Forest Management Guidelines for the Protection of the Physical Environment

VERSION 1.0

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Executive Summary

The *Forest Management Guidelines for the Protection of the Physical Environment* have been prepared to help resource managers prevent, minimize or mitigate adverse effects on the physical environment when planning and conducting forest operations. These guidelines are designed to contribute to the maintenance of the health and inherent long-term productivity of forested ecosystems on Crown Land in Ontario.

These guidelines provide an overview of the major site damage issues confronting land managers during harvest, renewal and maintenance activities. Relationships between site and stand attributes, environmental factors and forest operations are discussed in terms of potential impacts on the physical environment.

A series of site damage fact sheets are presented for compaction and rutting, erosion, nutrient loss, loss of productive land and hydrological impacts. Each fact sheet describes the type and impact of damage, and the site factors, environmental conditions and management activities that may contribute to increased risk of damage. The fact sheets then present Best Management Practices to consider in areas of planning, field layout, implementation and monitoring to prevent or minimize negative impacts. Where appropriate, mitigation techniques are described for the rehabilitation of damaged sites. Site damage hazard tables were developed for compaction and rutting, erosion and nutrient loss. These tables rate the risk of damage to soil and site factors.

The Best Management Practices described in these guidelines will assist in developing both Forest Units and Silvicultural Ground Rules, as described in the *Forest Management Planning Manual*. They will also provide direction to land managers when formulating site-specific treatments when developing Forest Operation Prescriptions during preparation of the Annual Work Schedule.

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Forest Management Guidelines for the Protection of the Physical Environment

1.0 Introduction

These guidelines were prepared to help resource managers prevent, minimize or mitigate adverse effects on the physical environment when planning and implementing forest operations. The preparation of this guide was required by EA Term and Condition 94b arising from the decision of the Environmental Assessment Board during the Class Environmental Assessment for Timber Management On Crown Lands in Ontario (Environment Assessment Board 1994)[1]. It complies with *Direction '90s* (OMNR 1992), the Crown Forest Sustainability Act (CFSA; Government of Ontario 1994), and the *Forest Operations and Silviculture Manual* (OMNR 1995). All these documents state that forest sustainability is the primary objective of forest management. Under the CFSA, the Ontario Ministry of Natural Resources (MNR) may direct forest operations to be stopped or modified if the operations are causing or are likely to cause site damage that impairs or is likely to impair Crown forest sustainability (S. 55).

1.1 About This Guide

The *Forest Operations and Silviculture Manual* lists these guidelines as one of a suite of guidelines that must be considered during the planning and implementation of forestry activities. Related guidelines which address specific aspects of protecting the physical environment include:

- Silvicultural Guides (OMNR 1997a, 1997b),
- *Timber Management Guidelines for the Protection of Fish Habitat* (OMNR 1988a),
- *Environmental Guidelines for Access Roads and Water Crossings* (OMNR 1988b), and
- *Code of Practice for Timber Management Operations in Riparian Areas* (OMNR 1991).

Broadly speaking, the physical environment includes soil, water and air. The primary focus of this guide is the effects of forest operations on physical forest site characteristics. Readers are referred to the above documents for further information on protecting the physical environment.

These guidelines were developed through a synthesis of current information and expert opinion. They will be updated periodically as our understanding of the impacts of forest operations on site productivity improves.

1.2 Using This Guide

These guidelines relate to the conduct of forest operations on Crown Forest Land in Ontario. We review the major types of site damage that could result from forest operations and present best management practices to prevent, minimize or mitigate these conditions. These guidelines formalize the requirements for protecting the physical environment and give forest practitioners (those involved in both planning and field implementation) a set of tangible objectives for which to plan.

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[1] T&C 94b requires production of guidelines to address operational considerations with the purpose of protecting the physical environment, and to provide direction in relation to harvest layout, configuration and clearcut sizes. These guidelines address the first requirement, while the guidelines regarding forest harvest parameters are forthcoming.

A series of site damage fact sheets describe the type, impact, and contributing factors for each type of damage and introduce Best Management Practices to consider in both planning and field implementation. Often, these practices are already followed in Ontario, and this guide serves to compile and document them in a consistent format. The authors recognize the inherent variability of both ecosystem conditions and forest operations, and therefore support the application of professional judgment at the local level to ensure the protection of the physical environment. These fact sheets will assist in developing both Forest Units and Silvicultural Ground Rules as described in the *Forest Management Planning Manual* (FMPM; OMNR 1996). These guidelines also provide direction for formulating site-specific treatments when developing Forest Operation Prescriptions (FOP) during preparation of the Annual Work Schedule (AWS).

In addition to the fact sheets, tables are included that rate the hazard of particular types of damage to site, operation or environmental factors. Site damage hazard potential is related to Forest Ecosystem Classification (FEC) Soil Types. The intent is to flag those sites and conditions that have moderate-to-high site damage potential, so the practitioner can address site damage concerns at the planning stage.

1.3 Consideration of Statement of Environmental Values

The MNR is responsible for managing Ontario's natural resources in accordance with the statutes it administers. In 1991, the MNR released a document entitled *Direction '90s*, which outlines the goals and objectives for the Ministry, based on the concept of sustainable development. Within MNR, policy and program development take their lead from *Direction '90s*.

In 1994, MNR finalized its Statement of Environmental Values (SEV) under the Environmental Bill of Rights (EBR). The SEV describes how the purposes of the EBR are to be considered whenever decisions that might significantly affect the environment are made in the Ministry. The SEV is based on *Direction '90s*, as the strategic directions outlined in *Direction '90s* reflect the purposes of the EBR.

During the development of these guidelines, the MNR has considered both *Direction '90s* and the SEV. These guidelines are intended to reflect the directions set out in those documents, and to further the objectives of managing our resources on a sustainable basis.

2.0 Concepts and Definitions

In the growing body of literature describing the basis for ecosystem management, forest health has been identified as a central issue across North America. Although we may still be without a well-defined and easily-measurable definition of forest health, most attempts imply that forest health is a condition of the forest ecosystem which sustains complexity or diversity while providing for human needs (Burnside *et al.* 1995). This is consistent with the definition of forest health under the CFSA, and supports the need to maintain the productive capacity of our managed sites.

2.1 What is Site Damage?

Site Damage in this document refers to negative impacts on long-term forest health and productivity due to forest operations. Site damage must be viewed in context with effects of natural disturbances (*e.g.*, wildfire, windthrow, erosion) on ecosystem form and function. Natural disturbance regimes and their effects are highly variable and it is important that effects of human disturbance stay within the range of natural variability. Although some natural disturbances are severe, the intent of our human activities is to emulate less catastrophic disturbance effects (*i.e.*, although some severe natural disturbance events can reduce site productivity, the goal of forest management is to maintain site productivity).

2.2 What is Site Productivity?

Site productivity can be defined as the ability of a given site to accumulate plant biomass over time. This is the *net primary productivity* of a site and is commonly expressed in kg/ha/yr. It represents the amount of matter which can be produced by all the primary producers (plants) on a site. The net primary productivity is the source from which all the other biota on a site receive their energy.

Forest productivity is a more general term which refers to the growth and maintenance of all or any part of the plant and animal communities that live in a forested ecosystem. In contrast, *timber production* or *yield* represents the portion of net primary productivity which is allocated to the production of commercially useable wood products. Yield is of great interest to forest managers, however, it is a fairly coarse indicator of absolute site productivity.

The productivity of any given site is determined by the efficiency with which matter and energy enter, move through, and are stored at various trophic levels. This efficiency is determined by many of the physical characteristics of a site such as soil depth, fertility, temperature and moisture, and local climate and physiography. In general, any permanent change to these important physical site characteristics will impact long-term site productivity.

2.3 Ecosystem Resilience

Stand-replacing disturbance of a forest ecosystem, whether arising from natural or human forces, causes changes in species composition, stand structure and function for a period of time. If the disturbance event is not too severe and the frequency of disturbance is low relative to the normal rate of recovery, ecosystems tend to recover to their pre-disturbance condition. Therefore, the period of time that an ecosystem takes to recover (ecological rotation) is dependant upon both the severity of disturbance and the period of time between subsequent disturbances, as well as the inherent stability of the ecosystem under consideration. For example, a boreal jack pine ecosystem on a moderately productive site may be able to withstand repeated clearcutting on a 60-year rotation; whereas a maple/beech forest in southern Ontario would likely be altered negatively by the same treatment. In general, forested ecosystems in Ontario are quite resilient and difficult to permanently damage when managed according to generally accepted forest management principles and practices. In addition, natural processes operating in forested ecosystems can repair damage to soils in terms of rutting or compaction, or even loss of fertility, given enough time. By using normal care and attention to site conditions, the amount of disturbance to sites caused by forest operations can be kept to levels which can be naturally ameliorated by ecological forces in relatively short periods of time.

The boreal forest in Northern Ontario is naturally adapted to frequent stand-replacing disturbance by forest fire, wind, insects, and disease. Many of the forested ecosites in this region are typically managed under the clearcut silvicultural system. The Great Lakes–St. Lawrence Forest and the deciduous forest regions of the southern part of the province are generally adapted to less severe disturbance regimes in terms of intensity or frequency. Uneven-aged tolerant hardwoods are adapted to frequent, low intensity disturbances as individual old trees die and fall out of stands and are replaced; these stands are successfully managed using the selection silvicultural system. White pine ecosystems are adapted to varying intensities and frequencies of disturbance. Intense fires may completely replace the stand on a fairly infrequent basis. Lower intensity fires or other forms of disturbance happen more frequently and alter the stand so that multi-storied conditions are created. These types of ecosystems can be successfully managed using the shelterwood silvicultural system or, in some cases, the clearcut system.

2.4 What are Sensitive Sites?

All sites are subject to alteration by forest operations. Under most conditions and standard operating practices, the alterations to these sites does not result in site damage. The term "sensitive sites," as used in these guidelines, refers to those sites which have a high probability of one or more types of damage occurring if managed according to standard operating practices.

Some sites become more sensitive to damage under a specific set of environmental conditions. For example, loamy soils are sensitive to rutting when saturated. Other sites may be susceptible to certain types of damage regardless of environmental condition. Very shallow soils over bedrock are often susceptible to significant nutrient loss as a result of full tree harvest.

In most cases, sensitive sites can be operated without causing damage through site-specific planning and implementation of forest operations. Management practices modified to prevent or minimize site damage are often called "Best Management Practices."

2.5 What are Best Management Practices?

Best Management Practices are practices that are not considered part of normal operating procedures and are conducted specifically to prevent or minimize damage to the physical environment. The concept behind Best Management Practices is that such practices should minimize any deviations in forest development from the range of conditions following natural disturbance. The purpose of Best Management Practices is to provide resource managers with options to consider when operating on sensitive sites. The Best Management Practices included in these guidelines are not to be considered the only management practices that may be used to prevent, minimize or mitigate site damage.

3.0 Altering the Physical Environment: Issues and Concerns

Site productivity is a key indicator of forest ecosystem health. In order to maintain site productivity, attention must be paid to the interaction of the physical properties of the site (*i.e.*, soil texture, moisture, fertility and topography) with environmental conditions (*i.e.*, weather and season), and the types of forest operations which are applied to the site. The impact of identical treatments on different sites will be vastly different based on the particular sensitivity of the site to disturbance under the current set of environmental conditions.

The major types of damage due to forest operations that can affect long-term site productivity are identified in Section 3.1. The contributing factors (site, operations and environmental conditions), their interactions and their potential impacts on the environment are described. When selecting Best Management Practices, there are general principles to understand, site-specific information to acquire and operational factors to consider.

3.1 Potential Impacts on the Physical Environment

3.1.1 Compaction and Rutting

Soil structure is simply defined as the manner in which soil particles are assembled into aggregates (Hausenbuiller 1985). The formation and stability of soil aggregates are dependent largely upon the quantity and state of clay particles, the presence of various forms of organic matter, and the natural forces (*e.g.*, freezing and drying) that organize them into specific structural units (peds) of definable shape and size. The most notable disturbances to soil structure caused by forest operations are soil compaction and rutting. These disturbances alter surface drainage and infiltration, soil pore distribution and soil water-to-air ratios—all critical factors controlling certain ecosystem functions (*e.g.*, root and microbial respiration, plant uptake of water and dissolved nutrients). Generally, finer-textured soils, especially those with a silt or clay component, are more susceptible to compaction and rutting than are coarser textured soils. This susceptibility increases significantly as moisture content approaches saturation. Organic soils are also highly susceptible to rutting and, in some cases, compaction.

3.1.2 Erosion

Erodible soils are susceptible to loss or movement of soil particles by wind, water or gravity. Soil texture, mode of deposition, 'soil' depth, depth of organic layer and slope influence the risk of erosion. Site conditions which are of particular concern include:

- *Aeolian (wind deposited) soils.* These areas are usually composed of a consistently fine grained sand which can be eroded by wind or water, if exposed.
- *Fine sandy and silty soil textures* are quite erodible, particularly where there is a uniformity of soil particle sizes. Loamy textures and the presence of coarse fragments (stones) tend to increase soil stability.
- *As slope increases*, the risk of erosion of exposed mineral soil increases. Little erosion can occur on slopes of less than ten percent. Sites with greater than 30 percent slope are at significant risk of erosion, particularly when mineral soil is exposed.
- *Thin soils (<30 cm) over bedrock* pose a greater risk of erosion than deep soils found on similar slopes.
- The presence of an *intact organic layer* (forest floor) significantly reduces erosion risk on most site conditions.

3.1.3 Nutrient Loss

The traditional argument regarding nutrient removals via harvesting on nutrient poor sites is that due to the limited soil nutrient reserves, a large percentage of total site nutrient capital is found in the above ground pool (tree stratum). Once these nutrients are removed, it could take an excessive amount of time for them to be replaced (*i.e.*, beyond the length of normal forest rotations). The length of this recovery period (replacement time) varies with:

- The degree of site nutrient depletion accompanying harvesting (Timmer *et al.* 1983, Mahendrappa *et al.* 1987).
- The rate of replacement of these nutrient losses (Wells and Jorgensen 1979). However, this harvest-related nutrient loss and subsequent replacement is complex, varying among species (Kimmins 1977, Alban *et al.* 1978, Mahendrappa *et al.* 1987, Maliondo 1988), site quality factors, age (White and Harvey 1979, Freedman 1981) and stand density.

3.1.4 Loss of Productive Land

As a result of timber harvesting operations, some of the productive landbase is lost to roads, slash and bark piles, skid trails and landings. It is important at both the planning and implementation phases of timber harvesting to minimize the area affected and rehabilitate the affected area after the wood is extracted.

3.1.5 Hydrological Impacts

Of particular importance in forested wetlands are the hydrological impacts caused by forest operations. The most obvious hydrological disturbance after harvesting is watering-up (a rise in the water table) which is largely the result of reduced evapotranspiration (due to tree removal) from the site. Watering-up can reduce the depth of the aerated zone in the soil which reduces the rooting space available to trees and other plants, depress decomposition rates, and cause denitrification due to anaerobic conditions. The sites which are most susceptible to watering-up are organic soils or poorly-drained mineral soils (Dubé *et al.* 1995). The lateral flow of nutrient-enriched water through the soil profile due to gravity is critical to maintaining the productivity of some sites. This is especially true of some organic soils. Deep rutting or the creation of barriers to the flow of ground water movement as a result of road or trail construction can reduce productivity of sites where the flow of nutrient-rich ground water is one of the major sources of nutrient input.

The removal of forest cover by harvesting or natural processes, such as fire or windthrow, increases the yield of water from the affected lands. Significant impacts on water quality, water temperature and water yield do not generally occur if less than 50 percent of a forested watershed is cleared (Plamondon 1993). The impact of forest operations on watershed hydrology is greatest in the upper reaches of watersheds.

3.2 Key Site Characteristics

3.2.1 Soil

i) Soil Depth

Limited soil volume on shallow-soiled upland sites can limit site productivity. Low nutrient and water holding capacity, and inherent physical site features, can lead to longer ecological rotations and increased erosion potential after disturbance. The risk of site damage rises with increased disturbance or loss of the forest floor. Benefits of increased soil depth are significant up to approximately 60 cm (*i.e.*, rooting zone), after which other factors may become limiting. Overall, soil depths throughout the Canadian Shield are highly variable, and shallow till soils over bedrock are characteristic of much of Ontario. In contrast, soil depths are consistently deeper in the Clay Belt Region of northeastern Ontario and much of southern Ontario.

ii) Soil Texture

Mineral Soil - Mineral soil texture refers to the relative proportion of sand, silt and clay in the soil medium. Finer textured soils (silts and clays) have the ability to hold more moisture and nutrients. Coarser textured soils (sand), although more sensitive to nutrient removals, generally have better aeration and drainage. Risk of compaction and rutting increases on finer-textured soils. Uniformly fine grained sands and soils with a high silt content are the most erodible. As coarse fragments (gravel, cobble, stone, etc.) content increases, soils become more resistant to damage by compaction and rutting.

Organic Soil - These soils are derived predominately from mosses, and herbaceous and woody material. Soils are classified as organic if the depth of organic matter is 40 cm or greater. Sites with organic horizons less than 40 cm in depth may still exhibit characteristics similar to organic soils in terms of their susceptibility to various forms of site damage.

Organic soils are characteristic of lowland swamps, fens and bogs. Organic soils are classified according to the state of decomposition from fibric (weakly decomposed), through mesic (moderately decomposed) to humic (highly decomposed). Organic soils are generally wet and have less load-bearing capacity for machinery than mineral soil. More highly decomposed organic soils have a weaker (more watery) consistency which reduces their load bearing capacity and therefore makes them more prone to rutting disturbance. Conditions of high moisture, high acidity and low temperatures result in slow rates of decomposition. This may result in low levels of nutrient availability despite high levels of stored nutrients in organic material.

iii) Forest Floor and Soil Organic Matter

Both unincorporated organic matter (forest floor) and soil organic matter (organic fraction within the upper soil levels) play an important role in regulating chemical, physical and biological relations. Organic matter accumulates over mineral soil when the rate of organic decomposition is less than the rate of accumulation. On some sites, this layer constitutes a significant proportion of total site nutrient capital, while regulating both moisture and temperature regimes. Well-decomposed organic material is incorporated into the mineral soil by the leaching action of water, action of plant roots, and activity of microorganisms, insects, earthworms, etc. Forest operations that minimize severe disturbance to the organic layer will generally minimize the risk of site damage.

iv) Soil Moisture Condition

The soil moisture condition reflects the current moisture content of the soil. It is meant to be an immediate and transitory condition affected largely by precipitation. Soil moisture regime is determined on the basis of soil texture, drainage, depth and slope position, and indicates the longer term average moisture conditions of a site. On many dry, coarser textured sites or on wet organic sites, soil moisture may be the most limiting factor for plant growth. In general, site damage potential from forest operations are more dependent on current moisture content of the upper soil strata than the longer term moisture regime. Soils are more prone to disturbance (compaction, rutting, and erosion) when saturated through precipitation or snowmelt.

v) Nutrient Status

Nutrients are distributed in the mineral soil, forest floor and above ground vegetation, and are continuously cycled between the various “pools” in the system. In addition, system inputs (*i.e.*, atmospheric deposition, weathering of parent material, subsurface water flow and nitrogen fixation) and exports (*i.e.*, deep leaching, surface runoff and denitrification) are also occurring. These imports and exports are generally equivalent to each other under relatively stable (*e.g.*, mature) forest conditions. At any point in time, most nutrients are in organic form and as such are unavailable for plant uptake. It is through the decomposition of organic matter and release in inorganic form (termed mineralization) by microorganisms that they become available for plant uptake and use.

3.2.2 Terrain

Critical elements of terrain include slope, aspect and topographic position. As slope increases, soils are drier due to accelerated surface runoff and reduced water infiltration. Soils on a slope are also more susceptible to erosion due to gravity and surface water runoff. Aspect can affect productivity primarily by increasing or decreasing soil temperature. Sites with a south facing aspect have a longer growing season and higher rates of nutrient cycling than sites with a north aspect.

Topographic position (relative position on a slope) affects the potential for soil erosion, hydrological change and nutrient status. Depressions will generally be wetter than upslope areas and will be more susceptible to watering-up if tree cover is removed. Crest positions tend to be the most well-leached and therefore the most nutrient poor. They are also the driest part of the landscape and generally not susceptible to erosion. Mid-slope sites vary according to their degree of slope and slope position. Lower slopes are often enriched by the subsurface flow of water and nutrients from upper slopes and will generally be moister than upper and mid-slope positions. Upper and mid-slope positions tend to be drier but are more susceptible to erosion resulting from forest operations.

3.2.3 Forest Vegetation

The development stage and type of vegetation can influence the physical, chemical and biological properties of a site. Deciduous-dominated stands tend to have less acidic soil and faster nutrient turnover than conifer stands. Forest types and associated site conditions largely dictate the silvicultural system (even-age or uneven) and therefore harvest, renewal and maintenance treatments. On nutrient-limiting or erosion-prone sites, rapid post-disturbance vegetation development can minimize nutrient leaching and stabilize soil movement.

3.3 Forest Operations

3.3.1 Silvicultural System

Silvicultural systems describe a planned set of treatments designed to achieve specific management objectives. The choice of system (*i.e.*, clearcut, shelterwood, selection) is based upon a combination of management objectives and the forest ecosystem under consideration. In general, clearcutting is the most ecologically appropriate system for the characteristic even-aged, fire-driven ecosystems of the boreal forest. Partial cutting systems (shelterwood and selection) are more appropriate to ecosystems adapted to gap replacement disturbance regimes (white and red pine, maple, beech, etc.). There are various modifications to these silvicultural systems (*e.g.*, careful logging around advance growth, seed tree), and careful planning and implementation of forest operations can avoid or minimize risk of site damage.

3.3.2 Logging Method

Logging method relates to the felling of trees and their movement to roadside. A variety of equipment combinations and harvest layout and traffic patterns have evolved in Ontario, each adapted to meet both management objectives and local site conditions. By far, most site damage from harvest operations occurs during the movement of wood to roadside. Repeated use of skid trails can lead to concentrated areas of disturbance on a small percentage of the site, while dispersed skidding may result in wide spread damage (or no damage) across the entire site. In order to minimize damage to the physical environment, the forest manager can select the season of harvest, plan optimal skidding systems, and match the ground pressure of equipment to site conditions. The manager may choose to delimb at the stump to maintain nutrient capital and distribute slash to increase the load bearing capacity of the soil for skidding. Matching harvest systems to dominant site conditions or site limitations is key to avoiding site damage.

3.3.3 Renewal and Maintenance

The forest renewal practice which poses the greatest risk of physical site damage is mechanical site preparation. This is due to the heavy equipment involved (*e.g.*, prime movers) and the deliberate modifications of the soil profile to meet micro-site objectives (*e.g.*, plowing). Prescribed fire, where fire severity is matched to ecological site conditions and management objectives, may be the best site preparation method for many sites.

Maintenance activities include tending for vegetation management, insect/disease control and pre-commercial thinning. As with site preparation, risk of site damage is primarily related to mechanized operations on the ground. However, any elimination of vegetation which results in less than full site occupancy may lead to site degradation due to nutrient loss or erosion of slopes.

3.4 Environmental Conditions

3.4.1 Season of Operation

Harvesting on frozen soils reduces ground disturbance, minimizing compaction, rutting, erosion potential and disruption of drainage patterns. On some sites, minimizing ground disturbance will reduce the risk of promoting excessive competing vegetation, while protecting desirable advance growth and residuals. Dormant season harvest, particularly on nutrient-poor deciduous sites, can help preserve nutrient capital.

Generally, greater snow cover depth results in better site protection during harvest operations. Under certain sites and conditions, high snow loads may delay frost penetration into the soil. The most hazardous seasons are spring and fall, when excessive soil moisture occurs due to snowmelt or late fall precipitation.

3.4.2 Rainfall

The amount, duration and frequency of precipitation largely determine upper soil moisture conditions. In general, the greater the soil moisture, the greater the risk of site damage from forest operations. On sites susceptible to compaction or rutting, monitoring site conditions during or immediately after significant rainfall is essential. In many cases, operations should be modified or temporarily halted. This is an on-the-ground decision based on professional judgement and experience.

4.0 Planning for the Protection of the Physical Environment

Effective planning at both the forest and stand levels represents a key proactive action to minimize impacts or damage to the physical environment. Strategies that ensure forest operations complement site conditions are central to protecting the physical environment and ensuring that silvicultural objectives are attained.

Forest Management Planning in Ontario is governed by the *Forest Management Planning Manual*. The planning process is comprised of three interrelated levels which describe forest operations in varying levels of detail:

- At the forest management planning (FMP) level, forest operations are described in terms of broad objectives and strategies for a 20 year term, and specific operations for the first five years are identified. Treatment package options which may be applied to given site types are described.
- Areas are selected for operations and included in an Annual Work Schedule (AWS) during each of the five years of the FMP. As part of the development of a Forest Operation Prescription (FOP) for each operation outlined in the AWS, actual site conditions are verified and the silvicultural treatment to be used on that site is selected.
- Operational design (on-site planning), conducted at the field level, is not regulated by the FMPM. The level of detail associated with this planning level varies with the complexity of the forest condition, and the type of forest operation being conducted. It is often at this level where many of the Best Management Practices outlined in this document can be implemented.

Determining that a site is “sensitive” will not by itself be interpreted as a requirement to undertake Area of Concern (AOC) planning as described in the FMPM. AOC planning is required for areas identified as containing values for forest users or uses which may be affected by forest management activities. The application of these guidelines will help protect the health and productivity of sites, regardless of future human use or value. Similarly, the Best Management Practices described in these guidelines are not to be interpreted as “modified operations” in the sense that this term is used in relation to AOC planning.

4.1 Forest Management Plan

4.1.1 Identification of Issues

The first step in planning for the protection of the physical environment is to recognize the potential site damage issues on a management unit level. Issues may relate to the impact of forest operations on specific site types which occur on the management unit or, they may be related to the cumulative impact of operations across the management unit.

i) Site Level Issues

Recognizing site level issues is based on identifying the types of sites that occur on the landbase which could be sensitive to damage due to the standard forest operations practised in the area. These sensitive sites are therefore the focus for designing modified management techniques and employing the Best Management

Practices found in this document. In most cases standard operating practices will continue to be employed on the majority of sites, however, significant changes to these normal practices may be required to protect sensitive sites.

To assist in recognizing site damage potential, soil-based hazard tables are provided along with the fact sheets. These fact sheets also include treatment options (Best Management Practices) to be used when developing Silvicultural Ground Rules. Issues which are identified based on specific site conditions may be documented in the *Issues* section of the FMP, or they may simply be identified as part of the rationale for determining Forest Units or Silvicultural Ground Rules.

ii) Management Unit Level Issues

Some issues related to protecting the physical environment need to be considered at a management unit level. These broader level issues may include:

- The impact of the forest access system on the amount of land removed from production, and on watersheds.
- The impact of forest harvesting on water yield needs to be considered. As the percentage of a watershed harvested increases, so does the impact of operations on water yield and the attendant risk of deteriorating water quality and damage to aquatic environments.
- The need to balance operations on a forest to ensure that the types of equipment available and the required schedule of wood deliveries is attainable given the limitations of sites across the management unit.

Management unit level issues may be documented in the *Issues* section of the FMPM.

4.1.2 Determining Objectives

Where appropriate, specific objectives related to the protection of the physical environment should be documented in the objectives section of the FMPM.

Objectives may be general or very specific in nature. Examples include:

- Numerical targets for limiting the amount of land lost to the construction of roads and landings.
- Commitment to conducting forest operations on a certain site type in such a manner as to minimize the potential nutrient loss from those sites.

4.1.3 Formulating Strategies

Strategies that will be used to achieve stated management objectives must be developed as outlined in Section 2.3.3.2 of the FMPM. Strategies related to managing specific species and stands of trees are documented through the development of Forest Units and Silvicultural Ground Rules.

Other strategies will relate to broad management unit level objectives or other objectives not specifically linked to the harvesting and renewal of trees (*i.e.*, watershed management concepts) and are therefore documented outside of the Silvicultural Ground Rules.

i) Forest Units

Stands are aggregated in the FMP into forest units on the basis of similarity of management potential. The selection criterion for defining forest units is based primarily on species with additional determining factors including site class, age and broad site type. In management units where a large proportion of a particular working group is found on sensitive sites, these stands may be stratified into a separate forest unit for management purposes. There must be sufficient area within each grouping to justify its identification as a unique forest unit.

ii) Silvicultural Ground Rules

Silvicultural Ground Rules identify one or more sets of acceptable silvicultural treatments (treatment packages) for each identified forest unit. It is at this level that some of the critical elements of forest operations can be prescribed to deal with the sensitivity of certain sites to particular types of damage. Treatment packages can be assigned to sensitive sites whether they have been aggregated into separate forest units or are subsets of other forest units.

Treatment packages set out in the Silvicultural Ground Rules for sensitive site areas should consider and apply those Best Management Practices (as discussed in the fact sheets) to the following specific forest operations:

- harvest method,
- logging method, and
- site preparation, regeneration and tending.

iii) Other Strategies

Many strategies for protecting the physical environment cannot be addressed by the Silvicultural Ground Rules. In some cases they should be documented separately or they may be elements which extend beyond the FMP into forestry business planning. The following are examples of such strategies:

- Many types of site damage can be prevented by season of harvest. Consequently, seasonal wood flows need to be planned in the context of the availability of sites. Strategies need to be formulated to manage mill and bush inventories to ensure continued wood availability during periods of the year when forest operations are reduced to protect sites from damage (*i.e.*, spring break-up).
- Specialized equipment (*e.g.*, high flotation equipment) can be used to prevent damage to some sites. Business planning must recognize the need to manage forestry equipment purchases, not only from the perspective of silvicultural and harvesting efficiency, but also from the vantage point of acquiring the equipment best suited to managing sustainably.
- The forest access program needs to consider site damage issues. Access strategies should be formulated which will:
    - minimize the impact of roads on waterways, natural drainage patterns and site hydrology, and
    - remove the minimum amount of land from production by optimizing the balance of all-weather access with seasonal access and maximum economic skid distances.
- Areas selected for harvest need to be viewed as a percentage of watershed area, and affected watersheds should be examined as to their sensitivity to disturbance. In some cases the sensitivity of a watershed to disturbance may be a factor in determining the extent and type of forest operations.

The Best Management Practices contained in the site damage fact sheets provide examples of factors to consider when selecting areas for operations in the FMP.

4.2 Annual Work Schedule

The AWS is a list of those treatments which were identified in the FMP which will be conducted on a year to year basis. When developing a FOP for each operation outlined in the AWS, actual site conditions are verified and the silvicultural treatment to be used on that site is selected. At this point, additional details regarding the treatment packages can be added.

4.3 Operational Design (On-Site Planning)

During on-site planning, before or during implementation of a forest operation, is when some of the most important elements of the Best Management Practices identified in this document can be applied.

Specific techniques for dealing with sensitive elements of a site, such as erodible slopes or wet swale areas, have to be prescribed in the field. Limiting factors and contingency plans should be determined (*e.g.*, In the case of excessive rain, operations should move from Area X to Area Y). The extent of tertiary road access, and the strategy for forwarding and landing wood needs to be determined. The location of landings should be chosen to minimize ground disturbance and loss of productive area.

Proper crew training and communication of specific objectives are important on all sites. However, it is even more important on sensitive sites where the potential for site damage will at times be greater. Field staff need to understand not only the specifics of the plans for a site but also the reasons behind modifying operations to protect the sensitive nature of some sites.

Involve field staff in the development of on-site planning, including the best locations for roads, landings and skid trails, and specific actions to prevent or minimize site damage. Explain clearly what the post harvest conditions should look like. If special operating conditions are required (*e.g.*, placing slash on main skid trails to reduce rutting, limiting operations based on temperature or rainfall), then these conditions must be communicated to everyone involved.

5.0 Compliance Monitoring

Everyone involved in forest operations needs to bear some of the responsibility for monitoring compliance. In the context of site protection this means that there needs to be a general recognition of what the job should or should not look like. Forest operators should feel personally accountable for the quality of the job that is done and should be prepared to cease or modify operations to protect forest sites from damage.

Both the OMNR and the forest industry are responsible for recording the occurrence of any undesirable conditions described in these guidelines that are observed in the areas of operations and in the forest, that appear to be related to forest management activities (*e.g.*, road washouts in AOCs and their observed environmental effects).

6.0 Operator Training and Education

Adequate training and education of field staff are the most critical factors in protecting the physical environment during forest operations. Machine operators must be able to recognize site damage potential and occurrence, and the options available to prevent or minimize negative impacts on the site. Therefore, coordination between planners, field supervisors and equipment operators is required.

Fostering an understanding of the benefits of Best Management Practices to both the company and the environment will provide considerable motivation for field staff. Developing workshops, field exercises, training manuals, videos, and recognition and reward programs are effective means to train forest workers in understanding the interaction between operational and environmental conditions that contribute to site damage.

Site Damage Fact Sheets

Site damage fact sheets are presented for each of the following potential impacts on the physical environment:

- Compaction and Rutting
- Erosion
- Nutrient Loss
- Loss of Productive Land
- Hydrological Impacts

These fact sheets are divided into two main sections:

- *Description:* The particular type and impact of damage, and the site factors, environmental conditions and management activities that may contribute to increased risk of damage.
- *Best Management Practices:* Practices to consider in the areas of planning, field layout, implementation and monitoring to prevent, minimize or mitigate negative impacts. Where appropriate, mitigation techniques are described for the rehabilitation of damaged sites.

  The use of the term Best Management Practices does not imply that these are the only acceptable practices for a given condition. Local conditions and circumstances may dictate the use of treatments not listed here.

Planning, in the fact sheets, refers to formal activities outlined in the FMPM, on-site decision making, and some elements of business planning. Site-level planning may be relatively structured, or simply represent problem-solving techniques for dealing with site protection in the field.

Site damage hazard tables were developed for compaction and rutting, erosion and nutrient loss. Site damage hazard is rated as low, moderate or high based on broad soil and site conditions. Corresponding Forest Ecosystem Classification soil types are listed for northwestern, northeastern and central Ontario (Racey *et al.* 1996; McCarthy *et al.* 1994; Chambers *et al.* 1997). These matrices are based on current scientific evidence and expert opinion, and can be used to identify those sites most susceptible to site damage. Once verified in the field, forest operations can then be designed after considering the Best Management Practices identified in the site damage fact sheets.

Appendices 1 to 3 relate the regional soil types to the broader ecosite/site type classifications which exist for each administrative region. Based on these relationships and a knowledge of local site conditions, managers can customize site hazard ratings to ecosites for their landbase.

Description

Compaction is the increasing of soil bulk density primarily by the application of pressure through the use of heavy equipment in forest operations. When soils are compacted, natural soil structure is damaged or destroyed resulting in reduced air space between soil particles. Soil compaction is normally associated with soil rutting. Compaction is differentiated from rutting by the extent and intensity of impact. Compaction occurs over broader areas but does not necessarily result in the visible depressions associated with rutting.

Rutting is the creation of trenches or furrows in the ground by breaking through the forest floor (slash, litter and humus layers) and compacting or displacing mineral or organic soil. Ruts are the result of having exerted ground pressures in excess of the weight bearing capacity of the soil. They are normally associated with the use of heavy wheeled or tracked logging equipment.

Puddling is a specialized form of disturbance that results in a compacted surface mineral soil layer. Puddling results from the destruction of soil structure in fine textured soils when these soils are exposed to the impact of rainfall.

Impacts

Compaction of forest soil may impact sites by:

- reducing porosity of the soil resulting in greater amounts of surface runoff and less infiltration of rainfall or melt water; movement of water and nutrients within the soil profile (hydraulic conductivity) may also be impaired;
- increasing the bulk density of the soil to the point where root penetration is inhibited;
- causing surface soil to warm up less quickly in the springtime, effectively shortening the growing season for new seedlings and causing silviculture operations to be delayed;
- impeding gas exchange between roots and soil (smothering);

Figure 1: Example of rutting damage caused by forest operations.

- reducing germination potential of some soils and impeding early seedling establishment (however the germination potential of sphagnum peats is increased by moderate compaction); and,
- reducing the overall productive capacity of an area.

Additionally, the creation of ruts may impact a site by:

- reducing the productive area of a site, by causing deformation of the forest floor and/or by creating an opportunity for water ponding (*i.e.*, less area available for immediate renewal);
- compacting the soil on the sides and beneath the rut such that water infiltration is impeded;
- inhibiting rooting and gas exchange;
- impeding lateral drainage of water on wetter sites; and,
- contributing to erosion and soil displacement if ruts are located on side slopes.

Site Factors Influencing Compaction and Rutting

Generally, finer texture soils (fine loamy–clayey) are more susceptible to compaction and rutting than coarse textured mineral soils (coarse loamy –sandy). Fine textured soils have physical properties (very small and uniform particle size) which allow them to exist in very compacted, massive forms. The productivity of fine textured soils (clays in particular) is dramatically improved as the surface layers of these soils are structured by the actions of biological organisms and weathering; this soil structure is fragile and subject to damage.

Sandy soils are generally far less prone to rutting and or compaction. However, very fine sands and fine sands characteristic of lacustrine (beach) or aeolian (dunes) deposits may be susceptible to some compaction and rutting, particularly when wet. Soils with a high percentage of coarse fragments (*e.g.*, stony tills or outwash) are less prone to rutting than stone free soils.

Soil susceptibility to compaction or rutting is greatly influenced by the moisture content at the time of disturbance. A dry clay, for example may be less prone to rutting or compaction than a wet loam would be. Since finer textured soils are inherently able to hold more water at field capacity than coarser textured soils, they will be more negatively influenced in terms of compaction and rutting risk when exposed to the same intensity and duration of precipitation. Moisture regime, which reflects the longer term average moisture conditions in a soil, is less significant in determining rutting hazard than the immediate moisture content of the upper horizons of the mineral soil and the organic layers.

The depth and type of litter, slash and organic material on a mineral site increases the load bearing capacity of the ground surface. Coarse woody debris such as tree tops and limbs can greatly increase the trafficability of a site. Ruts, by definition, cannot occur unless these surface layers of organic material are broken or removed. Overlying organic layers also protect the structure of the mineral soil by diffusing the potentially damaging impact of raindrops on the surface of the soil (*i.e.*, puddling).

Organic and peaty phase soils are inherently more susceptible to rutting damage than mineral soils. Organic soils may also be compacted. However, unless the surface of the organic layer is broken (*i.e.*, unless a rut is created) this compaction is short-lived and less significant than the compaction of mineral soil. Compaction of the living moss and fibric peat at the surface of an organic soil may be beneficial in terms of increasing seedbed receptivity.

Organic soils with surface horizons composed of highly decomposed peats (mesic and humic) are more susceptible to rutting than those with surface horizons of less well decomposed peats (fibric). Organic sites with Labrador tea and other ericaceous shrubs may be less prone to rutting disturbance than are the richer organic sites characterized by alders.

Environmental Factors Influencing Compaction and Rutting

Season of Harvest

The risk of damage by compaction or rutting is greatly reduced when soil is frozen. Normal winter conditions in northern Ontario result in sufficient ground frost to increase the load bearing capacity of the soil to the point where it can support most types of equipment used in logging. Extended autumns and earlier springs in southern Ontario may greatly reduce or entirely eliminate the frozen season. During winters with early or abnormally high snow loads, ground may not freeze sufficiently to support operations on some sites. A significant snowpack may itself prevent damage to the soil.

Spring snowmelt and ground thawing result in the maximum seasonal compaction and rutting hazard. The depth of winter snowpack and the duration of the spring thaw dictates how severe compaction hazard will be during the spring breakup period. Summer conditions usually reduce compaction and rutting hazard by reducing overall moisture content. Above normal rainfall may, however, increase the compaction hazard at this and any time of the year. In many parts of the province, autumn rains increase compaction and rutting hazard to spring levels.

Compaction and Rutting

Description

Precipitation

Wet soil is more prone to compaction and rutting than dry soil. Susceptibility to compaction and rutting is therefore a function of the amount, frequency and duration of rainfall. The actual impact of rainfall on the moisture content of a soil depends on its moisture holding capacity (*i.e.*, soil texture and organic component), the quality of soil drainage and the surface infiltration rate of a site. Prolonged droughty periods followed by high intensity but short duration rainfall may result in excessive surface runoff with little increase in actual soil moisture. On exposed fine textured soils, even brief periods of precipitation may significantly increase the risk of compaction and rutting.

The Impact of Forest Operations on Compaction and Rutting

Ruts occur when the ground pressure exerted by equipment exceeds the load bearing capacity of the surface of the ground. Therefore, weight and type of equipment (particularly forwarding or skidding equipment) has a great deal of influence on the degree of rutting. Ground pressure is a function of machine weight and ground contact area; therefore, equipment with wide tires or tracks will exert less pressure than conventional equipment of the same weight.

Soil compaction is often associated with rutting damage; however, compaction may occur in the absence of ruts since the degree of ground pressure needed to compact the soil may be less than that needed to break through the organic layers of the forest floor and deform the soil profile. Forest operations that break, or displace the forest floor may in turn contribute to compaction by reducing the overall load bearing capacity of the ground.

Repeated traffic on the same trail will increase severity of rutting and compaction while reducing the percentage of a site that is damaged. Conversely, dispersion of traffic may reduce the intensity of damage but may result in a higher percentage of the site being damaged to some degree. There is greater opportunity to disperse skid trails in conventional clearcut systems than in partial cut systems where repeated use of a few main trails is dictated. Maximum rutting often occurs where machinery is turned as on a corner of a main skid trail. Landings and trail convergence points are subjected to the most traffic and therefore are very likely to be damaged by rutting and or compaction.

Skidding and f orwarding equipment that do not have the ability to reach or winch, pose a greater degree of rutting hazard. Grapple skidders, for example, which must drive up to every pile (bunch) of wood, are less able to be used on selected trails than are cable skidders. They are also less able to avoid wet areas than a cable skidder which may use its winch to pull wood across wet areas. Equipment with greater load capacities, such as forwarders or clambunk skidders, cause less overall ground disturbance as fewer passes are required to move the same volume of wood.

Forest operations that break or displace the litter and organic layer of the soil may in turn contribute to rutting by reducing the overall load bearing capacity of the ground. The use of broadcast forms of site preparation such as summer blading (on fine textured silts and clays) can contribute to site damage by compaction. Damage may occur directly as a result of the ground pressure of the equipment used and also indirectly as a result of exposing the mineral soil to the impact of rainfall which can result in the loss of surface soil structure (*i.e.*, puddling). The creation of furrows by site preparation equipment such as scarification drags, Young's teeth or disk trenchers is normally beneficial from a silvicultural perspective. Inappropriate or excessive use of these types of equipment can result in a form of rutting damage and may lead to subsequent problems with erosion.

Road construction activities result in deliberately compacted soils with greatly reduced productivity. Lands converted to all weather roads are lost to forest production permanently or for an extended period of time. These issues are discussed in the *Loss of Productive Land* fact sheet.

Planning

Under non-frozen conditions, a certain degree of compaction and rutting is inevitable on all sites where heavy equipment is used. The degree of damage on most sites is not problematic however. As with most types of site damage, compaction and rutting can usually be avoided through careful planning beginning with the Forest Management Plan, through the Annual Work Schedule, and down to field level planning on a cut block level.

A Forest Management Plan should recognize that some sites are sensitive to compaction and rutting disturbance. Selection of areas for harvest must be made in recognition of these “sensitive sites” and a balance sought between stands that can be operated at any time of the year and those best operated in the winter or in the driest part of the summer months. If sufficient flexibility is provided in the plan, it should be possible to avoid operations on sites that are sensitive to compaction and rutting until the hazard is reduced by season or environmental condition. Traditional scheduling of winter and summer operations has been based primarily on the availability of access to the site and the ability of equipment to work without getting mired down. This level of site differentiation is often inadequate to prevent potential site damage. Unacceptable damage due to compaction and rutting may occur when equipment is still able to operate without getting mired down. Planning must be done in the context of equipment availability and the flexibility or limitations that it provides.

To differentiate those areas selected for harvest on the basis of site susceptibility to damage, a basic knowledge of local forest site types is required. The Forest Management Plan should address sensitive sites within the Silvicultural Ground Rules and identify special measures to minimize damage potential. Field inspection of sites during the preparation of FOPs will ensure that all forms of site sensitivity are recognized.

Recognition of the annual variations in mill requirements is critical to ensuring that the right blend of stands is chosen over a five-year term to allow that strategy to be translated down to Annual Work Schedules. Bush and/or mill yard inventories should be used to limit the need for operations at times of the year when sites are most susceptible to damage (*i.e.*, spring break-up period).

Proper access planning helps to prevent or minimize the hazards associated with compaction and rutting (and other site damage issues). In the Forest Management Plan, the access plan must compliment the balanced seasonal areas selected for harvest. Wherever possible, roads must be built sufficiently in advance so that the lack of access does not require off-season operations on sensitive sites.

A choice of operating blocks in the field is a good planning tool to allow for flexibility to avoid more sensitive areas during periods of abnormal environmental conditions (*e.g.*, high rainfall). All field blocks should be walked in advance of operations to identify areas within stands that could be prone to damage and an approach to dealing with these areas should be made and communicated to the operators. Similarly, an approach to access within the block (*i.e.*, skid trails) should be developed and communicated to the operators. Forest Operations Prescriptions will document the techniques that are to be used for both harvest and renewal treatments. An even finer degree of operational planning detail is required for sensitive sites, and the cut supervisor and/or operators should have a clearly defined approach that will include:

- the location of areas prone to compaction and rutting and how they will be addressed;
- the general plan for skidding or forwarding, or the specific locations of skid trails;
- the general plan for the progression of the cut;
- the location of landings, chipper pads, etc.; and,
- depending on the nature of the operation, (workers, closeness of supervision, etc.) specifics of the logging plan may need to be written and distributed to everyone involved in the operation. An accurate map of the cut block should be available to all operators.

Field Layout

Cut block boundaries should be flagged in the field using a specific, agreed-upon colour scheme. If it is necessary to limit traffic within the block through the use of a limited number of main skid trails, then these will normally be flagged using a different colour scheme from the block boundaries. Clearly identified skid trails are necessary to effectively implement the shelterwood or selection system. Sensitive areas within the block must be recognized by all operators and flagged if necessary.

The block can be subdivided into daily or weekly operating compartments by the operator, if desired. This subdivision of the block ensures personal accountability on the part of operators for problems caused by the operation and allows the supervisor to manage the progression of the cut.

Notwithstanding the sensitive spots within a block, in a clearcut system, less damage will occur if skidding across the block is as widely distributed as possible. It is not practical to have an infinite number of log landings, so convergence zones will develop. If these areas are identified and a primary trail is located where the ground has the greatest load bearing capacity, or if the convergence zones are strengthened with slash matting, then damage will be minimized. During operations to protect advance growth or in partial cut systems, the use of main trails is required throughout the block so the location of these should be chosen to take advantage of areas with the greatest load bearing capacity. Some damage to main trail areas is expected as a cost of minimizing damage to residual trees and the rest of the site.

Implementation

Careful planning and scheduling of operations can reduce the risks of compaction and rutting damage on most sites. On occasion, operations may be required when the risk of damage is higher. The following Best Management Practices can be used to minimize damage on these occasions:

- In a clearcut system, skid trails will normally be widely distributed while avoiding wet pockets or other sensitive areas. The exception to the above noted rule is where there is a significant risk of compaction or rutting damage caused by only a few skidder passes. In this case, skidder traffic should be concentrated on main trails. Locate main trails on areas with the highest load bearing capacity. Ensure that all operators are completely aware of their location. On main trails or convergence trails, a mat of slash can be used to increase the bearing capacity of the soil. In some cases gravelling of main skid trails may be considered.
- In partial cutting operations, such as the shelterwood and selection systems, skidding must be confined to a network of main trails and these should be located in advance of operations whenever possible. Locate skid trails on areas with good load bearing capacity and keep them as straight or as gently curving as possible while avoiding wet spots. The amount of area used for skid trails should not exceed 30 percent for shelterwood systems and 20 percent for selection systems (OMNR 1997b). As much as possible, wood should be winched to the skidder to minimize the extent of skid trails which are necessary.
- If summer logging chances must include large areas of organic soil, then high floatation equipment should be used. Operations should be closely monitored to ensure that damage is minimal. Summer logging on organic soils, even with low ground pressure equipment, is most suitable for fibric peats. Harvesting operations on more strongly decomposed mesic or humic peats should be avoided during frost-free conditions whenever possible. Sensitive wet swale areas can be dealt with by:
  - Avoiding them completely during harvesting or site preparation.
  - Reaching into them with a felling head or winching out of them using conventional cut and skid systems.

    - Having feller-bunchers cut them and bring bunches back to solid ground.
    - Using limbs and tops to increase the load-bearing capacity of the ground.
- The load bearing capacity of soil is greatly improved through the use of slash matting on equipment traffic areas. Cut-to-length systems that limb and top on site should place the slash in front of the machine on sites susceptible to compaction and rutting.
- Care should be taken in both harvesting and site preparation operations to minimize the disturbance/removal of the organic layers of the soil as these layers increase the soil's resistance to compaction and rutting. On fine textured soils, maintaining organic layers will prevent damage to soil structure by puddling. Broadcast site preparation techniques such as blading that expose large areas of mineral soil should not be employed on fine textured soils.
- Operations may be allowed or discontinued based on the actual compaction and rutting which is occurring. For example, in the late winter/early spring it may be possible to operate on night shift and until midmorning if frost conditions are satisfactory and then stop operations when the ground warms up. A shut down for a few days may be required after a period of high precipitation; if scheduling of operations has allowed sufficient flexibility then perhaps the operation can be temporarily located to less sensitive areas.
- Whenever possible, non-productive areas such as rock outcrops should be selected for landing sites.
- Proper planning of operations is required at all stages including day to day on-site planning. It is important that operators are competent and properly trained, and that they are aware of the objectives and plans for specific sites.

Monitoring

Continuous monitoring of all operations is critical to minimizing all types of site damage. A more complete understanding of site types and how they are impacted by forest operations, and better subsequent planning is the goal. Field supervisors and the operators must feel empowered and accountable for stopping or modifying operations to minimize compaction and rutting damage before it becomes a serious problem. Compaction is fairly insidious and may be difficult to detect in the field. The occurrence of rutting on a site may indicate that significant site compaction is also occurring.

Mitigation

Sites that have been rutted or compacted due to forestry operations, will naturally recover in part or completely, given enough time. Based on a review of the literature, Arnup (1997) suggests that soil recovery to pre-harvest conditions for soils compacted by harvesting operations on heavy-traffic areas varies from 5 to 10 years for well drained clayey soils, to 10 to 20 years for poorly drained clayey soils. In some cases, these types of damage can by mitigated through the use of the following techniques:

- Loosening the compacted surface soil with mechanical site preparation equipment such as a disc trencher.
- Mulching exposed fine textured soils to prevent further loss of soil structure and to encourage the restoration of structure through micro and macro faunal activity. Mulching can be done by distributing slash or chipper residue.
- Regenerating compacted sites with species that can tolerate these conditions (*e.g.*, jack pine does better on compacted sites than spruce).
- Choosing plug stock seedlings or regenerate from seed rather than using bare root stock on compacted sites.

Table 1: Compaction and rutting hazard for soils in Ontario. This table broadly classifies the risk of compaction and rutting into three categories (low, moderate, high) based on soil texture, soil depth and moisture condition.

Soil Description			Forest Ecosystem Classification Soil Type			Site Damage Hazard Rating (Soil Moisture Condition)			
Texture	Depth Mineral (cm)	Depth Organic (cm)	Northwestern Ontario	Northeastern Ontario	Central Ontario	frozen	dry	moist	wet
mineral–all	0–5	0–20	SS1, SS2, SS4	SS1, SS2, SS4	SS1, SS2, SS4 (S17)	low	low	mod	high
mineral–all	6–30	0–20	SS3, SS4, (SS5–SS8)	SS3, SS4	SS3, SS4	low	low	mod	high
sandy	31–60	0–20	SS5, (SS8)	S1, S2, S3, S4, (S15)	S1, S2, S5, S6, S9, S10, S13, S14	low	low	low	mod
sandy	61^+	0–20	S1, S2, S7, (SS5, SS8)	S1, S2, S3, S4, (S15)	S1, S2, S5, S6, S9, S10, S13, S14	low	low	low	mod
coarse loamy	31–60	0–20	SS6, (SS8)	S5, S6, S7, S8, (S15)	S3, S7, S11, S15	low	low	mod	high
coarse loamy	61^+	0–20	S3, S8, (SS6, SS8)	S5, S6, S7, S8, (S15)	S3, S7, S11, S15	low	low	mod	high
silty	31–60	0–20	SS7, (SS8)	S9, S10, S11, S12, (S15)	S3, S7, S11, S15	low	low	mod	high
silty	61^+	0–20	S4, S9, (SS7, SS8)	S9, S10, S11, S12, (S15)	S3, S7, S11, S15	low	low	mod	high
f. loamy–clayey	31–60	0–20	SS7, (SS8)	S13, S14, (S15)	S4, S8, S12, S16	low	low	mod	high
f. loamy–clayey	61^+	0–20	S5, S6, S10, (SS7, SS8)	S13, S14, (S15)	S4, S8, S12, S16	low	low	mod	high
organic–fibric	all	21–40	SS9, S11	S16	SS5, S18	low	mod	high	high
org.–mesic/humic	all	21–40	SS9, S11	S16	SS5, S18	low	high	high	high
org.–fibric	all	41^+	SS9, S12F, S12S	S17	S19	low	mod	high	high
org.–mesic/humic	all	41^+	SS9, S12F, S12S	S18, S19	S20, S21	low	high	high	high

Note: Brackets () indicate that these soil types are not closely related to the soil description *i.e.,* they are defined by other soil parameters and may be found on several lines in the table.

Site Damage Hazard Rating

Low: Minimal risk of compaction and rutting, providing that normal care is exercised during forest operations.

Moderate: Normal operating procedures may cause compaction and rutting. The use of Best Management Practices will normally avoid or minimize site damage.

High: Normal operating procedures will cause site damage. Best Management Practices may be able to minimize damage, however, in many cases operations should not be conducted until conditions change.

Soil Moisture Condition

Frozen: Organic or mineral soil horizons frozen due to normal winter frost.

Dry: Organic matter and surface horizons of the mineral soil are dry. Moisture content is nearing the permanent wilting point. This condition represents typical mid-summer conditions, where there has likely been no significant rain for several days. In organic soils, water table is at least 20 cm below surface.

Moist: Surface soil at average moisture condition, organic matter is moist, mineral soil is below field capacity. Normal precipitation has occurred, clay soils are slightly sticky. In organic soils, water table is between 10 and 20 cm below surface.

Wet: Surface soil is saturated, organic matter is soaked, and mineral soil is at or above field capacity. There has probably been considerable rain over the past 48 hours, or spring melt water conditions. Typical conditions for early spring and during wet autumns, clay soils very sticky. In organic soils, water table is between 0 and 10 cm below surface.

Description

Erosion is the accelerated movement of soil materials by the actions of water, wind or gravity. Surface erosion is normally the result of erodible mineral soils being exposed to the elements of wind and water. Gravitational erosion usually occurs on a more massive scale in the form of landslides, creeps and flows; these phenomenon are common on steep slopes and are categorized by the pattern of movement and the duration of the event. In general, the potential for erosion increases as percentage slope, length of slope and percentage of silt contained in the soil increases.

Impacts

Soil erosion may impact a site by:

- reducing productivity through the removal of nutrient rich, upper soil layers;
- rendering certain severely eroded sites unproductive because of the resultant orientation of soil (*i.e.*, exposed bedrock, steep gullies, nutrient poor exposed sub-soil materials or sub-soil materials smothering productive profiles);
- destroying vegetation through catastrophic erosion such as land slides;
- degrading water quality and fish habitat by depositing soil particles and nutrients into streams and water bodies; and,
- damaging or destroying soil structure in fine textured soils and depositing structureless eroded soil materials.

Site Factors Influencing Erosion

Topographic position (*i.e.*, crest, sideslope, depression) and slope influence soil susceptibility to erosion from both surface water runoff and gravity. Slopes in excess of a soil's natural angle of repose (slopes > 60 percent) are inherently unstable and subject to gravitational erosion. Lesser slopes, though more stable, are often subject to erosion due to surface water runoff. The risk of surface water erosion increases with slope and the degree of mineral soil exposure on a site. Topographic features such as gullies channel surface runoff, concentrating the effects.

The presence of organic matter on the surface of the soil has a great influence on the permeability of the soil, its resistance to deformation by the impact of rain drops and, ultimately, its susceptibility to erosion by wind or water. Exposed mineral soil is the most erodible substrate while soils that have a reasonable depth of litter and humified organic material can withstand greater erosional forces without damage.

Surface runoff is inversely proportional to the permeability of soil. A well developed layer of litter and humus can increase permeability and absorption and therefore limit surface runoff. Compacted soils also have lower infiltration rates and promote surface runoff on moderate to steep slopes. Uniformly fine textured soils such as clays and silts inherently have lower infiltration rates than coarse textured soils. The low permeability of clays can be reduced even further if soils are subjected to prolonged periods of drying followed by periods of high rainfall (flood events). Clay soils with an intact organic layer generally develop a well-defined structure over time, thereby increasing permeability. This soil structure is easily damaged if mineral soils are either compacted or exposed to the effects of rain drop impact by removal of the organic layers. This loss of soil structure is called puddling.

Wind erosion is a factor on uniformly textured fine and very fine sands when the organic layers of the soil are removed by forest operations. Soils which are of aeolian origin (i.e., wind deposited sands) are obviously the most susceptible to further wind erosion.

Soil depth is an important factor influencing the erodibility of sites. Shallow soils have lower soil volume and therefore lower total water holding capacity. When that capacity is exceeded, surface runoff must inevitably occur. On shallow soils over bedrock, there is a considerable amount of subsurface water flow at the interface between rock and mineral soil that can reduce the adhesion of the shallow soil to its rock substrate and increase the risk of erosion. Shallow till deposits over Precambrian Shield bedrock, such as are typical of much of northern Ontario, are often characterized by the rugged and complex slopes of the underlying strata. On these sites, soil deposited on or near the edge of precipitous bedrock slopes is highly susceptible to erosion; the typical pattern of practically bare ridges and depressions filled with moderately deep soils is due in part to progressive erosion of these soils since glaciation. Table 2 broadly classifies erosion hazard potential for soil and site conditions in Ontario.

An intact root mat, and forest slash and litter layers are perhaps the most important factors in protecting sites from erosion. Plant species such as grasses that have wide spreading interconnected root systems are effective protection against erosion due to surface runoff. The above-ground parts of plants and trees shelter the ground from the impact of rainfall and therefore also serve to reduce the risk of erosion.

Environmental Factors Influencing Erosion

Precipitation and soil moisture have a considerable influence on erosion. Gravitational erosion usually occurs when soils are saturated. In contrast, surface erosion is a phenomenon of high intensity, short duration precipitation. Obviously very little erosion occurs during the winter in Ontario, however, the spring melt greatly increases water yield from a watershed and can result in erosion problems.

Unlike compaction or rutting, only the immediate risk of erosion is limited by season and soil moisture. Erosion is an effect that occurs after forest operations, rather than during them. Selecting winter operations on steep slopes for example is not necessarily an effective means of preventing erosion as the conditions created by the forest operations will still be subject to erosionary forces after the spring thaw. Winter operations may lessen the risk of erosion by minimizing disturbance to ground vegetation and the forest floor.

The Impact of Forest Operations on Erosion

While erosion of soils is a natural phenomenon, certain forest operations have the potential to significantly accelerate these processes. Forest operations such as road construction and site preparation, which expose mineral soil, increase the risk of erosion, especially where these operations occur on moderate or steeper slopes. Ditches or ruts created up and down a slope channel surface runoff and often result in erosion. Skidding wood up or down a slope is a high-risk activity from an erosion perspective.

Where forest operations have resulted in sites being damaged by compaction or rutting (See the Compaction and Rutting fact sheet), the risk of subsequent erosion is significantly increased.

Road construction and water crossing activities are the most high-risk forest operations. Surface runoff from forest roads, ditches and cleared right-of-ways can be a major source of sedimentation and nutrient enrichment in lakes and streams. The Environmental Guidelines for Access Roads and Water Crossings contain mandatory standards, Best Management Practices and mitigation techniques to deal with erosion associated with access road construction. Forest road construction and maintenance must comply with the provisions of this document.

Forest harvesting (and natural disturbance events) inherently increases the risk of erosion by removing forest cover. Rapid reforestation is a major factor in limiting erosion. Choice of silvicultural system and regeneration method are therefore the principal factors in establishing the base level of erosion risk. For example, clearcutting is inherently more risky than partial cutting systems such as selection or shelterwood. The choice of species with prolonged regeneration periods for reforestation purposes may increase the risk of erosion as does the removal of competing vegetation through broadcast spraying or cutting.

Planning

Erosion damage associated with forest operations is largely preventable; certainly severe erosion is avoidable. The *Code of Practice for Timber Management Operations in Riparian Areas* is used in planning and implementing forest operations in areas near water. The directions in the code are designed to prevent deposition of unwanted soil and soil nutrients into streams and lakes, but also offer some practical guidance for preventing erosion elsewhere in the ecosystem. Adherence to this code of practice is mandatory on Crown lands in Ontario. Similarly the *Timber Management Guidelines for the Protection of Fish Habitat* should be followed; adherence to these guidelines provides for a filtering buffer of vegetation adjacent to streams and water bodies but may be insufficient to protect sites from erosion beyond the reserve area. The *Environmental Guidelines for Access Roads and Water Crossings* provide excellent direction and techniques that cannot only be used in riparian areas, but are valuable erosion control measures for the entire forest ecosystem.

Massive gravitational erosion (*i.e.*, landslides) is almost exclusively confined to the riparian areas of the larger rivers in the province. These events are quite infrequent and not entirely preventable, although they can have long-term effects on a landscape and watershed. Broad sloping alluvial deposits are the most sensitive and potentially destructive conditions encountered in Ontario. These areas should have a custom designed strategy geared towards land stabilization.

Past policies and practices have been designed to prevent or limit erosion damage in riparian areas. In the interest of maintaining site productivity, it is necessary to view erosion as a potential problem over the entire landscape.

As with the prevention of most types of site damage, the first step is to recognize potential problems within a specific management unit. If a management unit contains a high percentage of shallow soils perched on undulating bedrock, or large areas of productive forest located on moderate slopes along a major river, then it is prudent to identify those sites for the purposes of developing treatment packages within the Silvicultural Ground Rules.

Field Layout

On deep alluvial soil deposits associated with large river valleys, consideration needs to be paid to developing an allocation strategy to ensure a staged removal of timber. On moderate to steep slopes, simple protection of the riparian area with a reserve may be insufficient to protect against the threat of broad scale landslides and slumping. On broad sloping alluvial areas, care should be taken to orient cut blocks such that the entire width (with slope) of the area is not cut in a single operation. Clearcut blocks in these areas should generally be smaller than the average for the management unit.

Progressive reserves based on slope are required by the *Timber Management Guidelines for the Protection of Fish Habitat*. For the most part these reserves should be viewed as the minimal acceptable treatment. On steep slopes or on long gentler slopes, special care must be taken over the entire length of the slope adjacent to a riparian area. At a minimum, it is critical the reserves be laid out by ribboning in advance of operations.

Stream crossing locations and right-of-way approaches to crossings should be flagged in advance of operations. Depending on the experience of operators, it may be beneficial to not only ribbon the road centerline but also the narrowed right of way at the crossing location.

The layout of logging roads, and skidding/forwarding trails in areas of moderate or excessive slopes is critical. The natural tendency to skid logs downhill may create a severe risk of erosion. In cases where logs must be skidded up or down slopes, the best approach may be to disperse skidding so that repeat traffic does not cause rutting and compaction and, in turn, surface erosion. Within the limits of safe operation, cross slope skid trails are preferable.

Regardless of the approach taken, adequate communication between supervisors and operators, and good field layout are the critical first steps to ensuring that the planned approach is implemented in the field.

Implementation

The following Best Management Practices will help to protect sites from damage by erosion:

- Identify sites with a high risk of erosion and employ a combination of Best Management Practices to reduce risk.
- Carefully adhere to the Best Management Practices outlined in the fact sheets for Compaction and Rutting in areas with slopes greater than 10 percent.
- Adhere to the mandatory standards and good practices found in the *Environmental Guidelines for Access Roads and Water Crossings*.
- Apply the *Timber Management Guidelines for the Protection of Fish Habitat* as a minimum on all riparian areas. Where operations are permitted within a riparian Area of Concern, ensure that the highest possible standards of care are taken to eliminate the risks of compaction, rutting and erosion. On long simple slopes, extend the width of the reserve on the riparian area to the top of the slope or use a combination of Best Management Practices to reduce erosion risk.
- Wherever possible, avoid locating haul roads and skid trails on moderate to steep slopes. Wherever possible, winch wood off areas with slopes greater than 30 percent, or reach onto slopes with a feller buncher and place piles at the bottom or top of the slope, rather than skidding or forwarding it. Side slopes may be used for skidding and hauling to minimize erosion potential within the bounds of safe operations. Where roads must be located across contours, use runoff ditches rather than long continuous ditches to reduce the velocity and magnitude of surface runoff flow. Protect erodible road surfaces with aggregate on slope areas.
- Consider extremely steep slope areas as inoperable and do not conduct forest operations.
- To minimize the risk of erosion on high risk sites, consider the use of winter only operations to minimize ground disturbance and eliminate rutting and compaction risk.
- On shallow soil areas, modify silvicultural systems (particularly the clearcut system) to retain some trees adjacent to precipitous slope areas. Narrow winter strip cuts parallel to the contours of the land may be used to stabilize steeper slopes on shallow soils. Avoid harvesting those areas that clearly will erode as a result of the removal of trees (*i.e.*, areas with only a discontinuous layer of organic material over bedrock).
- Where practical and within the limits of safe machinery operation, ensure that site preparation patterns run across slopes (*i.e.*, with the contour of land). Site prepare to provide the minimum amount of mineral soil exposure that is acceptable to meet silvicultural objectives. Avoid the use of extreme site preparation techniques such as summer shear blading or the Martinni plow. Use natural regeneration, planting without site preparation, hand scalping and seeding or other light touch methods to regenerate steep slope areas. In this context, steep refers to those areas where mechanical site preparation cannot safely occur across the contour of the site.
- Consider erosion risk in the choice of species and regeneration method. Erosion risk is reduced by rapid reforestation so the use of fast growing species is advisable on high-risk sites. The use of species with a prolonged regeneration period that require extensive vegetation control is counterproductive.
- Proper planning and scheduling of operations is required at all stages including day-to-day on-site operations. It is important that operators are competent and properly trained, and that they are aware of the objectives and approaches to be taken on specific sites.

Erosion

Monitoring

Continuous monitoring of all operations is critical to minimizing all types of site damage. A more complete understanding of site types and how they are impacted will ultimately lead to improved planning in the future. Some soil movement is expected and acceptable as the result of forest operations. Erosion becomes unacceptable when:

- Best Management Practices are not employed on high-risk sites and site damage occurs.
- Soil erodes into streams and other water bodies.
- Massive gravitational erosion occurs as a result of forest operations.
- Land is rendered unproductive as a result of erosion.

Mitigation

If minor erosion appears on slopes following forest operations, the following techniques may be used to mitigate further damage to the site:

- Identify ruts or furrows on slopes that are channelling runoff and causing erosion.
- Limit further erosion by filling these ruts with slash, debris, or non-erodible soil.
- Divert mid-slope ruts with cross drains, obstacles, or berms (*i.e.*, water bars).
- Ensure prompt regeneration of exposed erodible slopes.

Table 2: Erosion hazard for soils in Ontario. This table broadly classifies the risk of erosion into three categories (low, moderate, high) based on soil texture, soil depth and percent slope.

Soil Description			Forest Ecosystem Classification Soil Type			Site Damage Hazard Rating*		
						Slope (%)		
Texture	Depth Mineral (cm)	Depth Organic (cm)	Northwestern Ontario	Northeastern Ontario	Central Ontario	0–10	11–30	>30
mineral–all	0–5	0–20	SS1, SS2, SS4	SS1, SS2, SS4	SS1, SS2, SS4 (S17)	low	mod to high	mod to high
mineral–all	6–30	0–20	SS3, SS4, (SS5–SS8)	SS3, SS4	SS3, SS4	low	mod	mod to high
sandy	31–60	0–20	SS5, (SS8)	S1, S2, S3, S4, (S15)	S1, S2, S5, S6, S9, S10, S13, S14	low	low to mod	mod to high
sandy	61+	0–20	S1, S2, S7, (SS5, SS8)	S1, S2, S3, S4, (S15)	S1, S2, S5, S6, S9, S10, S13, S14	low	low to mod	mod to high
coarse loamy	31–60	0–20	SS6, (SS8)	S5, S6, S7, S8, (S15)	S3, S7, S11, S15	low	low to mod	mod to high
coarse loamy	61+	0–20	S3, S8, (SS6, SS8)	S5, S6, S7, S8, (S15)	S3, S7, S11, S15	low	low to mod	mod to high
silty	31–60	0–20	SS7, (SS8)	S9, S10, S11, S12, (S15)	S3, S7, S11, S15	low	low to mod	high
silty	61+	0–20	S4, S9, (SS7, SS8)	S9, S10, S11, S12, (S15)	S3, S7, S11, S15	low	low to mod	high
f. loamy–clayey	31–60	0–20	SS7, (SS8)	S13, S14, (S15)	S4, S8, S12, S16	low	low to mod	mod to high
f. loamy–clayey	61+	0–20	S5, S6, S10, (SS7, SS8)	S13, S14, (S15)	S4, S8, S12, S16	low	low to mod	mod to high
organic–fibric	all	21–40	SS9, S11	S16	SS5, S18	low	low	
org.–mesic/humic	all	21–40	SS9, S11	S16	SS5, S18	low	mod	
org.–fibric	all	41+	SS9, S12F, S12S	S17	S19	low		
org.–mesic/humic	all	41+	SS9, S12F, S12S	S18, S19	S20, S21	low		

Notes: Brackets () indicate that these soil types are not closely related to the soil description *i.e.,* they are defined by other soil parameters and may be found on several lines in the table.

*Erosion hazard across all soil types and slope classes is reduced if organic material (forest floor, slash) is left intact on the site.

Site Damage Hazard Rating

Low: Minimal risk of erosion, providing that normal care is exercised during forest operations.

Moderate: Normal operating procedures may cause erosion. The use of Best Management Practices will normally avoid or minimize site damage.

High: Normal operating procedures will likely cause erosion where mineral soil is exposed. Best Management Practices may be able to minimize damage.

Description

Part of the total nutrient capital on a forest site is held in tree biomass, particularly in branches and foliage. On nutrient poor sites, the percentage of total site nutrients found in the above ground parts of trees is much greater than on richer sites. Forest operations on these nutrient poor sites may reduce total nutrient capital to critical levels, resulting in extended nutrient replacement time.

Impacts

It is widely believed that nutrient removals due to logging are not significant on most sites. Natural nutrient cycles replenish lost nutrient capital with minimal impact on ecosystems. The length of this recovery period is a function of the degree of site nutrient depletion and the rate of nutrient replacement. On some sites, nutrient loss due to logging is very significant since there is very little nutrient capital stored on the sites, except in the trees themselves. On these sites nutrient loss may:

- slow the growth and ultimately the yield of trees and other plants in subsequent generations,
- reduce overall tree and stand vigour thereby increasing vulnerability to subsequent disease and insect infestation, and
- reduce wildlife habitat and food production.

Site Factors Influencing the Significance of Nutrient Loss

The largest store of nutrients on most boreal sites is found in the organic material of the forest floor and incorporated in the upper mineral soil profile. The boreal forest is often characterized by large accumulations of relatively rich organic material because of the slow rate of decomposition on many sites. Low average temperatures, high soil acidity, and moisture conditions often reduce the rate of microbial decomposition, resulting in most nutrients being unavailable for plant uptake and growth. Historically, wildfire has

Figure 2: Example of nutrient-poor, shallow soil site which is sensitive to nutrient loss.

been the dominant disturbance agent that has restored these nutrients back into circulation. Logging, mechanical site preparation and prescribed fire can cause locked up nutrients to be cycled and made available for plant growth.

Fine textured soils with a clay component are able to hold nutrient cations within the mineral soil profile. This nutrient holding capacity is far less on coarse textured mineral soils such as outwash sand flats, or on sites where the mineral soil is extremely shallow. On these sites, the presence of organic matter represents a critical nutrient sink. The sites where nutrient losses due to forest management practices pose the greatest threat to long term productivity are those which have the least nutrient capital stored in the soil. These include :

- coarse textured sands with very low cation exchange capacity;
- soils with little or no accumulated organic matter and little organic incorporation in the mineral soil profile; and
- very shallow soils, especially where the organic mat may be lost or damaged after forest management (*e.g.*, very shallow soil over bedrock where the organic mat may either dry out and wind erode after logging, or may be removed by mechanical site preparation or prescribed burning).

Nutrient Loss

Description

Hardwood trees tend to be more effective nutrient cyclers than conifers. Hardwood stands typically have a well-developed soil profile with incorporated organic matter. Aspen and birch in boreal forests are able to capture calcium and potassium from deep in the soil and accumulate it for further cycling in tree biomass.

Site history (types, intensity and frequency of disturbances) largely dictates the current nutrient status of a site. Those sites that already have a low nutrient status will be most susceptible to additional depletions by forest operations.

Environmental Factors Influencing Nutrient Loss

The risks associated with nutrient depletion are a function of the amount of nutrient capital on a site and the amount removed by the forest operation; the direct influence of environmental factors on this relationship is limited. Subsequent damage to the site, such as erosion, may exacerbate the impact of nutrient depletion on a site. Factors influencing the potential for subsequent types of site damage may therefore be supplementary factors in determining the magnitude of nutrient loss.

During winter periods, less overall nutrient capital is contained within the upper parts of trees; annual leaf litterfall is complete and some of the trees' food stores and mineral nutrient capital is translocated to the roots. This is especially true for hardwood stands, but less clear for conifers. This nutrient shift within the tree, coupled with an overall reduction in site damage potential, suggests that sites most susceptible to nutrient loss may be better suited to winter harvesting. Season of harvest in this case, however, is far less related to actual nutrient loss than is the type of harvesting.

Rates of decomposition and cycling of nutrients increase as soil temperature increases. On sites with a closed conifer canopy which have not been disturbed for long periods, there can be a considerable accumulation of undecomposed organic matter.

The Impact of Forest Operations on Nutrient Loss

On high-risk sites, forest management operations that displace organic material, such as harvesting and site preparation, may reduce the nutrient capital on the site to the point where long-term site productivity is impacted. Reduced nutrient capital following forest harvesting and renewal operations coincides with the period of highest nutrient demand in the developing crop.

High severity fires or full tree harvesting on high-risk (nutrient poor) sites pose the greatest threats to nutrient depletion. Immediately after fire (wildfire or prescribed burning), there is an increase in available nutrients resulting from the cycling of nutrients locked in undecomposed organic matter. A portion of these nutrients is captured by rapid vegetative re-growth while some is lost due to runoff and leaching.

In general, full tree harvesting poses a greater risk of serious depletion of nutrient capital than do systems that leave limbs and tops in the cutover. Experimental comparisons in northwestern Ontario suggest that full tree harvesting, through its increased nutrient removals, increases replacement times by 10 to 20 years, depending on the macroelement in question (Morris 1997). The most susceptible elements appear to be K, Ca and Mg.

Short rotation forest cropping on sensitive sites may cause nutrient losses in excess of what natural cycles can replace in a single rotation. The potential exists for repeated short rotation harvest cuts to result in a substantial cumulative loss of nutrient capital.

Extremely heavy site preparation (which is no longer normally practised) such as the use of the Martinni plow or the use of summer blading on high risk sites could also result in significant site degradation. Slash and litter piling can remove 6 to 10 times more nitrogen than tree-length logging. The combined effect of nutrient removals due to forest harvesting and nutrient displacement due to heavy site preparation can seriously deplete nutrient reserves on sensitive sites.

Nutrient Loss

Planning

To protect sites from damage due to nutrient loss, it is first necessary to be able to identify those sensitive sites within the landbase. The Forest Resource Inventory stratifies the least productive sites within the landbase on the basis of site index. While not sufficiently accurate for operational purposes, this is a good start at identifying the least productive sites, some of which will be susceptible to damage by nutrient loss. Soils and ecosite maps, and local field knowledge may serve to improve the identification of these sites. The sites which are most at risk to damage from nutrient losses due to forest operations are relatively easily identified. It is more difficult, however to define the line where sites are marginally at risk. The accountability for site damage rests with the forest manager and consequently a conservative and adaptive approach should be taken to managing this issue. At a minimum, the following site conditions should be considered to be sensitive to potential site damage from nutrient loss associated with forest management practices:

- Extremely shallow sites. Sites with a discontinuous mat of organic material and/or less than 5 cm of mineral soil.
- Very coarse textured soils (pure medium to very coarse sands and gravels such as glacio-fluvial outwash plains).
- Soils with little or no accumulated or incorporated organic material. These conditions might be found on sites that were previously subjected to extreme or repeated wildfires.

Silvicultural Ground Rules should address how these sites will be managed to prevent or minimize damage due to nutrient loss. It may be appropriate to separate these sensitive sites by working groups into separate forest units for management purposes with their own allowable harvest calculation and their own customized rotation age which reflects the length of time required to allow nutrient poor sites to recover their soil nutrient equilibrium.

Implementation

Nutrient losses from full tree harvesting are more significant than from tree length or cut-to-length operations since a substantial percentage of the nutrient reserves in a tree are in the small branches and foliage. The use of harvesting techniques that maximize the amount of slash left on site is therefore recommended for nutrient poor site conditions.

The use of winter harvesting on shallow sites that are susceptible to nutrient losses is recommended. Winter harvesting will conserve slightly more mineral nutrients on site and is less likely to cause other subsequent forms of site damage such as erosion, compaction or rutting.

Full tree logging results in vast stores of nutrients being piled at roadside. These slash piles are often burned. In the case of full tree chipping, the debris left is an admixture of bark, leaves and needles which is very rich in mineral nutrients. There is considerable benefit in spreading this chipper debris back over the site despite the rather inefficient methods available to do this at this time. Using a grapple skidder to take a grapple full of debris back with each return trip is one method that is currently being employed. Another option to reduce chipping debris is to tree-length harvest.

Maintaining a diversity of tree and plant species on a site, including a hardwood component, will improve the cycling and capture of nutrient capital. Alder, for example, has a particularly valuable role as a nitrogen fixer. Where possible, maintain some trees and plants on site to act as a nutrient sink to capture mobile nutrient ions made available following harvest and site preparation. This reduces the risk of loss of these ions due to deep, post-harvest leaching. It is important to consider the value of non-crop species as a nutrient sink on sites that have been regenerated with spruce that may take a long time to establish. Herbicide release of slow growing spruces at too young an age (*i.e.*, before they are ready to capture the site) reduces the potential benefits of the non-crop species as nutrient sinks.

Nutrient Loss

Best Management Practices

Nutrient poor sites should be matched with lower nutrient demanding species when these sites are regenerated. In some cases, locally adapted species may be better able to cope with poor site conditions, therefore, good seed source control of regeneration material and or natural regeneration is important.

Direct forest fertilization could theoretically be used as a technique to restore nutrient capital on depleted sites. The economics of forest fertilization is questionable, and the technique is not currently approved under the terms of the *Class Environmental Assessment for Timber Management on Crown Lands in Ontario*.

Monitoring

Effects monitoring is essential to ensure that the landbase is properly stratified and that management strategies are working. Early establishment success is not an effective measure of the maintenance of soil nutrient capital. Signs of nutrient stress include reduced height increment, reduced tree vigour, insect and disease problems, yellowing, delayed crown closure, stand stagnation and poor natural thinning. Forest units that have been identified as being sensitive to nutrient loss should be monitored to assess the effectiveness of treatments.

Table 3: Nutrient loss hazard for soils in Ontario. This table broadly classifies the risk of nutrient loss into three categories (low, moderate, high) based on soil texture, soil depth, silvicultural system and logging method.

Soil Description			Forest Ecosystem Classification Soil Type			Site Damage Hazard Rating		
						Clearcut		Selection and Shelter-wood
Texture	Depth Mineral (cm)	Depth Organic (cm)	Northwestern Ontario	Northeastern Ontario	Central Ontario	Full Tree	Tree Length	
mineral–all	0–5	0–5	SS1, SS2, SS4	SS1, SS2, SS4	SS1, SS2, SS4 (S17)	high	high	mod
mineral–all	0–5	6–20	SS1, SS2, SS4	SS1, SS2, SS4	SS1, SS2, SS4 (S17)	high	high	mod
mineral–all	6–30	0–5	SS3, SS4, (SS5, SS8)	SS3, SS4	SS3, SS4	high	high	low
mineral–all	6–30	6–20	SS3, SS4, (SS5, SS8)	SS3, SS4	SS3, SS4	high	mod	low
sandy	31–60	0–5	SS5, (SS8)	S1, S2, S3, S4, (S15)	S1, S2, S5, S6, S9, S10, S13, S14	high–mod	mod–low	low
sandy	31–60	6–20	SS5, (SS8)	S1, S2, S3, S4, (S15)	S1, S2, S5, S6, S9, S10, S13, S14	mod	low	low
sandy	61^+	0–5	S1, S2, S7, (SS5, SS8)	S1, S2, S3, S4, (S15)	S1, S2, S5, S6, S9, S10, S13, S14	mod	low	low
sandy	61^+	6–20	S1, S2, S7, (SS5, SS8)	S1, S2, S3, S4, (S15)	S1, S2, S5, S6, S9, S10, S13, S14	low	low	low
coarse loamy	31–60	0–20	SS6, (SS8)	S5, S6, S7, S8, (S15)	S3, S7, S11, S15	low	low	low
coarse loamy	61^+	0–20	S3, S8, (SS6, SS8)	S5, S6, S7, S8, (S15)	S3, S7, S11, S15	low	low	low
silty	31–60	0–20	SS7, (SS8)	S9, S10, S11, S12, (S15)	S3, S7, S11, S15	low	low	low
silty	61^+	0–20	S4, S9, (SS7, SS8)	S9, S10, S11, S12, (S15)	S3, S7, S11, S15	low	low	low
f. loamy–clayey	31–60	0–20	SS7, (SS8)	S13, S14, (S15)	S4, S8, S12, S16	low	low	low
f. loamy–clayey	61^+	0–20	S5, S6, S10, (SS7, SS8)	S13, S14, (S15)	S4, S8, S12, S16	low	low	low
organic–fibric	all	21–40	SS9, S11	S16	SS5, S18	low	low	low
org.–mesic/humic	all	21–40	SS9, S11	S16	SS5, S18	low	low	low
org.–fibric	all	41^+	SS9, S12F, S12S	S17	S19	low	low	low
org.–mesic/humic	all	41^+	SS9, S12F, S12S	S18, S19	S20, S21	low	low	low

Notes: Brackets () indicate that these soil types are not closely related to the soil description *i.e.,* they are defined by other soil parameters and may be found on several lines in the table.

1. The category “Tree Length” indicates any logging method that leaves limbs and tops in the cutover.
2. For sandy, shallow soil sites, increase hazard rating one class if sand texture is very coarse to medium.

Site Damage Hazard Rating

Low: Minimal risk of nutrient loss, providing that normal care is exercised during forest operations.

Moderate: Normal operations may cause nutrient loss. The use of Best Management Practices will normally avoid or minimize site damage.

High: Normal operating procedures will cause site damage. Best Management Practices may be able to minimize damage.

Description

In the process of conducting forest operations some productive land is removed from production on a long term or permanent basis as a result of the construction of roads, landings, and as a result of smothering by piles of slash or chipper debris.

Impacts

The removal of productive land reduces the overall productivity of harvest blocks and management units. Unlike other forms of site damage, land loss is a total removal of the affected lands from production rather than a reduction of productivity. It is in the best interest of the forest industry to limit these self imposed losses of productive land to maintain long term yields.

Site Factors Influencing the Loss of Productive Land

The principal cause of loss of productive land is road construction. Landscapes that are dissected by natural obstacles such as ridges, lakes and streams may require a more extensive road network per unit area accessed.

On sites that are only accessible by winter roads, the permanent loss of land to roadbeds is greatly reduced. Highly trafficable sites (*i.e.*, dry coarse textured soils) result in easy road construction with little need for aggregate use or the building of roadbeds. On these sites, the tendency is to build more roads because they are relatively inexpensive to construct. Finer textured soils are usually moister necessitating more extensive roadbed construction, ditching and application of aggregate resulting in permanently non-productive areas.

Sites that have good deep subgrade material enable roads to be constructed with a minimum amount of grubbing. This results in a narrower disturbance area, thereby reducing the amount of land lost to production.

Figure 3: Land loss due to full-tree chipping debris.

The Impact of Forest Operations on Loss of Productive Land

Construction of winter access results in less land loss than all-weather access roads. Upland winter roads can be built with a minimal amount of bulldozing of mineral soil resulting in very little loss of productive area. Lowland swamp roads built in the winter are not permanently lost from production when ground disturbance is minimal.

Roads constructed with a minimal right-of-way on areas with good road building material on site are more efficient in terms of disturbing less land than are roads which are constructed in areas where a bulldozer has to scrape sub-grade material from a broad area to construct a road bed.

All landings result in some loss of productive land due to rutting, compaction and smothering of these sites. Efficiency in the extent of landings can minimize the amount of land lost.

The burning of roadside slash piles helps to recover productive land as does the redistribution of slash or chipper residue. Limbing at the stump in tree length or cut-to-length systems results in less smothering of land by top and limb piles near the roadside. These systems may, however, increase the costs of silviculture and limit the treatment options available. Site preparation techniques that result in the creation of windrows or hummocks of slash reduce productive land. Increasing the effective distance between roads by moving from skidding to forwarding equipment can result in less land being lost to road development.

Loss of Productive Land

Planning

Strategic roads planning is key to minimizing the area lost to access development. It is important to ensure that planning of primary road corridors is done well, as these form the basic gridlines upon which an efficient secondary and tertiary road system can be built.

Use natural boundaries such as major riverways and lake systems to subdivide the unit for planning primary access. Secondary and tertiary roads should be planned as a network. To minimize the amount of road disturbance, ensure that roads are located far enough apart that operators are working at their maximum cost effective skidding or forwarding distance from the road. On very good ground the tendency is to over-access; this approach is very cost effective in the short term but it maximizes long term loss of productive land.

Excessive use of loop turnarounds results in a higher percentage of road area. The road network should be designed to as closely approximate a grid as possible.

Consider opportunities for the use of winter roads in strategic access planning. Where the demands of the silviculture program allow for winter-only access, every effort should be made to adapt the harvesting and delivery schedule to accommodate winter operations and access development. Winter-only access is often a useful tool for resolving tourism/harvesting issues where access is a major concern.

Field Layout

All roads, including tertiary roads, should be planned, then located with ribbon in the field in advance of operations. It is not advisable to allow equipment operators to develop tertiary access within the cut block on their own, without a strategy, as this will almost always result in a less efficient road network (*e.g.*, over-accessing, trespassing, poor locating).

The number and location of landings should be decided upon and communicated to equipment operators before operations begin. Plan the size and extent of landings required; adopting a laissez faire approach to landings will result in more land being used than necessary.

Implementation

The following Best Management Practices will help to minimize the amount of productive land lost due to forest operations.

- Invest in good road location to ensure that roads are as direct as possible.
- Build roads with a backhoe rather than a dozer to minimize width of disturbed area.
- Locate landings on areas of non-productive soil (*e.g.*, bedrock) whenever possible.
- Choose equipment that can maximize the distance between roads (*e.g.*, forwarders may extend the distance between roads in some cases).
- When possible, select cut-to-length or tree length logging systems to minimize the size of slash piles at roadside.
- Soil contamination with fuel and oil is entirely unacceptable. Practice environmentally friendly, zero discharge maintenance and refueling.
- Pile roadside wood as high as safety permits.
- Minimize bush inventory. Haul wood as quickly as possible to minimize the amount of landing area required.
- Wherever possible, site prepare and regenerate tertiary roads, ditches, right-of-ways and landings which will not be in periodic use.
- Do not use site preparation techniques which rely on piling slash in unproductive windrows or mounds unless these will be burned.
- Burn slash piles and redistribute chipper residue piles.

Monitoring

The amount of land lost to roads, landings and slash piles will be significant. Common sense should dictate when techniques employed are resulting in more productive land being lost than is necessary. Road construction, harvesting and silviculture operations should be scrutinized to ensure that minimal disturbance occurs. Minimizing roads and landings may increase logging costs. Therefore, operators need to be informed as to why this is beneficial in the long term.

Description

Water moves through the soil, plants, animals and atmosphere of a forested ecosystem in pathways termed the hydrological cycle. Forest operations may have a negative influence on the hydrological cycle in terms of site productivity and site regrowth in both the short and long term.

Impacts

Typical hydrological impacts resulting from forest operations include:

- *Watering-up:* Removal of tree cover by harvesting (particularly in the clearcut silvicultural system) can result in the water table on some lower land sites coming close to or above the surface of the soil, as the effect of transpiration by trees is reduced or eliminated. This effect is greatest immediately after harvesting. In extreme cases, where this condition persists for several years, poor revegetation and/or substantial changes in plant cover may result (*e.g.*, creation of alder swales or grass and sedge meadows). Watering-up effectively reduces the rooting zone available for plants and trees. On sites where the water table is already at the surface of the soil, harvesting may have the opposite effect and may cause the site to dry out slightly as a result of increased evaporation.
- *Surface drying:* Well drained soils may be subject to excessive surface drying when forest cover is removed, due to greatly accelerated evaporation rates. On some sites, loss of organic material due to the effect of drying winds is possible under these conditions.
- *Disruption of lateral water flow through the soil:* Road construction, rutting and occasionally furrowing resulting from site preparation can cause the lateral drainage/ movement of water in soil to be interrupted or altered. This can result in ponding or other changes in the position of the water table (*e.g.*, strategically placed furrows or ruts can effectively drain some forest sites). The lateral flow of water is a major source of nutrient flow on some sites (telluric flow) and disruption of this flow may result in areas becoming impoverished from a nutrient perspective.

Figure 4: Raised water table resulting from disruption of lateral drainage during harvest.

- *Disruption of infiltration rates in soil:* Soil compaction, rutting and smothering by road and landing construction can effectively reduce or eliminate water infiltration into the soil and thereby impact site productivity. Conversely the removal of forest cover can increase the amount of water which percolates down through soil horizons and therefore can also increase the amount of leaching of nutrient cations which occurs.
- *Increased water yield:* Extensive forest harvesting in a watershed can greatly increase the flow of water through that watershed (*i.e.*, greater stream flow and possibly greater surface flow resulting in potential erosion problems). With increasing water flows, nutrient loading into streams and water bodies is likely to increase to the detriment of cold water fisheries. Spring snowmelt occurs earlier and is more rapid in cutover areas and could result in increased erosion, nutrient leaching and downstream flooding.

Hydrological Impacts

Site Factors Influencing Hydrological Impacts

Sites which have excessively dry moisture regimes and very rapid drainage, and sites which have extremely wet moisture regimes and poor drainage tend to be the most adversely affected by forest operations with respect to hydrological change. For example, areas that are relatively poorly drained because of soil texture or topographic position, will be most prone to watering-up as a result of timber harvesting. Conversely, those sites that are very well drained and dry prior to harvest may experience excessive drying of the soil surface after timber harvest due to increased evaporation rates.

Sites that are susceptible to compaction and rutting, as discussed in the *Compaction and Rutting* fact sheet, are therefore also susceptible to hydrological impacts as a result of forest operations.

Environmental Factors Influencing Hydrological Impacts

Frozen conditions may reduce the influence of forest operations on the lateral flow of water and infiltration rates to the extent that winter operations reduce compaction and rutting. There is no appreciable difference in the impact of winter versus summer harvesting operations on watering-up.

Hydrological changes relate to changes in the potential rates of flow of water through various parts of the forest ecosystem. Changes in precipitation may either exaggerate or reduce the impact of hydrological changes on actual site conditions. These circumstantial changes provide only a short-term respite from the long-term influence of hydrological change.

The Impact of Forest Operations on Hydrological Changes

Forest operations that result in compacted or rutted soil (see *Compaction and Rutting* fact sheet) also result in poorer water infiltration through the soil and impeded lateral movement of water in the soil.

The construction of all-weather roads across peatlands using corduroy or fill can effectively create a dam that interrupts the lateral flow of water in the soil. Even winter roads constructed across peatland areas can effectively limit the flow of water through a bog area for a prolonged period of time. This effect can also occur on upland soils where roadbeds are not designed to allow sufficient cross drainage.

Changes in the height of the water table due to watering-up or excessive drying are hydrological changes which are most exaggerated when sites are cut clear. Modified clearcutting or partial cutting greatly reduces the degree of hydrological change resulting from harvesting.

Water and nutrient yields from a watershed increase proportionately with the amount of area harvested in one cut or in a series of cuts over a short period of time. The effect of large scale cutting on a watershed increases as the slope of that watershed increases, as the depth of soil decreases, and as the rates of infiltration of the soils in the watershed decrease. The upper reaches of watersheds are the most sensitive to hydrological change since slopes are often greatest in this area, and stream beds are narrower and less likely to be able to accommodate increased flows. If a small valley containing the headwaters of a feeder stream is completely clearcut then the impact on that part of the watershed will obviously be very great (*i.e.*, greatly increased water and nutrient flow, erosion, siltation) even though the effects felt at the bottom end of the watershed may be negligible.

The faster a site is revegetated, the faster normal hydrological flows and processes will resume. Vegetation management that is used to promote a slow growing conifer species at the expense of more rapidly growing species, can prolong the period that site hydrology is impacted following forest harvesting.

Site productivity on some organic soils can be significantly increased through the use of peatland drainage. Drainage is not currently approved under the terms of the *Class Environmental Assessment for Timber Management on Crown Lands in Ontario*.

Hydrological Impacts

Best Management Practices

Planning

As with most types of site damage, the key to avoidance is recognizing those sites that are sensitive to disturbance. Sites most sensitive to negative hydrological change are those "excessively" moist to wet peatland or mineral soil sites. Most of these sites will also be sensitive to rutting and compaction disturbance and could possibly be stratified for management planning purposes into separate forest units. Modified clearcutting (*e.g.*, strip cutting, group seed tree harvest, careful logging around advance growth) should be examined in the Silvicultural Ground Rules for wet peatland areas. If modified clearcutting techniques are considered, the impact on the allowable harvest must be considered in the preparation of the management plan. Where silviculturally appropriate, selection and/or shelterwood harvesting greatly reduces the impact of harvesting on the water table.

The development of allocation strategies should consider the impact of harvesting on water yield at the watershed level. A general rule of thumb is to harvest no more than 50 percent of the watershed in a single operation or over several operations, where the previously cut areas have not yet reached free-to-grow condition (Plamondon 1993). Pay particular attention in the upper reaches of watersheds where topography is rolling or hilly (*i.e.*, where slopes are commonly in excess of 10 percent).

Implementation

The following Best Management Practices should be considered in order to protect sites and ecosystems from damage due to hydrological change:

- The overall degree of harvesting in a watershed should be considered when areas are selected for harvest. Where greater than 50 percent of a watershed is planned for harvest during a five-year management plan term or where cumulative cutting (harvested areas not yet free-to-grow) will include more than 50 percent of a watershed, the issue of water yield should be addressed in the management plan.
- On sites which are sensitive to hydrological change (*i.e.*, wet organics and extremely xeric sites), modified clearcutting techniques should be considered, including the use of strip cutting, preservation of advance growth and reduction in the extent of cut blocks.
- On very dry sites, the retention of some trees, shrubs and even slash can reduce overall ground temperatures and therefore control excessive drying.
- Adherence to the Best Management Practices outlined in the *Compaction and Rutting* fact sheet will lessen changes to water infiltration rates and rates of lateral water movement of water through the soil.
- Both the placement and methods used in the construction of forest access roads should be sensitive to potential changes in hydrology. Roads built in upland areas should have sufficient cross drainage to allow for surface or subsurface flow of water. This is especially true where roads are constructed on midslope positions. Locations of springs and intermittent streams should be considered in road construction. All-weather roads built across peatlands may significantly disrupt internal drainage. Roads should be located to minimize this effect, with drainage culverts used to prevent ponding.
- Landings should be located so that skidding traffic is not forced to cross and disrupt natural drainage patterns.
- Sites should be reforested as quickly as possible.

Monitoring

Forest operations must be monitored for hydrological change in order to design future management programs and to ensure that Best Management Practices are being applied. Removing trees will inevitably alter hydrological cycles (particularly in the clearcut system) as will natural disturbance events. Past harvesting practices which resulted in the watering-up of lowland mineral soil areas and peatlands have resulted in regeneration periods for black spruce which are, in some cases, unacceptably long.

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Appendix 1 Characteristic Soil Types for Forested Ecosites in Northwestern Ontario*

Ecosite	Characteristic Soil Types
ES11, ES12	SS1–SS4, SS5, SS9
ES13, ES14, ES15, ES16	S1, S2, SS5
ES17	S3, S4, S6, S9, S10, SS7
ES18, ES21	S3, SS6
ES19, ES20	S1–S3, SS5, SS6
ES22, ES23	S7, S8, SS8
ES24, ES25, ES27, ES28, ES30	S4, S5, SS7
ES26, ES29	S5, S6, SS7
ES31, ES32, ES33	S9, S10, S11
ES34, ES35	S12S, S12F
ES36	S12S, S12F, S11
ES37	S12S, S12F, S11
ES38	S9, S10, S11

* adapted from Racey *et al.* (1996)

Appendix 2 Percentage of Soil Type by Site Type in Northeastern Ontario*

Soil Type

Site Type

	SS1–4	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19
1	89																			
2a		15	11	3		10	33	5												
2b		24	11	10		3	8													
3a										12	7	17	11			3				
3b		34	39	20	11	43	25	35												
4		13		37	44	7	8	12	20											
5a														17	14					
5b										4	20	7	15							
6a														30	31	3				
6b										19	20	7	33							
6c		15	36	13	33	20	25	23	20							3				
7a														49	31					
7b										35	47	31	15			16				
8				3	11			9	20						6	3	44			
9			4					7	40			10	22		9	20	44			
10				10				5		4	7	7	4	4	9	57	13			
11																		38	9	27
12																		33	27	17
13																		16	50	57
14																		14	14	
15	11					10		2		12		10				3				
16				3		7		2		15		10				3				

* adapted from McCarthy *et al.* (1994)

Appendix 3: Percentage of Soil Type by Ecosite in Central Ontario*

Soil Type

Site Type	SS1–SS4	SS5, SS6	S1–S4	S5, S9	S6, S10	S7, S11	S8, S12	S13, S14	S15	S16	S17, S18	S19–S21
26.1	14		86									
26.2				10		70	20					
25.1	32		68									
25.2	3				11	82	5					
24.1	27		73									
24.2				3	9	77	9		3			
23.1	33		67									
23.2	6					77				18		
35			11		11	41	5	3	5	22		3
34	2		5		3	16	2	8	26	10	3	25
29.1			100									
29.2				5	8	73	5	3	8			
27.1	13		87									
27.2	1			10	9	54	6	8	5	5		
28.1	11		89									
28.2				2	9	81	1	1	3	2		
30.1	28		72									
30.2				5	13	64	5	4	5		2	2
17.1	9		91									
17.2	3			3	10	62	7		10	3		
18.1	16		84									
18.2	2			5	11	58	7	4	5	9		
19.1	9		91									
19.2					22	72			6			
20.1	18		82									
20.2					27	47		13	7	7		
21.1	41		59									
21.2					25	38		6	6		6	19
14.1	27		74									
14.2				2	9	80	7			2		
11.1	28		73									
11.2	4			31	24	35	3	1		1		
12.1	12		88									
12.2				19	15	63		4				
13.1	55		45									
13.2				14	29	50				7		
32			2		4	7		2	2	2	6	76
22	24		17	7	7	45						
33		3						11	24	8	5	49
16.1	59		41									
16.2	8	4			12	42		12	15			8
15.1	42		58									
15.2	7				7	36		21	21		7	
31	4				4	11			7		14	61

* adapted from Chambers *et al.* (1997)

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