured soils and organic soils. Under the base scenario, about 2.5 million acres are at risk for magnesium loss. Finally, potassium loss is primarily associated with harvest of aspen-birch on coarse-textured soils and of all deciduous types on organic soils. About 1.5 million acres are at risk for potassium loss under the base scenario.

### Increased Harvest Scenarios

As more area is harvested under the medium (figure 4.24) and high scenarios (figure 4.25) under the second model run, the area at risk for nutrient loss also increases. Increased calcium loss is primarily associated with increased harvest of upland hardwoods (figures 4.24 and 4.25), with some increase in harvest of aspen-birch and lowland hardwoods at the high scenario (figure 4.25). As a result, over 0.5 million acres are at increased risk of calcium loss under the medium scenario and nearly 2 million acres under the high scenario. Increased harvest of black spruce on organic soils, and increase harvest of most species on coarse-textured soils at the medium scenario (figure 4.24), leads to an increase of about 0.5 million acres at risk for magnesium loss under the medium scenario. Further increases in harvest on coarse-textured soils (figure 4.25) increases the area at risk for magnesium loss to 1.2 million acres at the high scenario. Finally, increased area at risk for potassium loss is also associated with increase in harvest on coarse-textured soils, leading to an increase of about 100,000 acres at risk for potassium loss under the medium scenario and 300,000 acres under the high scenario.

The results of this analysis indicate little change in total area at risk for nutrient depletion when the initial and second model runs are compared. The model did not explicitly include measures that could reduce nutrient drain, such as increasing rotation lengths on coarse-textured soils or leaving all residue, including bark, at the stump. Measures such as these, if implemented, could be expected to considerably reduce the area at risk for nutrient loss by harvesting.

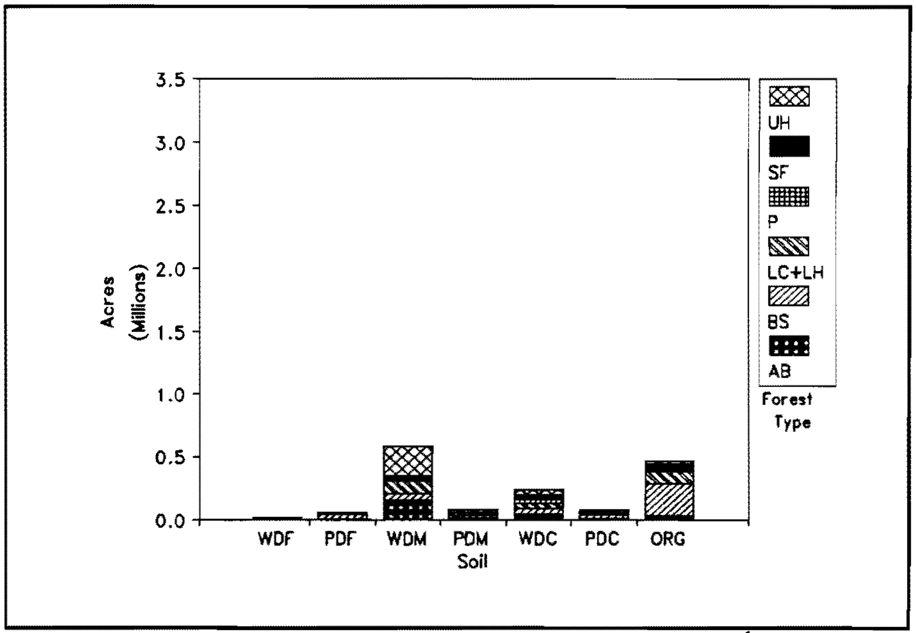

**Figure 4.24.** Increased area of forest types[a], on each of seven soil groups[b], that are clearcut under the medium compared to the base harvest scenario of the second model run.

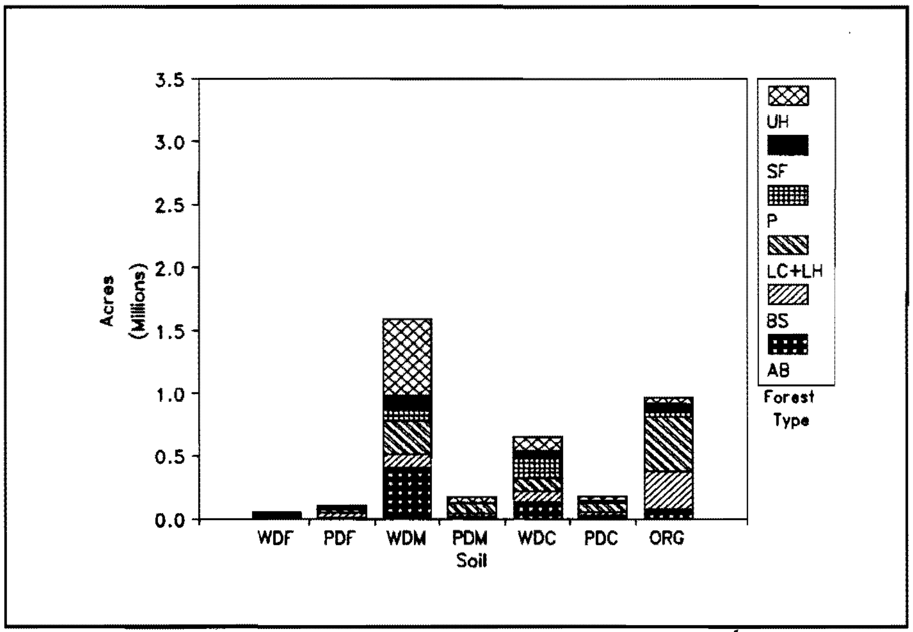

**Figure 4.25.** Increased area of forest type[a], on each of seven soil groups[b], that are clearcut under the high compared to the base harvest scenario of the second model run.

[a] Forest types; AB=aspen-birch, BS=black spruce, LC + LH=lowland conifers and lowland hardwoods, P=pine, SF=spruce-fir, UH=upland hardwoods.

[b] Soils; WDF=well-drained, fine-texture; PDF=poorly-drained, fine-texture; WDM=well-drained, medium-texture; PDM=poorly-drained, medium-texture; WDC=well-drained, coarse-texture; PDC=poorly-drained, coarse-texture; ORG=organic.

### 4.5.3
### Compaction and Related Disturbances

Results from the second harvesting scenarios were very similar to those from the first model run. The state-wide analysis of significant harvest unit impacts are presented in figure 4.26. Slightly more acreage was harvested under the base and medium scenarios during the second run than during the first run (figures 4.2 and 4.5). This resulted in a slight increase in the area where significance criteria were exceeded. As in the initial run, these impacts were most frequent on the well-drained medium textured soils, which are the most common soils in the state, and the poorly-drained medium and poorly-drained fine soils which have the lowest strength.

The second model run was not specifically constrained to avoid harvesting sites potentially impacted by compaction and related disturbances. Consequently, it was not expected that there would be a major change in compaction impacts.

### 4.5.4
### Soil Erosion

There were only very minor differences in erosion impacts between the initial and second model runs. In both cases, surface erosion rates exceeded T-values on less than 1 percent of the area harvested, and this significant impact was predominantly limited to well-drained soils which exist on steeper slopes (figures 4.28 and 4.29). There was a slight increase in erosion during the second run which can be attributed to the slightly greater area that was harvested.

As with compaction, the second model run was not specifically constrained to avoid sites that carry a high risk of erosion impacts. This was not done because of the relatively small area affected and to avoid adding to the complexity of the model.

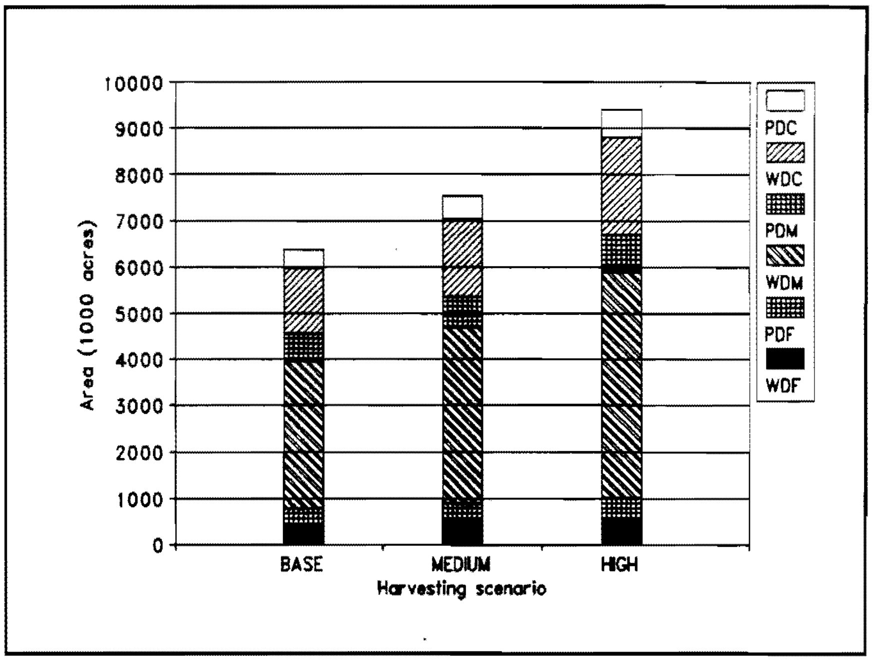

**Figure 4.26.** Area of each mineral soil harvested under each scenario of the second model run. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

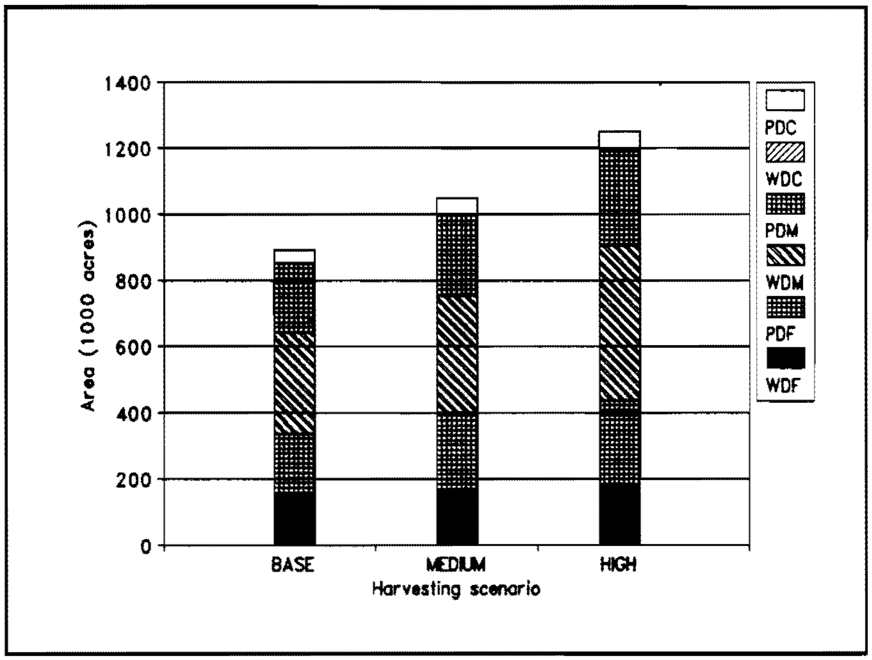

**Figure 4.27.** Harvest unit area with significant compaction impacts under each scenario of the second model run. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

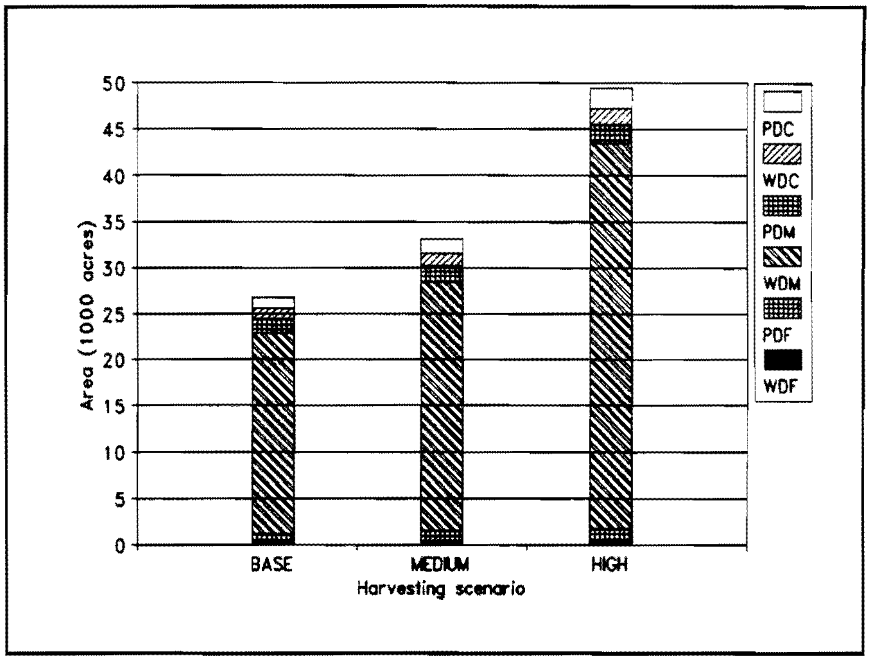

**Figure 4.28.** Harvest unit area where surface erosion exceeded T-values under each scenario of the second model run. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

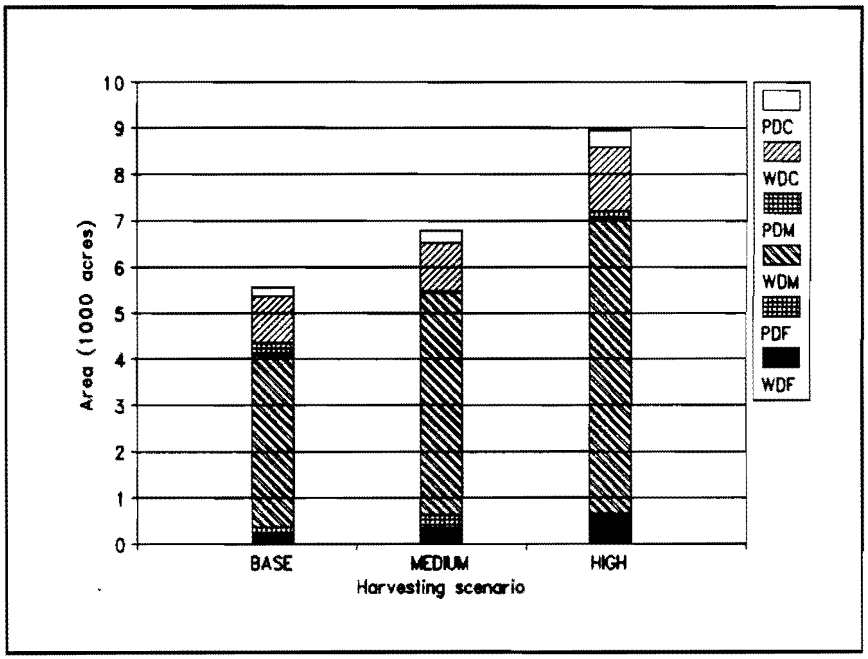

**Figure 4.29.** Area of haul roads where surface erosion exceeded T-values under each scenario of the second model run. PD=poorly drained, WD=well drained, C=coarse, M=medium, and F=fine.

# 5
# POTENTIAL MITIGATION MEASURES TO ADDRESS SIGNIFICANT IMPACTS

## 5.1
## Mitigation Alternatives Criteria

These criteria will identify mitigation actions with the potential to address the significant impacts previously identified. The purpose behind this stage of the process is to identify mitigation actions which are effective and practical in a physical context, as well as the political, financial, and administrative environments in Minnesota.

Input from the technical experts, Advisory Committee, and the EQB are reflected in the criteria as presented. Unlike the significance criteria, the criteria developed to identify potential mitigation alternatives will be applied uniformly across all issue areas documented in the FSD (MEQB 1990).

Major considerations used in the development of criteria to identify mitigation alternatives include:

- financial considerations;
- administrative considerations;
- certainty of effectiveness; and
- social implications.

A mitigation alternative to address identified significant impacts will be considered if the mitigation is physically and biologically *feasible to implement*[1] in Minnesota taking into account the:
- administrative requirements to implement and oversee policy changes;
- the financial requirements to undertake the action; and
- social considerations (ability to organize support and effect implementation).

The mitigation action must also be supported by some degree of certainty regarding its effectiveness, both in terms of the relative extent of mitigating the impact and its duration at maintaining the mitigative effectiveness.

In practice, the verbal and written input from the Advisory Committee on the potential mitigation strategies led to acceptance, rejection and/or refinement

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[1] *Feasible* implies that the mitigation action can realistically be implemented and addresses the impact being considered.

of the potential strategies. These results were then approved by the EQB and comprise the strategies considered and evaluated in detail.

## 5.2
## Nutrients

### 5.2.1
### Dormant Season Harvest

*Restrict harvest to the dormant season.*

**Effectiveness**
Restricting harvest to the dormant season has only a minor effect on nutrient depletion. The potential for this strategy to be effective is limited to the case of full-tree harvest of deciduous trees during the growing season. No matter what the season, full-tree harvest of conifers removes all nutrients above the stump. Full-tree harvest of deciduous trees during the dormant season retains the leaves that were lost during autumnal leaf fall on the site. This is only of marginal value because a relatively small proportion of all the nutrients in the tree are contained in leaves during the growing season (e.g., ca. 20 percent for aspen), and because nutrient resorption from leaves to branches at senescence further increases the proportion of nutrients in the woody material during the dormant season. If the harvest method is not full-tree, and if the slash remains at the stump (see below), then season of harvest has no impact on nutrient depletion.

**Workability**
Restricting harvest to the dormant season would require development of storage facilities for wood so that raw material would be available to industry during the remainder of the year.

### 5.2.2
### Retain Nutrient-Containing Material on Site

*Retain slash and especially bark at the stump during harvest, or return it to the harvest area after it has been removed to the landing or elsewhere.*

**Effectiveness**
As described in the Technical Review, all parts of the tree contain nutrients. Technologies that minimize removal of material from a site will therefore retain nutrients at the site. In other words, harvesting techniques that retain not only branches and tops, but especially bark, *at the stump* will markedly reduce nutrient drain. Analysis indicates that removing only the bole (without bark) at harvest would allow nutrient inputs to keep pace with harvest removals on nearly all forest lands. Harvesting techniques that move material to a landing also remove nutrients from the site; slash (branches,

tops, etc.) *must* remain at the stump. If appropriate machinery is available, tops, limbs, and bark could be removed at the landing and returned to the site.

**Workability**
This mitigation alternative is partially feasible. Harvest can be limited to the merchantable bole including bark, with branches and tops retained at the stump. Removal of bark at the stump is limited by availability of necessary equipment. Bark of most species can be relatively easily removed during a short period of time in late spring, but even at that time significant labor costs would be incurred. If material were returned to the site from the landing or elsewhere, it would be difficult to distribute uniformly, additional cost would be incurred, and soil compaction and puddling from equipment use would be likely to result. The best season for such return would be winter, with snow cover to protect the soil from disturbance.

### 5.2.3
### Longer Rotation

*Increase the length of the rotation.*

**Effectiveness**
As length of the rotation increases, natural processes will have a greater potential to replenish the nutrients lost in harvest or in site preparation. This is an effective technique of keeping nutrient removal in balance with replenishment. This technique would be especially important on coarse-textured and organic soils.

**Workability**
There are two major factors against the use of this technique to mitigate impacts of nutrient depletion. First, for most forest types the incidence of damage and loss due to insects and disease increases with stand age. For some forest types (e.g., aspen-birch), mortality may be so high that the entire stand is lost before harvest (i.e., aspen break-up). Second, added length of rotation leads to a lower return associated with an increase in the length of the investment period without a commensurate increase in yield.

### 5.2.4
### Change of Species - Site Conversion

*Establish pine or other species with high nutrient-use efficiencies on sites with the lowest rate of nutrient replenishment.*

**Effectiveness**
Tree species differ in their nutrient use efficiency, the volume growth per unit nutrient. Conifers, and especially red and jack pine, are relatively efficient in nutrient use while deciduous trees, including aspen and upland

hardwoods, are much less efficient. Spruce and fir are also relatively inefficient in nutrient use. As a long-term mitigation strategy, establishment of pine on sites with the lowest rate of nutrient replenishment (coarse-textured soils) would be efficacious.

**Workability**
This is a long-term strategy, and requires change in forest type. Such a change may be relatively simple and therefore of minimal cost, or may be difficult and incur high costs. The present stand must be removed by harvest or other technique, or killed and retained on the site. The former method would further deplete the nutrient capital on the site, while the latter method would be costly and may require use of chemicals with their associated impacts. Site preparation for establishment of the pine stand, if aggressive, could further deplete nutrients. Finally, successful establishment of extensive areas of pine stands may affect biodiversity and incidence of insects and disease. Few species are as efficient as pine in the use of nutrients. In general, late-successional species, especially hardwoods, approach or exceed aspen in terms of nutrient depletion per unit volume of wood. As a result, replacement of aspen by natural succession may not achieve a low-nutrient stand.

### 5.2.5
### Appropriate Site Preparation Techniques

*No site preparation technique that displaces material from the site should be used. Only techniques that incorporate materials (e.g., discing) or displace them short distances (e.g., Brakke scarifier) are acceptable.*

**Effectiveness**
As discussed in the Technical Review, site preparation techniques that create slash piles or windrows either remove nutrients from the site or localize them, thus depleting them from the remainder of the area. Although most concern about site preparation is usually focused on displacement of mineral soil, both slash and forest floor also contain significant amounts of nutrients. There is virtually no justification, from the standpoint of nutrient status, for use of any site preparation technique that displaces material. Site preparation techniques that incorporate materials (e.g., discing), or only displace materials short distances (e.g., Brakke scarifier) do not have negative impacts on nutrients.

**Workability**
There is *no* justification for removal of mineral soil in site preparation. In fact, the energy needed to displace mineral soil leads to higher machine costs per acre. Depending on the efficacy of alternative techniques, presence of slash on the site may interfere with both machine and hand planting. In cases where natural regeneration from seed (not advanced regeneration) is

desired, a thick and uniform forest floor may interfere with seedling establishment. New investment in appropriate machinery or economic loss due to abandonment of present machinery are also considerations in mitigation strategies.

### 5.2.6
### Fertilization/liming

*Sites can be fertilized or limed after harvest to replace nutrients that have been removed.*

**Effectiveness**
The majority of fertilization trials to date have been centered on additions of N and P. In most forested regions of both the Northern and Southern Hemispheres, additions of N have increased growth while those of P have been effective in a few locations with highly weathered soils (those soils do not occur in Minnesota). However, nutrient budgets for Minnesota forests indicate sufficient rates of natural return of both N and P to compensate for losses associated with forest management activities. Such budgets indicate major potential losses of calcium and magnesium. Both these nutrients can be replenished through liming. European research on the efficacy of liming on forest growth is equivocal, and usually indicates a depression in growth associated with application of lime because of disruption of availability of other nutrients.

**Workability**
Addition of fertilizers, including lime, to forests is an expensive management technique. Fertilization may not be justifiable in Minnesota both on the basis of the relatively low value of forest products and on the slow growth rates with long investment periods necessary to recover costs. The difficulty of clearly ascertaining the short-term reductions in growth that are associated with nutrient depletion further reduces the justification for fertilization.

### 5.2.7
### Partial Stand Harvest - Thinning, All-Age Management, etc.

*Partial harvests can be carried out to reduce nutrient removal associated with that harvest.*

**Effectiveness**
Reducing the volume of material removed from a site by harvest reduces the removal of nutrients. As described earlier, the amount of nutrients removed from a site is directly related to the volume removed, and to the tree species and components that contribute to that volume. If the stand is not clearcut, but instead partial removals associated with all-aged management or thinning occur, then less nutrients will be removed in *each* harvest.

**Workability**
Although less nutrients will be removed in a partial harvest, less volume will also be removed. If, over the long term, silvicultural prescriptions result in the removal of equivalent volumes of equivalent materials, then equivalent amounts of nutrients will also be removed. Only if harvest shifts to different species or tree components will changes occur in amounts of nutrients that are removed. In addition, repeated stand entries associated with all-age management or thinnings may negatively affect disease occurrence and soil compaction and puddling.

### 5.2.8
### No Harvest

*Harvest can be prohibited from sites very low in nutrients.*

**Effectiveness**
If trees are not harvested, and hence no volume is removed from a site, then nutrients are similarly not removed.

**Workability**
Depending on management goals, this is a viable strategy to retain nutrients. However, the rationale for such retention in terms of wood production is obscure. Animals and birds can generally obtain sufficient nutrient elements by their foraging so that dietary deficiencies are unlikely to occur, even in low-nutrient sites. Areas that are excluded from harvest may be beneficial in terms of old-growth issues such as biodiversity. As sites accumulate nutrient elements, they will tend to reach an equilibrium in which nutrient loss by leaching equals inputs by weathering and atmospheric deposition. This loss may have adverse effects on water quality.

## 5.3
## Compaction and Related Disturbances

### 5.3.1
### Identify Susceptible Sites

*Identify sites that are potentially susceptible to equipment impacts.*

**Effectiveness**
It is far more effective to prevent compaction and related disturbances than it is to reclaim disturbed sites. Not all sites are equally susceptible to compaction and related disturbances. Consequently, identification of susceptible sites is requisite to developing strategies for minimizing these disturbances. As discussed above, site sensitivity is almost exclusively a function of soil texture and soil water status, with soil water status often fluctuating with season. Table 5.1 identifies those scenarios (e.g. soil types and seasons) where sites would likely be susceptible to equipment related

disturbances. While the same scenarios are identified for both mechanical and hand felling, the percent of the site impacted varies between the two equipment configurations.

**Table 5.1. Seasons where significance criteria would be exceeded (indicated by X) for each soil type for mechanical and hand-felling operations.***

| Soil type | Mechanical felling | | | | Hand felling | | | |
|---|---|---|---|---|---|---|---|---|
| | Win | Spr | Sum | Fall | Win | Spr | Sum | Fall |
| Well-drained fine | | X | | X | | X | | X |
| Poorly-drained fine | | X | X | X | | X | X | X |
| Well-drained medium | | X | | | | X | | |
| Poorly-drained medium | | X | | X | | X | | X |
| Well-drained coarse | | | | | | | | |
| Poorly-drained coarse | | X | | | | X | | |

*These results reflect the broad assumptions required for conducting a statewide analysis over a 50-year period. It is possible that results for individual sites in individual years may vary from those presented here.

**Workability**

Site susceptibility must be identified at an operational scale if preventative measures are to be effective. In most areas, soil maps and other tools are *not* available at the stand or harvest unit scale. Confirmation of site susceptibility will require on-the-ground inspection by natural resource professionals. This may require additional training and staffing of forest management organizations.

### 5.3.2
### Seasonal Controls on Operations

*Limit equipment operation to periods when soil strength can support heavy equipment.*

**Effectiveness**

Medium- and fine-textured soils will most often exhibit low soil strength during the spring and fall, with low strength most often occurring in poorly drained positions. Forest managers will have to be aware that the strength of medium- and fine-textured soils can decrease rapidly during the summer and fall in response to intense rain storms. Equipment operation on some poorly-drained soils will be limited to frozen soil conditions. The strength of coarse-textured soils will be adequate for all but the wettest conditions which generally occur in poorly-drained areas in the spring. Where possible, well-drained, coarse-textured soils should be identified and held in reserve for wet season harvesting.

**Workability**

Site disturbance can be effectively reduced by carefully monitoring soil strength conditions before and during forest management operations. However, this may require additional staffing of forest management organizations and could cause financial hardship to operators by limiting harvesting seasons or delaying operations that are already underway. It may be possible to alleviate the financial hardship to loggers and supply problems to mills by stockpiling wood near all-weather roads during the winter. This wood can then be delivered during the spring.

### 5.3.3
### Traffic Control

*Concentrate harvesting equipment trafficking in as small an area as possible.*

**Effectiveness**

A majority of compaction and related disturbances occur during the first few equipment passes. Concentrating equipment trafficking would minimize the overall amount of disturbance.

**Workability**

This strategy is particularly applicable to yarding operations where preplanned or designated skid trails can significantly reduce the area impacted. Under intensive forest management, designated skid trails can be identified for use during future harvesting operations. These activities can lead to increased costs by requiring additional planning and monitoring by forest managers and reductions in productivity for operators.

*Develop long-term transportation plans.*

**Effectiveness**

Forest road construction and utilization cause some of the most severe soil disturbances associated with forest management activities. Proper planning of a transportation network will ensure that adequate access is achieved with a minimum of road area.

**Workability**

However development of a comprehensive forest road system is complicated by the fact that such a system would be required to traverse a variety of ownerships and would require close cooperation for planning, construction, maintenance and closure.

*Develop site specific disturbance guidelines, such as those that have been adopted in British Columbia.*

**Effectiveness**

Voluntary or mandatory disturbance guidelines can be established to limit the amount of disturbance that can occur on individual sites.

**Workability**

Such guidelines would have to be implemented in coordination with continuing education for loggers and managers regarding site evaluation and methods of minimizing negative impacts.

Guidelines could lead to financial hardship for operators by limiting or delaying operations on some sites, and could periodically lead to supply problems for local mills. Guidelines would also create a significant burden for public forest management agencies, assuming they would be given the responsibility of maintaining and documenting guideline compliance.

### 5.3.4
### Modified Harvesting Techniques

*Utilize surface organic materials to support harvesting and other heavy equipment.*

**Effectiveness**

Slash and an intact forest floor layer can absorb some of the compactive forces before they reach the soil. Operating equipment on top of slash can reduce the amount of compaction and other disturbances that occur. This could have the greatest benefit during mechanical site preparation when heavy equipment makes one or two passes over much of the site.

**Workability**

Many operators are reluctant to operate on top of slash because of possible equipment damage and because it slows their travel time. Heavy slash accumulations can also hamper some regeneration efforts.

### 5.3.5
### Modified Harvesting Equipment

*Use wide tires or other high flotation equipment.*

**Effectiveness**

This equipment has lower ground pressures and reduces compactive forces. It can reduce the magnitude of some disturbances, though is unlikely to eliminate them.

**Workability**

This equipment is expensive and is currently not widespread in Minnesota. Additional research is needed to document the overall impacts of high flotation equipment on soil properties because there is conflicting evidence regarding its ability to reduce the magnitude or areal extent of negative impacts.

*Employ aerial based yarding systems (methods of transporting wood from the stump to the landing).*
**Effectiveness**
Much of the physical soil disturbance in Minnesota occurs during ground-based skidding operations. Aerial methods of yarding are employed in other parts of North America. The most common of these employ cables that transport logs to the landing by either dragging them or lifting them completely off the ground. Other aerial methods utilize helicopters or in some cases, helium balloons to transport logs.

**Workability**
The terrain in Minnesota is generally not conducive to cable yarding systems, particularly in the flatter landscapes where the compaction and puddling risk are greatest. The costs of helicopter logging would be prohibitive for most products grown in Minnesota.

*Change the type of equipment used to fell trees.*
**Effectiveness**
In mechanical felling operations, a considerable portion of the site can be trafficked if the feller buncher has to drive to every tree to be harvested. This is typical of fixed head machines. In contrast, boom-type feller bunchers with a shear head mounted on a 20- or 25-ft boom can reduce the area trafficked during felling.

**Workability**
The existing ratio of fixed head to boom-type feller bunchers is approximately 2:1 (Jaakko Pöyry Consulting, Inc. 1992g). The proportion of boom-type machines could be increased if these machines were purchased in preference to fixed head machines. The typical age of logging equipment in Minnesota is high (64 percent of machines are older than six years) (Jaakko Pöyry Consulting, Inc. 1992g). As a consequence, it is likely that any transition to boom-type machines would take place over the midterm.

### 5.3.6
### Ameliorative Measures

*Discing or subsoiling (with or without soil amendments) to ameliorate site disturbance.*
**Effectiveness**
These practices have been used with some success in parts of North America to loosen compacted soils and restore porosity. They are predominantly used in primary skid trails and landings. However, discing does not work well

in all situations. It is of less value on finer texture soils because of the great amount of energy required to pull the implements through the soil and because it often produces large clods that do not form a good rooting environment. Discing also seriously damages existing root systems and can essentially preclude successful regeneration of species such as aspen that regenerate by root suckering.

**Workability**
This practice would require modifications to existing equipment such as crawler tractors or use of specialized machinery. Ownerships with comparatively large numbers of sites in close proximity could consider purchasing and operating specialized equipment. Smaller ownerships would logically have to rely on loggers to undertake these works at the completion of the harvest. This would favor modification of existing equipment. These practices could be incorporated in the Minnesota BMPs.

## 5.4
## Soil Erosion

Mitigation strategies to minimize erosion should be concentrated around forest roads. These analyses were in close agreement with the literature in identifying roads as the major potential source of accelerated erosion associated with forest harvesting and management. While roads can cause problems in many regions throughout the state, the mitigation strategies outlined below would be particularly important in southeastern Minnesota because of the steep slopes that exist there.

If the guidelines for reducing compaction and related disturbances outlined above are followed, erosion will be reduced. These physical disturbances can contribute directly to increased surface erosion. Compaction, puddling, rutting, and scarification decrease the rate of water movement into the soil which increases overland flow, channel and concentrate surface runoff, and reduce protective surface cover. All of the strategies discussed above to minimize compaction will also reduce erosion.

### 5.4.1
### Preventive Measures

*Construct water bars across skid trails in sloping topography.*
**Effectiveness**
Water bars divert surface runoff from skid trails before rills and gullies develop.

**Workability**
This requires operator education and cooperation. Specific guidelines for construction and spacing applicable to Minnesota are outlined in the BMPs manual.

*Revegetate or mulch areas of exposed mineral soil as quickly as possible.*
**Effectiveness**
This is perhaps the most effective method of reducing erosion rates. Studies indicate that initial erosion rates associated with road construction can be reduced by as much as 98 percent by seeding, mulching, and/or netting exposed cutbanks and fillbanks.

**Workability**
This would require additional effort and expense to implement, particularly on lower standard temporary roads and tracks.

*Construct haul roads rapidly using approved engineering guidelines.*
**Effectiveness**
The major cause of erosion caused by forest management activities is associated with forest roads. A considerable portion of this erosion occurs during the actual construction process when both surface erosion and mass movements occur along bare and oversteepened slopes. Erosion can be reduced by constructing, grading, and revegetating cut and fill banks as quickly as possible. After construction, erosion can continue to occur along road surfaces and in drainage ditches. This erosion rate can be reduced by properly grading roads and controlling water movement on and adjacent to the road. When possible, roads should be constructed with minimum road surface widths and cut/fill ratios. Properly outsloped road surfaces minimize erosion and eliminate the need for ditches and ditch relief culverts.

**Workability**
Engineering guidelines for proper forest road construction applicable to Minnesota conditions are available in the BMPs manual. Therefore, the workability of this alternative is linked to the level of compliance with BMPs. Implementation of these guidelines would require additional training for those involved in road construction.

### 5.4.2
### Road Closure

*Close roads following use.*
**Effectiveness**
Continued use of forest roads by recreational or other traffic can retard revegetation of road surfaces and can lead to rutting and puddling. Temporary haul roads that are not scheduled to be monitored or maintained are particularly susceptible to this type of disturbance. Permanently blocking

these roads to vehicular traffic will alleviate further disturbance and allow them to revegetate.

**Workability**
Decisions on which roads to close are an important part of the wider transportation plans described previously. Road closure also requires cooperation from the public, particularly ORV and ATV enthusiasts.

## 6
## PREFERRED MITIGATION STRATEGIES

A variety of strategies can mitigate against adverse impacts of timber harvesting. The final criteria document (Jaakko Pöyry Consulting, Inc. 1992) describes how such strategies would be identified and selected. The identification of strategies is described in the earlier section 5, Potential Mitigation Measures to Address Identified Significant Impacts.

### Framework for analyzing mitigations and selecting preferred mitigation strategies

Criteria for selecting strategies are drawn from the final criteria document noted above and reproduced below:

> Based on an analysis of mitigation alternatives identified, preferred mitigation strategies will be selected by considering in relative terms:
> 1. the effectiveness at mitigating the identified significant impacts;
> 2. the beneficial effects on other resource values;
> 3. the adverse effects on other resource values;
> 4. the physical, biological, administrative (implementation and oversight), financial (costs, public and private, direct and indirect), and social (ability to organize, support and effect implementation) feasibility; and
> 5. the probability of success and duration of success.

In practice, the verbal and written input from the Advisory Committee on the potential mitigation strategies led to acceptance, rejection and/or refinement of the potential strategies. These results were then approved by the EQB and comprise the strategies considered and evaluated in detail. Additionally, for this analysis the above criteria were grouped as follows:

1. *Effectiveness* addresses a mitigation strategy in terms of its ability to either avoid or reduce the identified impacts.

2. *Feasibility* addresses the likelihood that the mitigation strategy can be implemented, based on existing or future economic, social, biophysical, or administrative constraints.

3. *Duration* of mitigation can best be scored into four classes: 1 = long-term—greater than 50 years; 2 = medium-term—10 to 50 years; 3 = short-term—2 to ten years; 4 = very short-term—less than 2 years.

4. *Concomitant effects* refers to those strategies that have the potential to significantly affect other resources. It is clearly fallacious to consider that any forest management practice will only affect a single resource; forests are intricately interacting ecosystems, and each practice affects many resources.

5. *Probability of success*, though not tabulated explicitly in the following tables, is a combination of effectiveness, feasibility and duration with minimal negative concomitant effects. The strategies identified as highly effective, highly feasible, of long duration and with minimal negative concomitant effects are assumed to have the greatest chance of success in the long run.

These criteria were then applied to the various mitigation strategies for the purpose of comparison among them and to help determine preferred mitigation strategies.

### Evaluation of Specific Strategies—Soil Nutrients

A variety of strategies can mitigate potential adverse impacts of forest harvesting on soil nutrients. A comparison of the strategies considered is summarized in table 6.1.

**Table 6.1.** Evaluation of mitigation strategies for minimizing negative impacts of timber harvesting on soil nutrients. Rankings for effectiveness and feasibility from 1 = high to 3 = low, and for duration from 1 = long- to 4 = very short-term. Concomitant effects refers to potential positive (+) or negative(-) effects on issues of concern from the FSD.

| Mitigation Strategy | Effectiveness | Feasibility | Duration[a] | Concomitant Effects (±)[b] |
|---|---|---|---|---|
| Dormant season harvest | 3 | 2 | 1 | |
| Retaining material | 1 | 1 | 1 | |
| Longer rotations | 2 | 2 | 1 | Forest Health (-) |
| Species conversion | 2 | 3 | 2 | |
| Appropriate site preparation | 2 | 1 | 1 | |
| Fertilization | 1 | 3 | 3 | Water Quality (-) |
| Partial harvest | 3 | 1 | 2 | |
| No harvest | 1 | 3 | 1 | Biodiversity (+)<br>Water Quality (-) |

[a] 1 = long-term—greater than 50 years; 2 = medium-term—10 to 50 years; 3 = short-term—2 to ten years; 4 = very short-term—less than 2 years.

[b] Effects that are noted are those with potential to *significantly* affect another resource.

Explanations of the ranks for these mitigation strategies are as follows:

*Dormant season harvesting* retains material on the site, but its effectiveness is limited to the case of full-tree harvesting of deciduous trees. It is feasible for upland covertypes and its duration is long-term. It is not very effective at reducing nutrient loss because a relatively small proportion of nutrients are in the foliage of those deciduous species whose harvest tends to most seriously deplete site nutrients, and conifer species retain foliage all year.

*Retaining or returning material* on the site is an example of a very effective strategy for reducing nutrient loss. In some cases it can be implemented relatively easily. However, overall feasibility will depend upon operational and technical constraints, particularly on the harvesting technique, the equipment available, and to some extent the season of harvesting as it facilitates removal of bark. Equipment to remove branches and bark at the stump is currently operational for Eucalypts in Australia. In the long-term feasibility should be high. Return of slash to a site from a landing or elsewhere would also be similarly effective and long-term. Its feasibility would be affected by the added cost of another pass of equipment over the site and the potential compaction and puddling associated with such an activity. Returning material in winter would minimize the latter effect. The duration of the effect is long-term.

*Longer rotations* are effective by allowing natural processes to replenish the nutrients lost in harvest or in site preparation. The duration is long term, but effectiveness is reduced with time as species reach advanced ages and become less vigorous and more susceptible to forest health problems. Older stands are generally more susceptible to a variety of insects and diseases when compared to younger stands of the same species. Thus this mitigation may negatively affect the forest health issue area. Feasibility is problematic for short-lived species and benefits diminish with time as nutrient levels return to preharvest levels.

*Species conversion*, though moderately effective and initially appealing, would incur considerable cost because it primarily involves converting sites from nutrient-demanding species (aspen and upland hardwoods) to early-successional nutrient-conserving species (jack and red pine). This conversion would require substantial inputs for site preparation, seeding or planting, etc. Alternatively, allowing natural succession to replace aspen stands would lead to either upland hardwood or spruce-fir stands, both of which, like aspen, retain relatively large quantities of nutrients in aboveground tree components. Species conversion would also require overt action at nearly every rotation to maintain the effect, whereas the effect of such measures as retaining material and appropriate site preparation would continue well-beyond a single cycle. This is especially true if those latter practices were adopted as standard procedures.

*Appropriate site preparation* techniques are useful and can be implemented relatively easily, and they are often less costly than more adverse (i.e., heavy-handed) techniques. The effect of such measures would also continue well-beyond a single rotation. This is especially true if such practices were adopted as standard procedures.

*Fertilization* is a strategy that corrects or replaces nutrients that are lost. It is effective, but only for short periods. It would require repeated applications during a rotation or within cutting cycles to maintain the positive effect, thus raising questions about feasibility and costs. It is an expensive technique. Additionally, the practice could have adverse (negative) impacts on other resources, notably water quality.

*Partial harvest*, whether by thinning or all-aged management, only reduces the nutrient depletion associated with a single stand entry. Over the long-term, equivalent volumes of products would be removed from a site and hence equivalent amounts of nutrients. It is therefore a feasible practice, but is of limited effectiveness. Its duration, similarly, would be only of medium term.

*No harvest* is another potential management strategy on sites with both very low nutrient capital and rates of replenishment. Because nutrients are not removed, this method is effective and long-term. If the management goal is wood production, however, this technique is not feasible and is equivalent to nonmanagement. Unharvested stands may positively contribute to management goals that are associated with old-growth. Because nutrients will ultimately leach from systems that do not have net volume growth, this strategy may have negative impacts on water quality.

### Preferred mitigation(s)

Retaining material is the mitigation with the greatest chance for success in minimizing negative impacts of forest harvesting on soil nutrients. Thus it is the preferred mitigation. However, each of the mitigations may be useful depending on site specific and operational circumstances. The least successful mitigation applied on a broad scale would appear to be fertilization.

### Evaluation of Specific Strategies—Soil Compaction

A variety of strategies can mitigate potential adverse impacts of forest harvesting on soil compaction. A comparison of the strategies considered is summarized in table 6.2.

*Identifying sites that are potentially susceptible to equipment impacts* would be an expensive and time consuming process if applied to all Minnesota sites. This limits its feasibility as this work would have to be done in advance of harvesting.

Table 6.2. Evaluation of mitigation strategies for minimizing negative impacts of timber harvesting on soil compaction. Rankings for effectiveness and feasibility from 1 =high to 3 =low, and for duration from 1 =long-term to 4 =very short-term. Concomitant effects refers to potential positive (+) or negative(-) effects on issues of concern from the FSD.

| Mitigation Strategy | Effectiveness | Feasibility | Duration[a] | Concomitant Effects (±)[b] |
|---|---|---|---|---|
| Identify sites that are potentially susceptible to equipment impacts | 2 | 2 | 1 | Economics<br>(-) |
| Limit equipment operation to periods of high soil strength | 3 | 2 | 1 | Economics<br>(-) |
| Concentrate equipment trafficking | 2 | 2 | 1 | |
| Traffic on top of surface organic residues | 2 | 2 | 1 | Forest Health<br>(-) |
| Use high flotation equipment | 2 | 2 | 1 | |
| Employ aerial yarding systems preparation | 3 | 3 | 1 | |
| Change type of equipment used to fell trees | 2 | 2 | 1 | Economics<br>(-) |
| Develop long-term transportation plan | 2 | 2 | 1 | Wildlife<br>(+)<br>Recreation<br>(+) |
| Develop site disturbance guidelines | 3 | 2 | 1 | |
| Ameliorative measures | 2 | 2 | 1 | Economics<br>(-) |
| No harvest | 3 | 3 | 1 | Biodiversity<br>(+)<br>Water Quality<br>(-) |

[a] 1 =long-term—greater than 50 years; 2 =medium-term—10 to 50 years; 3 =short-term—2 to ten years; 4 =very short-term—less than 2 years.

[b] Effects that are noted are those with potential to *significantly* affect another resource.

***Limiting equipment operation to periods of high soil strength*** is the most effective mechanism of minimizing compaction and related disturbances when ground-based equipment is used. Its feasibility is somewhat limited because it requires careful monitoring by natural resource professionals and may cause economic hardship to operators and some mills.

*Concentrating equipment trafficking* can effectively reduce the areal extent of site disturbance, though high levels of compaction and other disturbances can occur in areas that are trafficked. It may force operators to travel greater distances when skidding, which can reduce their productivity.

*Trafficking on top of surface organic residues* can protect the soil surface from equipment impacts for one or two equipment passes, provided the residues form a relatively continuous mat. This practice loses its effectiveness after the first several passes because the organic residues are broken down or displaced. Operators may be reluctant to operate on top of slash because it may get caught up in their equipment or slow them down.

*Using high flotation equipment* may be partially effective in reducing site disturbances. Previous research is not conclusive regarding the benefits of this type of equipment. Feasibility is limited because of the high cost of this equipment.

*Employing aerial yarding systems* would eliminate most if not all of the soil disturbances. However the feasibility of these systems is very low in Minnesota because of their high cost and the low value of most forest products in Minnesota. A possible exception is in the southeast where the high species value and the steep topography may justify the introduction of cable systems. Their feasibility is further limited because there is currently no infrastructure to support these systems in Minnesota.

*Change the type of equipment used to fell trees* is potentially feasible for a proportion of harvesting operations. The feasibility of this alternative is limited by the ability to alter decisions on equipment choice that are made by loggers.

*Development of a long-term transportation plan* would effectively minimize the area disturbed by forest haul roads. It would require coordination between forest management organizations to implement properly.

*Developing site disturbance guidelines* would effectively limit the amount of disturbance on individual sites. Additional research would most likely be required to establish and document allowable disturbance limits. Also, it would take considerable debate to evaluate the pros and cons of voluntary versus mandatory guidelines. Creation of guidelines would require additional human resources to monitor their implementation and effectiveness.

*Ameliorative measures* such as discing and subsoiling may restore porosity in some areas. These practices are most effective on medium- and coarse-textured soils, particularly when compaction is limited to specific areas such as landings, skid trails, and haul roads. Tillage would be less effective on fine-textured soils because of the difficulty in pulling implements through these soils and the clodiness that can result. An additional concern of tillage is the potential damage that can be done to aspen roots which can reduce regeneration of this important species. Finally, all operators may not have access to the equipment necessary to perform these types of operations.

*No harvest* is another potential management strategy on sites sensitive to equipment impacts. If the management goal is wood production, however, this technique is not feasible and is equivalent to nonmanagement.

### Preferred mitigation(s)

Limiting operations to periods of adequate soil strength, concentrating equipment trafficking, and development of long-term transportation plans are the preferred mitigation strategies. These are all potentially feasible under current conditions, though they would require the commitment of additional resources to planning and management. They would effectively reduce compaction and related disturbances.

### Evaluation of Specific Strategies—Soil Erosion

A variety of strategies can mitigate potential adverse impacts of forest harvesting on soil erosion. A comparison of the strategies considered is summarized in table 6.3.

**Table 6.3. Evaluation of mitigation strategies for minimizing negative impacts of timber harvesting on soil erosion. Rankings for effectiveness and feasibility from 1 = high to 3 = low, and for duration from 1 = long- to 4 = very short-term. Concomitant effects refers to potential positive (+) or negative(-) effects on issues of concern from the FSD.**

| Mitigation Strategy | Effectiveness | Feasibility | Duration[a] | Concomitant Effects (±)[b] |
|---|---|---|---|---|
| Construct water bars | 3 | 3 | 1 | Water quality (+) |
| Revegetate and or mulch areas of exposed mineral soil | 3 | 3 | 1 | Water quality (+) |
| Proper road engineering | 3 | 2 | 1 | Water quality (+) |
| Close roads after use | 2 | 2 | 1 | Water quality (+)<br>Recreation (-) |
| Operator training in road design and construction | 2 | 2 | 1 | Water quality (+)<br>Economics (-) |

[a] 1 = long-term—greater than 50 years; 2 = medium-term—10 to 50 years; 3 = short-term—2 to ten years; 4 = very short-term—less than 2 years.

[b] Effects that are noted are those with potential to *significantly* affect another resource.

*Constructing water bars* can effectively divert overland flow from steeply sloping skid trails. Water bars can be constructed with the blades of standard harvesting equipment. Some training would be required to ensure proper construction techniques and spacing.

*Revegetating or mulching bare soil areas* effectively reduces erosion rates in steeper topography. These areas most commonly develop along roads, skid trails, and landings. This would require additional expense and training for individuals not traditionally involved in road construction operations.

*Proper road engineering* is an integral component to minimizing erosion wherever overland flow can accumulate on or adjacent to roads. The technology is available to accomplish this goal; however, it requires careful training and additional expense for individuals not traditionally involved in road construction operations. Vehicle safety and haul speed must always be considered during road design.

*Closing roads after harvest* will allow them to revegetate and decrease the chances of additional disturbances by vehicular operation on these roads when they are wet. This technique is most feasible for temporary roads that are constructed with minimal effort and end at log landings. The effectiveness of this technique can be significantly reduced by continued use by off-road vehicles which can retard revegetation and cause additional rutting that can lead to rills and gullies.

*Operator training in road design and construction* is required to properly construct roads. Such training is particularly useful when building roads in steep topography or adjacent to rivers and streams. Such training would require an additional commitment of human resources.

**Preferred mitigation(s)**

Proper road engineering, revegetating bare soil areas, and closing temporary roads after harvest are the preferred mitigation strategies. These activities would reduce soil erosion along forest roads and major skid trails which are the predominant source of erosion problems caused by forest management activities. The additional expense incurred in implementing these measures would lead to important and long-term reductions in erosion problems.

## 7
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