SOIL RECONSTRUCTION DESIGN FOR THE RECLAMATION OF OILSANDS TAILINGS

Prepared for

Oilsands Environmental Study Group

And The

Reclamation Research Technical Advisory Committee

of the

Alberta

Land Conservation and

Reclamation Council

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FOREWORD

This report contains the result of a study jointly financed by Alberta Environment, Petro Canada, Suncor Inc., Alsands Project Group, Syncrude Canada Ltd. and the Oil Sands Environmental Study Group.

The objective of the study was the definition of physical and chemical soil properties required to support the forest ecosystems which are the targets of oil sands tailings reclamation research in the Athabasca region, Alberta.

We wish to thank Dr. K.A. Armson of the Ontario Ministry of Natural Resources and Dr. T.M. Ballard, Faculty of Forestry, University of British Columbia for their review of the Manuscript and their valuable suggestions.

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INTRODUCTION

CHAPTER 1 - INTRODUCTION

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1.1 NORTHEASTERN ALBERTA: ITS OIL AND ECOLOGY

The environment of northeastern Alberta is hostile. The winters are long and cold, frosts have been recorded in every month of the year, and average winter temperatures are less than 20°C. The summers are short - there are less than 95 days of growing season between June and August - and relatively dry: although annual precipitation amounts to 40 cm, total potential evapotranspiration is estimated to be 48 cm.

The native vegetation of northeastern Alberta consists primarily of poplar, aspen, white and black spruce and jack pine. The treed landscape is dotted by muskeg bogs - water laden depressions which contain partially decayed vegetation to a depth of five metres. Overall, northeastern Alberta forms a part of the boreal forest region of Canada.

In spite of the harsh climate and limited merchantable timber resources, the federal and provincial levels of government in Canada and some of the largest companies of the world are investing billions of dollars to locate an oil extraction industry along a short stretch of the Athabasca River near Fort McMurray (Plate 1-1).

The ore deposits are known as "oilsands" or "tarsands" and contain a viscous, crude bitumen that must be mined or treated thermally before it can be extracted. Even though the extraction costs are high the Alberta enterprise is a forerunner of new technology to be applied to world oil production and processing. Heavy oils make up half the world's known petroleum reserves, and the Alberta oilsands contain one trillion barrels in the ground, six times the Saudi Arabian pool of conventional oil (Maugh 1980). North and South America have 99% of the world's remaining reserves of conventional crude.

Oil production in northeastern Alberta today centers around a pioneer plant started in 1969 by Suncor (formerly Great Canadian Oil Sands Limited), recently expanded to extract 55,000 barrels per day, and a much larger (150,000 barrels per day) plant owned by the province of Alberta and a consortium of oil companies, known collectively as Syncrude.

Mining the oilsands and extracting the heavy bitumen product involves the removal of the vegetation, soil and unweathered geological material (overburden) above the mineral deposits and moving the oilsands by means of draglines, buckwheel excavators and conveyor belts to the extraction plant in the same area. In the case of the muskeg deposits the depressions must be drained and the organic and mineral overburden removed to mine the oilsands below.

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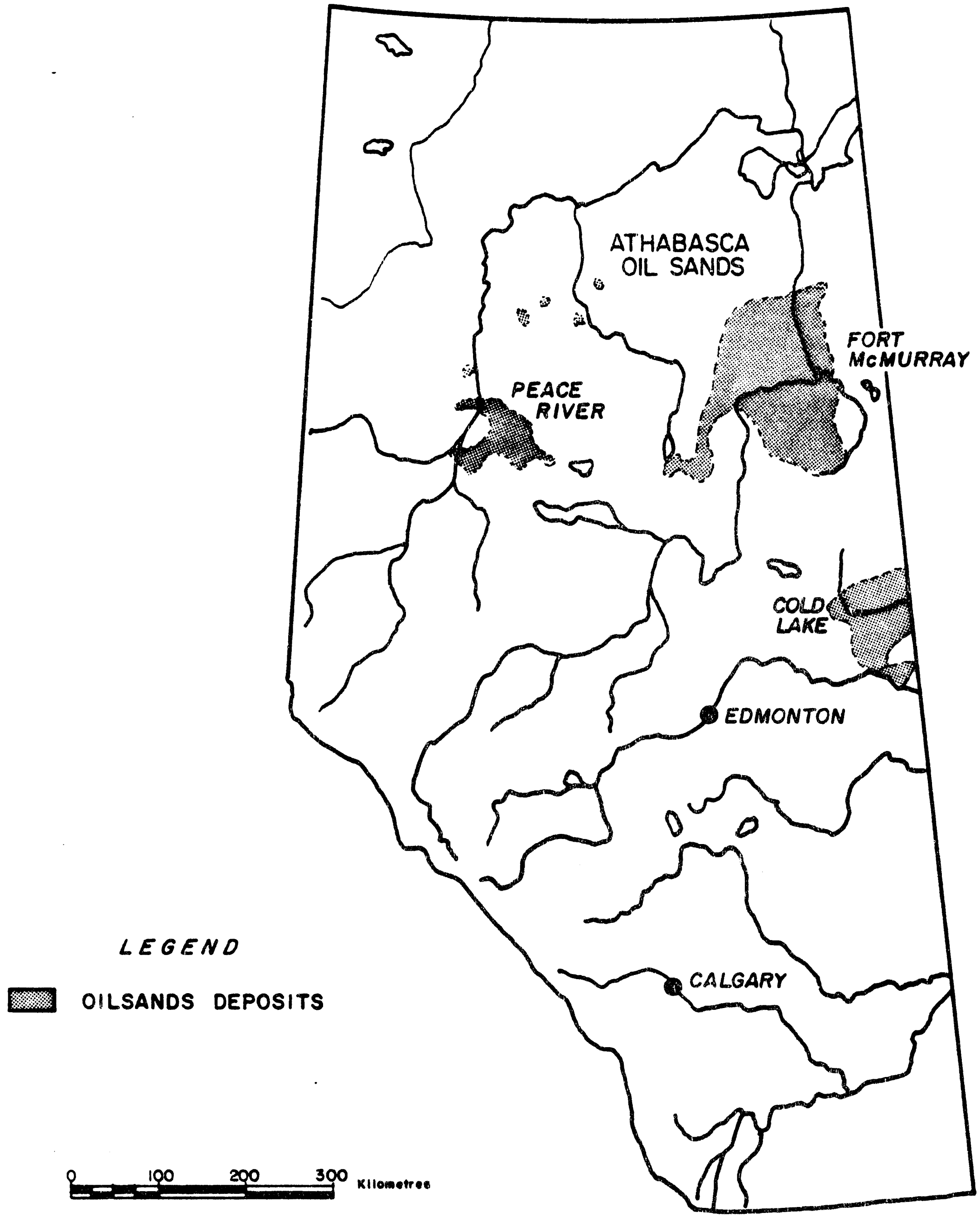

PLATE I-I

THE LOCATION OF MAJOR OIL SAND DEPOSITS
IN NORTHEASTERN ALBERTA, CANADA

1.2 THE RECLAMATION OF OILSANDS

This report is concerned with the question of the reclamation of northeastern Alberta after the oil has been extracted. The landscape is drastically disturbed: instead of a dissected morainal plain containing rivers, bogs, jack pine and mixedwood forests, there are now massive sand plains, earthern dikes to contain tailing water and storage piles of peat and mineral overburden. The goal in reclaiming the oilsands is to re-establish soils and vegetative communities which will interact to develop into self-maintaining ecosystems.

Ecological self-maintenance is used in this study to signify the achievement of biological and physical equilibrium whereby specified plant communities develop and progress to maturation without the input of additional nutrients, water (excepting precipitation), seeds or seedlings. Furthermore, self-maintenance, in this context, means that the ecological system will be designed to recover from infrequent, naturally-occurring environmental disturbances such as fire, floods or drought without need for outside intervention. It is expected that the soil properties in general will change slowly, especially the parts of the soil profile below the surface horizon; on the other hand vegetation is expected to change rapidly, both in terms of population diversity and the maturation of each species.

The specific objectives of this study are to review the relevant scientific literature with the intent of defining, with supporting arguments, the following:

1. The minimal physical and chemical properties required of a soil reconstructed from tailings sand, peat and overburden which will evolve to support:

    a) a self-maintaining, erosion-controlling vegetation for dike slopes;
    b) a self-maintaining, erosion-controlling, mixedwood boreal forest with a mean annual increment of at least 1.4 m^3/ha/year; and
    c) a self-maintaining, erosion-controlling, jack pine forest of low productivity on flat and gently rolling areas.

2. To identify weaknesses in the supporting arguments developed under objective 1 and to recommend studies which would strengthen those arguments.

This study is based on the existing literature; it does not report the results of any experimentation conducted by the authors. The study does include the results related to oilsands reclamation research conducted by government agencies, universities, privately owned oil companies, consulting groups and private individuals. In addition, the relevant literature from forest and grassland ecology and soil science has been incorporated.

1.3 STRATEGIES FOR SOIL RECONSTRUCTION AND REVEGETATION

The ordering of soils and vegetation information into a workable plan of landscape reconstruction and revegetation means that specific strategies for each component are necessary. For instance, it is possible to think of several means of using mineral overburden, tailings sand and peat to construct a soil. Tailings sand can be mixed with mineral fines in the overburden and subsequently covered with a uniform layer of peat, or mineral overburden and peat can be pre-mixed and laid down over the sand so that the major part of the root zone has a low sand content. But there are theoretical and practical limitations to each alternative. Rather than discuss the various possibilities for soil reconstruction procedures and revegetation techniques, this study has selected an appropriate strategy and used it throughout. A more detailed description of each strategy follows.

1. Soil Reconstruction Strategy

The soils for all three vegetation types are designed to perform three essential functions in relation to plant establishment and growth:

a) store and supply sufficient moisture within the rooting zone;
b) yield an adequate supply of nutrients; and
c) provide a physically stable (non-eroding) medium for growth.

The choice of properties and depth of root zone materials is critical to the successful performance of each function. Furthermore, each plant community has somewhat different requirements in terms of water and nutrients; and, because the three plant communities are assigned to distinctive topographical positions, each will have different soil requirements for the prevention of erosion.

The materials available for use in soil reconstruction - mineral overburden, peat and tailings sand - are assumed to be homogeneous. Therefore, the individual requirements for each plant community will be satisfied by varying the depth and mixture of materials.

For purposes of this study the soil reconstruction strategy will consist of constructing the required depth of root zone material (above an underlying massive body of uniform tailings sand) from a homogenized mixture of selected quantities of mineral overburden, peat and tailings sand. In practical terms this means that a tailings sand surface will be graded to conform to the topographical structure designated to each plant community. A certain quantity of peat and mineral overburden will then be distributed in even layers over the surface and, finally, the three materials will be mixed uniformly (rotovated) to a predetermined depth.

The particular choice of soil reconstruction strategies made for this study is not capricious; there is a small body of empirical evidence from reclamation trials in the oilsands area that shows that erosion control and plant growth are enhanced by mixing all three materials together, rather than by layering the root zone with individual material types (Rowell 1977, Logan 1978).

2. Revegetation Strategy

a) Dike Slope Vegetation

Dike slopes composed of mineral fines and tailings sands must support at all times a stable, erosion-controlling vegetation. Because of the high erosion potential of these materials, it is important that they are stabilized quickly. Consequently, a vegetative cover of grasses and legumes is recommended. In this way effective erosion control is achieved in the first season. Other reasons for utilizing grasses and legumes include:

- i) grasses provide a more continuous ground cover than trees or shrubs;
- ii) wind-throw and die-back of trees and shrubs could lead to rill and gully erosion on the slopes;
- iii) berm security is more easily monitored under a vegetative cover of grasses and legumes.

When the grasses and legumes are established and the tailings sand stabilized, other local plant species may invade. This is expected to result eventually in natural processes of vegetative succession.

b) Jack Pine Forest

The jack pine forests will be established in areas of gently undulating topography on sandy materials. A stabilization strategy similar to that for dike slopes is recommended. After seeding grasses and legumes the first year, jack pine seedlings are introduced in vegetation-free areas (circles) during the second year. This practice can provide initial stabilization of the whole area and aid in the prevention of "gullying" and rill erosion between the tree seedlings. A higher tree survival rate is expected when competition for moisture is reduced (by controlling undergrowth), and root exposure due to soil washout is minimized.

The resulting vegetation type is jack pine with a grass and legume understory. Planting of the usual understory species associated with jack pine stands, i.e. Arctostaphylos uva-ursi and Vaccinium vitis-idaea, is not recommended. These species may invade if the conditions become favourable.

c) Mixedwood Forest

The strategy for establishing a mixedwood forest is based on three considerations:

i) the mixedwood forest must achieve a minimum productivity of 1.4 m^3/ha/year by the end of its rotation (assume 80 years);

ii) mixedwood soils contain higher contents of silt and clay (fines) and, therefore, there is less chance of a moisture and nutrient deficit throughout the year; and

iii) although a higher fines content normally means an increase in erosion potential, mixedwood sites are planned for low gradient slopes where erosion hazards are minimized.

It is recommended that aspen poplar and white spruce be planted in the first year. Rosa acicularis, a common shrub of mixedwood forest, is interplanted to provide additional ground cover. Planting densities will be high in order to achieve the base level of productivity and to ensure protection against erosion without a grass understory.

The strategy of mixedwood establishment proposed above signifies a high level of soil and forest management, but the requirements should decrease quickly when an adequate tree population is attained.

1.4 IMPORTANT ASSUMPTIONS

The key assumptions used to limit the scope of this study were:

1. The definition of the three vegetative associations was based on a general description taken from the existing literature. The plant community as a whole, not any individual species within the community, provides the basis of description.

2. Conditions and materials were "generalized" to exclude the influence of such things as:

a) the heterogeneity of local materials (peat, tailings and inorganic overburden);
b) the occurrence of slimes or sludges in the processed tailings;
c) the accumulation of toxic elements in sloughs or seeps (e.g. excess salinity);

d) microclimatic variation due to topography, aspect, slope, etc.; and
e) plant emissions (e.g. sulphur).

3. It will be assumed that there will be no significant addition of chemicals to the tailings that will affect revegetation.

4. The definition of engineering a soil from local materials with desired properties will not consider the actual availability (surface area) of those materials in the oilsands area.

1.5 SUMMARY OF REPORT COMPONENTS

The main body of the report is comprised of six components:

1. the oilsands environment;
2. plant communities and associated soils;
3. starter soils on tailings sand;
4. the development of reconstructed soils over time;
5. a summary of major findings and conclusions; and
6. a list and discussion of recommendations for further research.

The first two components are combined to explain the kinds of soil and geo-materials found in the oilsands area prior to mining, and the functional role of soil in supporting the existing vegetation. Climatic factors are quantified to clarify the requirements of plant survival and how the soil acts as a mediator in regulating plant growth.

The definition of the minimal physical and chemical soil properties necessary for the initial establishment of three vegetation types incorporates two basic considerations:

1. The differences in the major properties needed for each vegetation community; and

2. The definition of a starting point that can develop with time into a stable ecosystem capable of self-maintenance.

The first consideration necessarily includes an analysis of how sufficient water and nutrients are made available to the plant community. It also requires an analysis of how special problems, such as water erosion on dike slopes, are best avoided by the correct selection of materials and management techniques.

It is desirable to limit management inputs to the first few years. The initial soil properties are expected to evolve over time in accordance with the development of the vegetation to supply adequate levels of nutrient elements and water and to prevent erosion and soil degradation. The fourth chapter, the development of reconstructed soils, shows how the information on the genesis of natural soils can be brought to bear on soil development in the oilsands area. The changes in pH, organic matter accumulation, and nutrient cycling are predicted from previous experience and study of the interrelationship between plant succession on similar soils with comparable climatic patterns.

Chapters 5 and 6 provide the conclusions and recommendations for further research. The conclusions summarize the requirements of each vegetation-soil complex. Chapter 6 identifies conceptual assumptions and information deficiencies and recommends specific studies to strengthen them.

1.6 DATA VARIABILITY AND INTERPRETIVE DIFFICULTIES

The natural complexity and variability of forest ecosystems make this report a first stage in the eventual formulation of a complete reclamation plan for the oilsands area. There are basically two aspects of data collection and interpretation which create uncertainties in regard to definitive conclusions: first, the disciplines of forest ecology and edaphology cover widely diverse biological and geochemical phenomena; second, sampling, analytical and interpretive methodologies for ecology are not well-established.

In terms of the diversity and complexity of the vegetation and soils in forest ecosystems, several qualifying considerations must be accounted for in data interpretation:

- there are numerous factors operating on both plant and soil that affect the measured response, therefore each function is a multiconditioned process;

- the environment is extremely heterogeneous; there are marked spatial and temporal variations which should be taken into account and spatial variation shows vertical and horizontal stratification;

- the environment is dynamic, and the rate of change, the duration of particular intensities and the extreme values are all important aspects of data interpretation;

- the requirements of a plant vary at different stages of the life cycle and the requirements of vegetative communities vary in relation to the diversity of species, stage of maturation and state of soil development.

The problem is complex when one considers only the reasons for caution in data analysis listed above. However, plant ecology and soil science are young disciplines and consequently are still developing acceptable tools of sampling and analysis. The main weaknesses influencing the quality of data reported upon in this report are:

- the lack of specificity of sampling design used in the original collection of the data; bias is often introduced under the guise of a lack of trained personnel, time, finances or an understanding of valid sampling techniques;

- the differing analytical procedures used in the field or laboratory for plant, soil or meteorological characteristics; for example, "available" phosphorus may be the variable under study, but the method of extraction and analysis can cause enormous differences that go undetected because methods are often unreported.

A careful, complete information search has been executed to provide the data base for this study. The cautionary notes on the complexity of forest soils and forest communities and the sampling and analytical difficulties encountered are meant to qualify the tone of certainty of the remainder of this document. This material - however incomplete - represents the state of reclamation knowledge applied to northeastern Alberta today.

CHAPTER 2

COMPONENTS OF THE EXISTING ENVIRONMENT

CHAPTER 2 - COMPONENTS OF THE EXISTING ENVIRONMENT

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2.1 OILSANDS ENVIRONMENT

211 INTRODUCTION

This section characterizes the oilsands environment by analyzing the two most important parameters which affect plant establishment and growth after reclamation: the water balance and the properties of the materials available for soil reconstruction. The first is subject to the temperature and precipitation regimes of the area and functions in relation to the rooting depth of the established plant cover. The second, soil materials and their properties, is divided into chemical and physical characteristics. Successful soil reconstruction will be based on a knowledge of these properties, the requirements of an initially established vegetative cover, and the interaction over time of the mixture of materials and growing plants.

212 WATER BALANCE

The potential problem of an excess or deficiency of water in the reclamation of the oilsands is related to the weather and to the reserves of plant available water in the soil. An overview of water dynamics in the soil-plant-atmosphere system includes components associated with the soil water reservoir, its depletion and replenishment, and the efficient use of water for plant establishment and vegetative productivity.

Accurately evaluating the available soil water reservoir is vital to optimizing the processes of materials handling and soil reconstruction in areas within marginally dry climatic regions. Water can drain out of the root zone, and not all the water remaining in a drying soil can be taken up by the plant as rapidly as it is needed because it is held too tightly by soil particles.

The methods of determining the capacity of the soil water reservoir and the demand made upon that reservoir by the vegetation are not exact, but the concept has evolved into calculations of "water balance" and its effect on plant growth.

In this study, a simply expressed model of water balance will be employed (Thornthwaite and Mather 1957), based on climatic and soils information collected from the Fort McMurray region. In its most general form, this model may be expressed as:

$$P = ET + R + D$$

Where: P = precipitation;
ET = evapotranspiration;
R = surface runoff; and
D = drainage through the soil (modified from Verma 1968).

"Water balance" refers to the balance between the income of water from precipitation and the outflow of water by evapotranspiration and drainage. From a comparison of the seasonal averages of precipitation and evapotranspiration, the magnitude of other related moisture parameters - water surplus, water deficit, water runoff, drainage and changes in soil moisture storage - can be estimated.

There are more recent models of soil water balance which yield more precise results. For example, the American Society of Civil Engineers (1973) evaluated the accuracy of many equations for estimating maximum evapotranspiration when the supply of water is unlimited. These included energy balance and aerodynamic equations, humidity- radition- and temperature-based equations. The well known combination equation of Penman (Penman and Schofield 1951) resulted in estimates with the least error. A more recent calculation of maximum evapotranspiration based on the correlation with equilibrium evaporation was formulated by Priestly and Taylor (1972). The concept of equilibrium evaporation has been used in water balance modelling of forested ecosystems at the University of British Columbia (Spittlehouse and Black 1981, Spittlehouse 1982). A similar radiation-based equation for estimating maximum evaporation was developed by Jensen and Haise (1963) and has been used to calculate the water balance in the plains areas of the United States (Wright and Hanks 1981, Rasmussen and Hanks 1978) and Canada (de Jong 1974).

Although there are several excellent models available for use in water balance calculations, the requirements for meteorological data are complex and are based on short time periods. Given the paucity of meteorological information in the oilsands area and the unavailability of short-term averages, the use of the Thornthwaite model is deemed most appropriate.

The calculations for evapotranspiration and a resulting water balance derived from the Thornthwaite and Mather (1957) method have several limitations:

- evapotranspiration values are valid for monthly and yearly periods but incorporate large errors for shorter time periods;
- monthly temperature and precipitation averages used by this method can ignore important daily fluctuations and rainfall events;
- potential evapotranspiration values are determined from heat indices which do not include the low values for Fort McMurray, and therefore calculated potential evaporation should be regarded as a maximum (Hackbarth and Nastasa 1979); and
- potential evapotranspiration calculations are valid only for regions (mostly temperate) where temperature and radiation are strongly correlated (van Bavel 1956, Sanderson 1949, 1950; cited in Verma 1978).

The remainder of this section on water balance calculations discusses the representative values of climatic variables from the oil-sands area for use in the Thornthwaite and Mather model. Although these calculations are normally applied to regional hydrological problems, this report uses additional information concerning runoff and drainage to estimate specific characteristics of water balance in soils.

.1 Climate

Climate is the driving force of the hydrological cycle. Temperature and moisture may be considered the most important climatic factors in terms of water balance. A study of their seasonal distribution yields information pertinent to limiting conditions of growing season, water availability, and evapotranspiration.

Temperature

The study area is one of the coldest areas in Alberta with a mean annual temperature of -0.5°C. Mean monthly temperatures and mean maximums and minimums with 10 and 90 percentiles of hourly values are given in Figure 2-1. Only one recorded observation in ten shows hourly temperatures above or below the 90th and 10th percentiles. December and January have the greatest range of temperatures, approximately 42°C, while July and August have the most restricted range, approximately 25°C (Longley and Janz 1978).

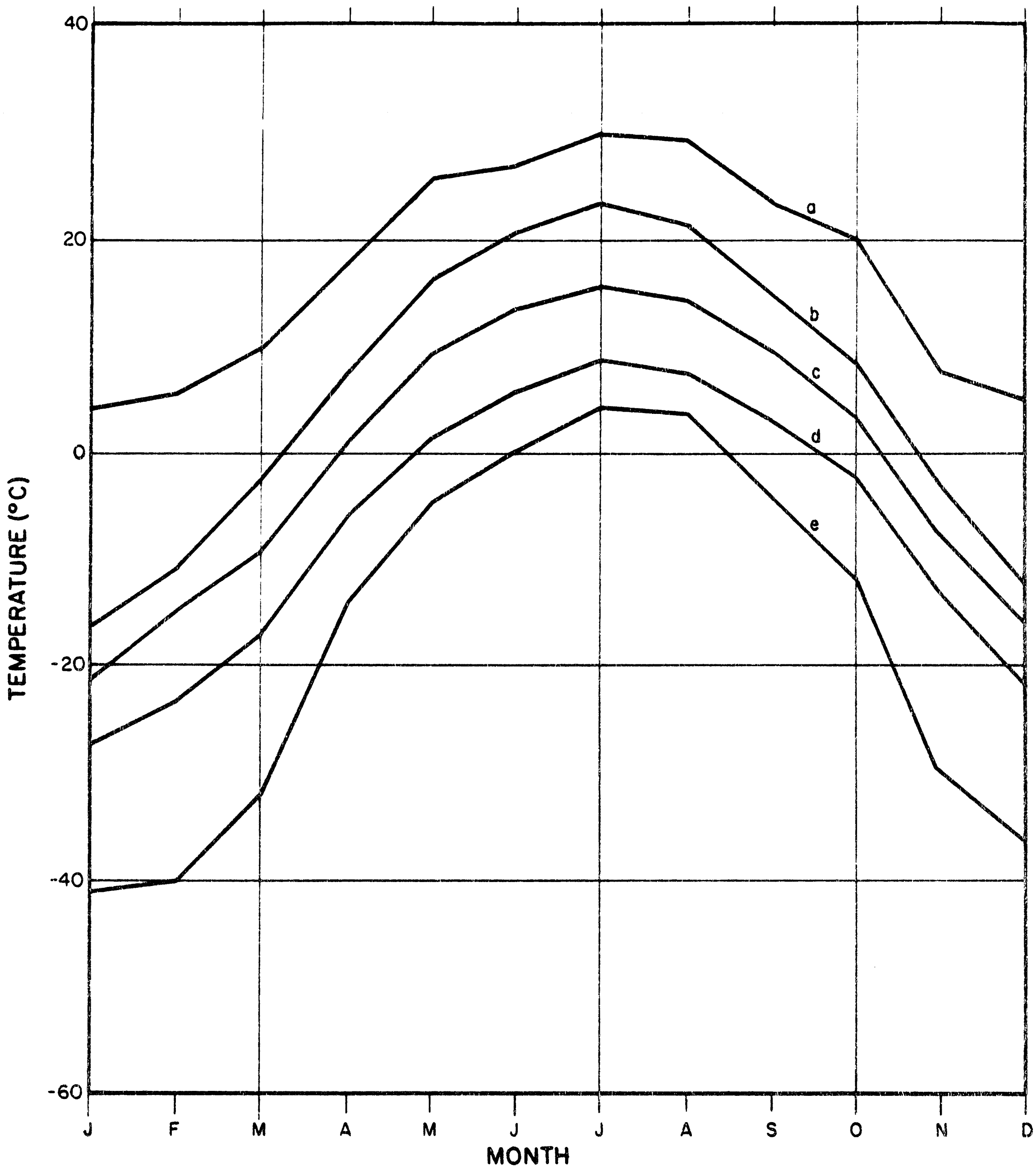
The average frost-free period at Fort McMurray lasts from 15 June until 25 August, or 69 days (Longley and Janz 1978). The shortest frost-free period on record is 8 days, from 9 to 18 July; the longest is 115 days, from 24 May to 17 September.

Precipitation

The mean annual precipitation at Fort McMurray (1951-1977) is 488 mm with a standard deviation of 95 mm (Figure 2-2).

The average annual snowfall is 139.7 cm with a mean snow cover of 46 cm (Longley and Janz 1978). Indications are that both snowfall and rainfall increase with elevation. In general, the snowpack is deeper during middle and late winter at the higher elevations. Snowmelt starts during the end of March and the snow is usually gone by mid-June (Niell and Evans 1979).

The frequency of storm occurrences, their intensities, durations and rainfall amounts are necessary for runoff predictions, drainage design and erosion control. Storr (1963; cited in Longley and Janz 1978) has determined the highest one-day rainfall that occurs for return periods of 5, 10, and 25 years (Table 2-1). July has the greatest rainfall.



a. 90th PERCENTILE OF HOURLY VALUES, 1957-1966

b. MEAN MAXIMUM, 1941-1970

c MEAN MONTHLY, 1941-1970

d MEAN MINIMUM, 1941-1970

e 10th PERCENTILE OF HOURLY VALUES, 1957-1966

DATA SOURCE: ENVIRONMENT CANADA 1975a

FIGURE 2-1

MONTHLY TEMPERATURES AT FORT McMURRAY

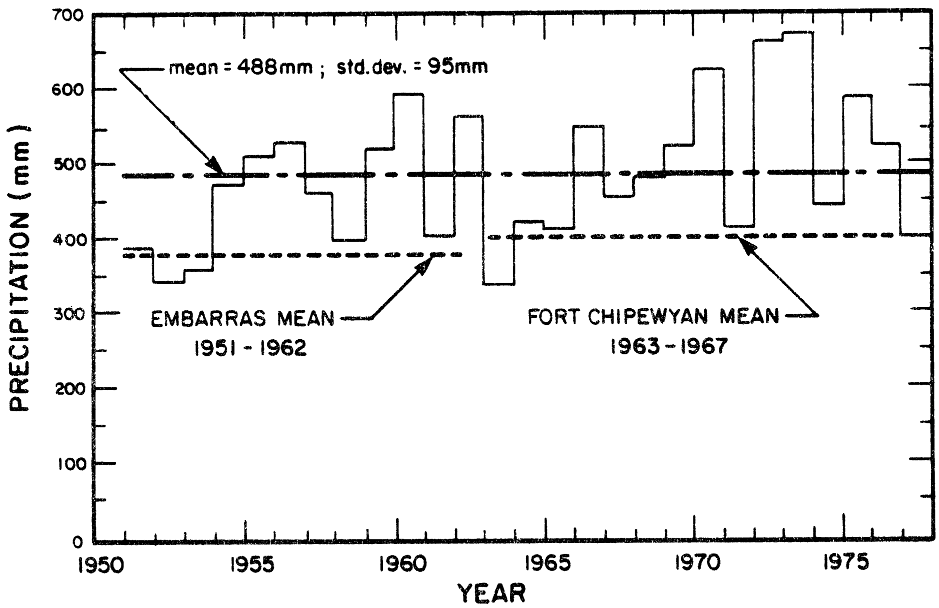


FIGURE 2-2
VARIABILITY OF ANNUAL PRECIPITATION
AT FORT McMURRAY

TABLE 2-1

Maximum One-Day Rainfall
In Fort McMurray

Return Period	May	June	July	August	Season
yrs.			mm		
5	18	25	37	33	50
10	24	32	51	46	64
25	32	41	71	64	81

SOURCE: Longley and Janz (1978)

.2 Evapotranspiration

The effect of the interaction of moisture and temperature on vegetation is best measured as evapotranspiration. Evapotranspiration may be defined as the combined loss of water due to evaporation from the soil and transpiration from plants. Definitions of the various terms involved with the determination of evapotranspiration by the Thornthwaite and Mather method are given in Table 2-2.

Potential evapotranspiration uses air temperature and day length to express a theoretical water demand of the vegetative cover. If the potential evapotranspiration is greater then precipitation, a soil water deficit will occur, and actual evapotranspiration will be less than the potential. If potential evapotranspiration is equal to or less than precipitation, no soil water deficit will occur, and actual evapotranspiration will equal potential evapotranspiration.

In the case of potential exceeding actual evapotranspiration, the amount of the latter is dependent on five factors:

- potential evapotranspiration as determined by temperature and day length;
- the difference (in millimetres of water) between potential evapotranspiration and precipitation;
- the amount of available water left in the soil;
- the ease with which this water may be extracted by the plant; and
- the rooting depth.

The primary factors contributing to potential evapotranspiration are external climatic inputs: temperature, solar radiation, time of the year and the latitude; secondary factors are atmospheric advection, surface roughness and soil thermal properties (Hillel 1980). Most approximations only consider the primary factors.

Actual evapotranspiration is generally a fraction of potential evapotranspiration and depends upon the density of plant cover, the soil moisture content, the availability of the soil moisture and the root distribution. Since the total soil water content is not accessible to plants, an estimation of available water content is necessary for an estimation of actual evapotranspiration (Thornthwaite and Mather 1957). For purposes of this report, available water in sandy materials will be the difference in soil water content at -15 bars (permanent wilting point) and -1/10 bar (field capacity). Actual measurements in sandy materials in the oilsands area show the difference to be approximately 7.5% (MacLean 1980). An explanation and justification of these figures are given in the section on soil water balance (page 2-12).

TABLE 2-2

The Definition of Terminology Used to Calculate Water Deficiencies in Accordance with a Method Proposed by Thornthwaite and Mather (1957)

Term	Abbreviation	Definition
Potential evapo-transpiration	PE	The amount of moisture, when it is unlimited, that can be transferred from the earth's surface to the atmosphere.
Actual evapo-transpiration	AE	The actual amount of moisture transferred from the earth's surface to the atmosphere.
Precipitation	P	The measured annual precipitation.
Available soil water	AW	The amount of moisture (%) held by the soil which can be absorbed by a plant cover. This amount of moisture is conventionally expressed as the difference in soil water content at 1/10 bar and 15 bars, corresponding to field capacity and permanent wilting point respectively.
Soil moisture storage	ST	The amount of available water stored in the soil (mm) to a given depth.

A series of annual calculations of various components of water balance in the oilsands area of northeastern Alberta is presented in Table 2-3. Potential evapotranspiration is estimated in three ways: open lake evaporation multiplied by a terrain coefficient; recorded pan evaporation multiplied by a "pan" coefficient; and the Thornthwaite and Mather method as explained earlier. Actual evapotranspiration is either a Thornthwaite and Mather (1957) calculation or a derived value obtained by subtracting runoff from precipitation. The latter method estimates actual evapotranspiration as the difference between watershed precipitation and water lost through stream flow (Niell and Evans 1977).

There is a recognizable conformity in evapotranspiration estimates for all methods. Potential evapotranspiration ranges from 471 to 531 mm/yr; actual evapotranspiration estimates range from 370 to 430 mm/yr. The water balance calculations show a potential deficit of 82 mm for a warm year (1980) to a surplus of 99 mm in a cool year. The average water budget over 20 years, however, shows a deficit of 37 mm/yr.

Monthly values of water balance components, as calculated by the Thornthwaite and Mather method, for long-term averages for Fort McMurray are presented in Figure 2-3. The actual evapotranspiration values are for a one metre root zone. As these values are monthly averages, they are only approximations of actual conditions. A more precise evaluation would require site-specific information on rooting depth, soil material, wind and barometric pressures, and temperature and precipitation data on a daily basis. The evapotranspiration values calculated indicate that soil water deficits will begin in June, and the largest deficit will occur in August.

.3 <u>Runoff</u>

The amount of water which does not enter the soil after a precipitation event is termed runoff. Water occurring as runoff is unavailable for plant use. Because runoff is the major mechanism whereby soil particles are detached and transported during rainfall-erosion sequences, it is an important parameter for quantifying erosion losses.

The empirical information relevant to an estimation of runoff coefficients (voume of runoff water per volume of precipitation) for the oilsands area is extremely sparce. A regional estimation of runoff, however, has been completed as part of the hydrological characterization of the oilsands areas (Niell and Evans 1979) and a site-specific experiment testing the effect of soil treatment on the reduction of runoff was done by Logan (1978).

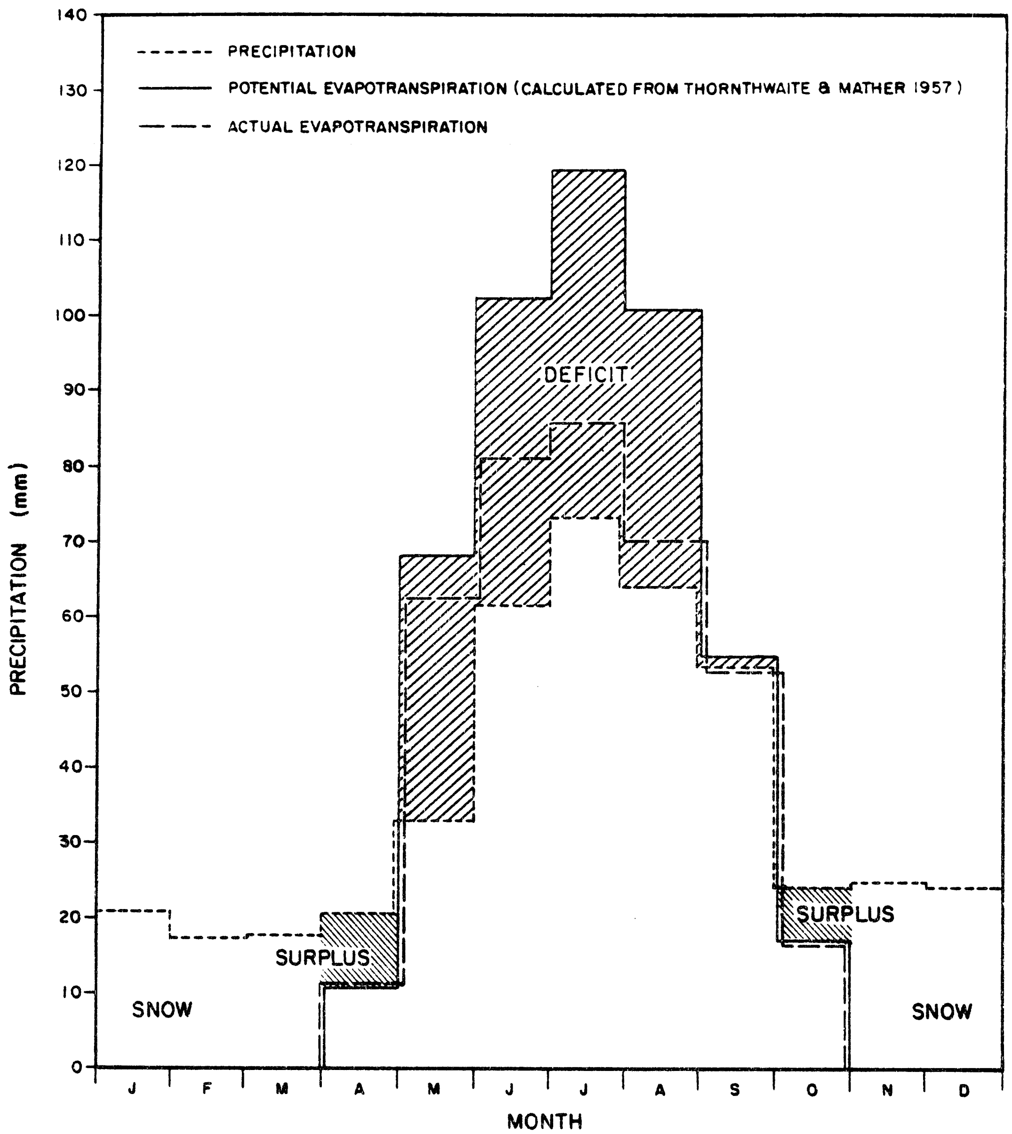
In the regional survey, the average coefficient for the period 1976 and 1977 is 0.16 with a standard deviation of 0.06. Measured runoff coefficients for specific storms range from 0.02 to 0.28. The average value of 16% included snowmelt and rainfall events. Hydrograph data from many of these streams show that snowmelt starts about the end of March, rises sharply to a peak within the first two weeks of April and gradually recedes to the end of June.

TABLE 2-3

Annual Water Balance Components for the Fort McMurray Region

Location	Year	Components of Water Balance: Precipitation	Potential Evapo-transpiration	Actual Evapo-transpiration	Runoff	Estimated Water Deficit	Method	Source
		m						
Fort McMurray								
	1978	460	510	370	90	-50	Hyd. Atlas Canada[1]	Niell and Evans 1977
	1951-1970	435	471	379		-36	Thornthwaite and Mather	This Report
	1972[2]	548	450	282		+99	Thornthwaite and Mather	This Report
	1980[3]	483	565	393		-82	Thornthwaite and Mather	This Report
Tributaries north of Fort McMurray								
	1976-1977	440		360[4]	80[5]		By difference	Niell and Evans 1977
Beaver River								
	1972-1977	550	531	430[4]	124[5]		By difference	Niell and Evans 1977
		(108)[7]	(39)	(86)	(30)			
	1976	525	549[6]	396	129		Pan Coefficient	Niell and Evans 1977

1 Hydrological Atlas of Canada estimation of potential evapotranspiration multiplies estimates of lake evaporation by a "terrain" coefficient.
2 1972 data are based on lowest mean monthly temperatures between Apr. and Oct. at Fort McMurray for the period 1970-1980.
3 1980 data are based on highest mean monthly temperatures between Apr. and Oct. at Fort McMurray for the period 1970-1980.
4 Derived actual evapotranspiration where $ET_{(a)} = P-R$.
5 Measured runoff, not derived.
6 Potential evapotranspiration estimated by multiplying recorded pan evaporation by a "pan" coefficient of 0.7.
7 Numbers in brackets are standard deviations.



CALCULATIONS

FORT McMURRAY 1941 - 1970

ANNUAL PRECIPITATION	435.4 mm
ANNUAL POTENTIAL EVAPOTRANSPIRATION	471.2 mm
TOTAL DEFICIT	- 35.8 mm
ANNUAL ACTUAL EVAPOTRANSPIRATION	379.2 mm

ASSUMPTIONS

AVAILABLE WATER	=	7.5 %
ROOT ZONE	=	1 metre

FIGURE 2-3

MEAN MONTHLY PRECIPITATION
POTENTIAL & ACTUAL EVAPOTRANSPIRATION
AT FORT McMURRAY AIRPORT

Runoff measured *in situ* in the oilsands area averages 2.2% for individual rainfall events (Logan 1978). Although there are many complicating factors associated with this estimation - the range is from 0 to 17%, the slopes are steep (>20 degrees), and the soils had been disturbed and treated with various amendments - it is apparent that runoff represents a small percentage of the total precipitation. This report will assume that approximately 10% of the total yearly precipitation (43.5 mm) is lost as runoff. It is probable that most of this runoff will occur during the spring snowmelt when the soil is saturated and a frost layer exists near the surface (MacLean 1980).

.4 Drainage

Water which has infiltrated into the soil but is permanently lost to plant use because of percolation beyond the root zone is termed "drainage". Water lost through drainage is also a major mechanism of nutrient removal. A function describing the relationship of water storage to drainage flux in free draining uniform materials is shown in Figure 2-4) (Black *et al.* 1969).

Under these conditions, the hydraulic gradient is approximately equal to the gravitational gradient, and hydraulic conductivity can be estimated from the volumetric water content in the lower part of the soil profile (Ritchie 1981, Spittlehouse and Black 1981). Drainage flux is estimated on the basis of changes in hydraulic conductivity.

The soils in the oilsands area can be considered as mainly uniform and free draining sand. Two days after a saturating rain, measured volumetric water contents at 200 cm depth in two soils with uniform deep sands ranged from 6 to 14% (MacLean 1980). From Figure 2-4, the drainage rate can be inferred to range from 0.05 to 1.0 cm/d. Therefore, drainage rates in these materials can be high, and a water balance must consider drainage as a principal component of water loss. MacLean used volumetric water content and measured suction pressures taken from field measurements to show that drainage in the oilsands can average 100 to 130 mm/yr on sandy sites of which 60 to 80% occurs as a result of snowmelt. From this calculation, approximately 25% of the annual total precipitation is lost through drainage.

.5 Soil Water Budget

An accurate evaluation of soil moisture deficit considers all the previously discussed components of the water balance. The key component in determining the soil water budget over the growing season is plant available water. The amount of water available to vegetation is related to the moisture holding characteristics of the soil, the rooting pattern of the plants, and the amount of suction the plant can exert before the wilting point is reached.

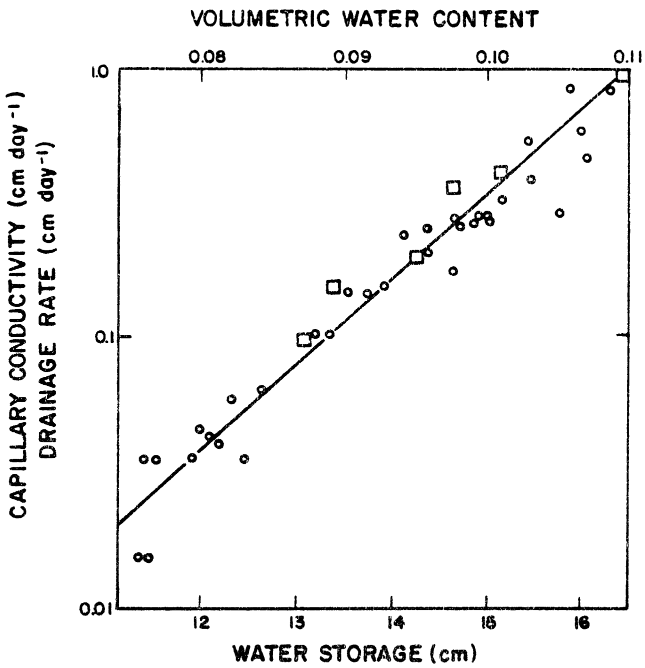


FIGURE 2-4

DRAINAGE RATE AS A FUNCTION OF WATER STORAGE (CIRCLES) AND CAPILLARY CONDUCTIVITY OF A SANDY SOIL AS A FUNCTION OF SOIL WATER CONTENT (SQUARES). THE UPPER SCALE GIVES THE SOIL WATER CONTENT CORRESPONDING TO A GIVEN STORAGE ASSUMING A UNIFORM WATER CONTENT DISTRIBUTION.

In the last four decades, soil science research has focused a great deal of attention on problems of available water. The traditional approach is to evaluate the limits of available water by measuring "wilting point" and "field capacity" of soil samples. Field capacity is normally taken as the soil water content of samples subjected to either -0.30 bars, -0.10 bars or -.06 bars (pF 2.5, 2.0 and 2.8 respectively), and wilting point as -15 bars (pF 4.2). The differences between upper and lower limits of availability are summed for samples taken from the total rooting depth to determine total plant available water (Ritchie 1981).

Although there has been much criticism of this definition of soil water due to the "static" characterization of a "dynamic" process (Armson personal communication, Ritchie 1981), a number which estimates the amount of plant available water held by a given soil is required in situations involving soil water management (Cassel and Nielson 1981).

For purposes of this report, the upper limit of available soil water will be the water content at -0.10 bars and the lower limit will be at -15 bars. The choice of -0.10 bars for estimating field capacity is based on the pore size distribution and water retention in sandy textured materials (Webster and Beckett 1971, Black et al. 1969, van Eck and Whiteside 1958, Jamison 1955, Richards 1949). Furthermore, field capacity estimated at suction pressures of -0.10 bars follows a conservative average of MacLean's (1980) field measurement of water potential in undisturbed forest soils 48 hours after a heavy rain.

The soil water budget of sandy soil materials for a growing season near Fort McMurray can be calculated accurately only if daily meteorological information is available. The following paragraphs use monthly averages to estimate critical time periods in the growing season and to infer the probable distribution of soil water throughout the season.

In the beginning of the growing season, the root zone is saturated; the effects of snowmelt can extend until June in soils on north facing slopes. A typical jack pine vegetated, sandy site has 7.5% available water to two metres depth (MacLean 1980). It is assumed that a site remains saturated and draining until the end of May, at which point evapotranspiration starts to deplete the soil moisture. Data for 1977 at Mildred Lake in the oilsands area show a decrease in soil water content and an equal decrease in drainage until June; the moisture content to 150 cm continued to decrease until September (MacLean 1980).

Psychrometers installed in jack pine communities showed that during periods of greatest stress (mid-August) the soil water suctions were 4 to 9 bars at 20 cm depth. The soil water suction decreased with depth.

The soil moisture status from June to October of sandy soils in the oilsands area illustrates the time frame of moisture deficits and the conditions which lead to them (Figure 2-5). In the case of summer precipitation, water loss is due almost entirely to evapotranspiration because runoff and drainage have ceased with water depletion from the soil profile. The greatest soil suctions (7 to 10 bars), and consequently the lowest soil contents, coincide with the predicted months of highest water deficit using the Thornthwaite and Mather model in Figure 2-5.

In conclusion, soil water deficits in the top metre of soil limit vegetative growth during late summer. Deeper rooted trees are less susceptible to a water deficit. In undisturbed areas, soil suction generally does not exceed 7 bars at 50 cm depth. Most of the precipitation falling during June to September will be lost by evapotranspiration. Most of the water losses due to runoff (43 mm) and drainage (100 to 130 mm) occur during snowmelt in the spring.

213 LOCAL MATERIALS

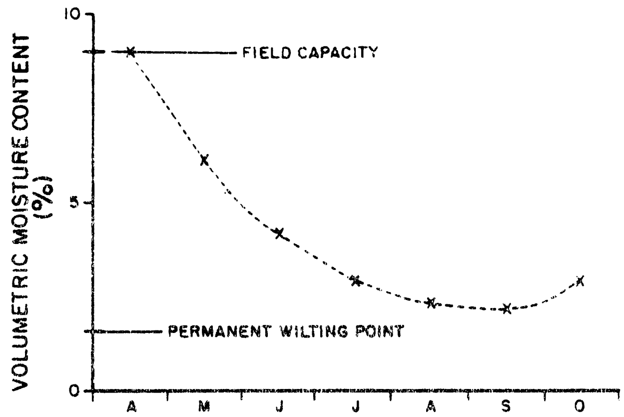
The materials available on a local basis for reconstructing soils in the post-mining reclamation program are: (1) overburden, or all mineral materials situated above the economically mined (>6% bitumen) oilsands; (2) organic soils formed in poorly drained depressions in the surface of the glacial deposits; and (3) tailings sand, the oilsand ore body less the removed bitumen product and less the tailings sludge or that fraction which settles very slowly after bitumen recovery.

.1 Mineral Overburden

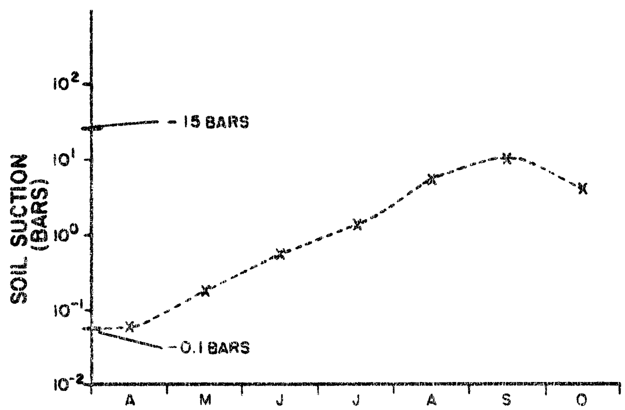
The overburden components in the McMurray oilsands formation are characterized by considerable variation in depth and stratigraphy. Table 2-4 lists the average depths of the deposits in five of the larger areas where mines could be developed in the area (Scott *et al*. 1979). Thus the average thickness would be 33 m. The Suncor lease is reported to have overburden thicknesses ranging from one to 72 m and a mean depth of 22 m (Hardy and Associates 1978a).

Mineral overburden consists of soil underlain by glacial deposits consisting of glaciofluvial sands, gravel and finer textured glacial till (Hardy and Associates 1978a). All unconsolidated materials are of Pleistocene origin.

Below the glacial drift are grey to green glauconitic sands and shales of the Clearwater Formation which rest, in turn, on low bitumen content quartzose sands pertaining to the McMurray Formation (Watson 1979). The secondary units of the latter formation are the main ore bodies of the oilsands area. All stratigraphic units of the McMurray Formation exhibit rapid changes in composition with thin seams to thick beds of silty clay-shale alternating with bitumen-loaded sands (Scott *et al*. 1979).



(a)



(b)

(a) DEPLETION OF SOIL WATER IN SURFICIAL 1METRE OF A SANDY SOIL WITH A FIELD CAPACITY OF 9%, AS ESTIMATED BY METHOD OF THORNTHWAITE & MATHER (1957) FROM DATA COLLECTED BY MACLEAN (1980)

(b) CHANGE IN SOIL SUCTION PRESSURES IN SURFICIAL 1METRE OF A SANDY SOIL AS DETERMINED BY METHOD OF THORNTHWAITE & MATHER (1957) APPLIED TO DATA FROM SOIL MOISTURE RETENTION CURVES IN MACLEAN (1980)

FIGURE 2-5

AVERAGE MONTHLY SOIL WATER CONTENTS AND SOIL SUCTION VALUES FOR SANDY SOILS OF THE FORT McMURRAY AREA

TABLE 2-4

Average Mine Area Characteristics

Mine Area	Overburden Thickness	Oilsands Thickness			Bitumen Content of Plant Feed	Total Thickness Overburden and Centre Reject
		Total	Centre Reject	Plant Feed		
	m	m	m	m	% by mass	m
1	18.6	35.6	7.6	28.0	12.2	26.2
2	14.9	61.9	19.5	42.4	10.9	34.4
3	19.2	72.3	24.1	48.2	10.0	43.3
4	11.6	56.4	14.9	41.5	11.5	26.5
5	22.3	63.1	12.8	50.3	11.7	35.1
Typical	17.0	58.0	16.0	42.0	1.0	33.0

SOURCE: Scott et al. (1979)

The unconsolidated portion of the mineral overburden, consisting of glaciofluvial sands, finer textured till and lag gravel along with the associated soils developed on these materials, represents the most appropriate materials to be included in programs of soil reconstruction. Table 2-5 gives an indication of the relative amounts of the various size fractions comprising each member of the glacial drift (Hardy and Associates 1978a).

Other physical properties, such as water holding capacity and hydraulic conductivity, are closely related to the dominant texture of each member of this group of materials. Soils developed on clay till have from 20 to 40% water by volume at field capacity; sandy soils range from 10 to 25% water content at field capacity; and soils on gravels and coarse sands usually have less than 15% water at field capacity (Turchenek and Lindsay 1979). MacLean (1979) reports a similar change in hydraulic conductivity (unsaturated) associated with a change from high clay contents (low conductivity) to high sand content (high conductivity).

The chemical characteristics of the mineral overburden presented in Table 2-6 are extracted from one lease in the oilsands area and, thus, are based on limited data. The overburden is non-saline and moderately alkaline with a pH of approximately 7.8. Calcium and magnesium are present in high concentrations and dominate the exchange complex. The exchangeable calcium content of the third example under glacial drift (row 3) is relatively high (11 me/100 g) for sand. In explanation, the particle size distribution of these materials can vary greatly and this sample probably contains substantial amounts of silt and clay. The sodium adsorption ratio (SAR) values indicate that sodium is not present in toxic concentrations. More recently, there have been higher SAR values reported in the overburden materials on other leases within the oilsands area (Fessenden personal communication). The predominant anion is sulphate, and it occurs in components of glacial drift and the Clearwater Formation. All nutrient elements are present in reduced quantities.

.2 Peat

Organic deposits occupy approximately 80% of the oilsands area (Lindsay et al. 1962). In one of the areas currently undergoing surface mining, Syncrude Lease 17, Regier (1976) reported that peat occurred to a depth of at least one metre over most of the area. The peat soils in Alberta have been mapped in either Kenzie Series (moss peats) or Eaglesham Series (sedge peats). Most of the moss peats are derived from the genus *Sphagnum*. Some peats are mixtures of moss and sedge types (Logan 1978).

Although classification systems based on botanical origin, morphology, chemical properties and topographical geography have been used to group peat types (Farnham and Finney 1965), the Canadian System of Soil Classification (Canada Soil Survey Committee 1978) uses the relative degree of decomposition to distinguish the three main great groups of the

TABLE 2-5

Relative Grain Size Distribution
of Various Materials in Glacial Drift
on Lease 86

Material Description	Components (Percent by Volume)				
	Boulders	Cobbles	Gravel	Sand	Fines (silt and clay)
Lag Gravel	0-20	9-50	20-46	10-60	0-25
Glaciofluvial Sands	Trace	Trace	2-8	60-90	10-40
Clay Till	0-35	0-30	0-20	0-50	30-100

SOURCE: Hardy and Associates (1978a)

TABLE 2-6

Chemical Properties of Overburden

Overburden Material	pH	Elect. Cond.	Total Nitrogen	Water Soluble Ions							SAR*	Exchange Complex			
				P	K	Na	Ca	Mg	Cl	SO_4		K	Ca	Mg	Na
		mhos/cm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm		me/100g			
Glacial Drift															
Clay	7.9	1.0			5.0	20	360	36	15	360	0.2	0.6	16.0	2.6	0.8
Clay	7.9	1.4			38.0	122	440	164	35	1400	1.3	0.8	13.0	3.7	1.2
Sand	7.7	1.2			39.6	42	316	304	16	1600	0.4	0.6	11.0	2.8	1.0
Sand	7.8	1.4			37.5	122	348	320	19	1550	1.1	0.7	4.3	3.9	1.8
Clearwater Formation															
1	7.7	1.4			33.1	65	320	424	15	1600	0.6	0.7	19.0	4.0	1.0
2	7.7	2.0			47.3	444	348	384	26	2100	3.9	0.6	5.4	3.7	1.0
McMurray Formation															
Lean Tar Sand 1	6.8	0.2	370	2.0	7.5	45	145					2.9	5.0	0.4	0.2
Lean Tar Sand 2	7.5	2.5									4.8		27.0		8.6

SOURCE: Hardy and Associates (1978a)

* Higher values of SAR have been recently reported

organic order. A control section (160 cm) is divided into three tiers, and classification is based mainly on the middle tier. A Fibrosol has a fibric (relatively undecomposed) middle tier; a Mesisol has a mesic middle tier; and a Humisol a humic (highly decomposed) middle tier. Since many of the important characteristics of peat are related to the degree of decomposition, the Canadian system of organic soil classification has proven extremely useful.

Typical chemical properties of peats taken from two areas of Alberta are given in Table 2-7 (Logan 1978). The pH, percentage of base saturation, and carbon-nitrogen ratios conform to the degree of decomposition of each type. The fibric peat is very acid, has a low content of exchangeable calcium (relative to the other peat types), a very low base saturation percentage and a high carbon-nitrogen ratio. Both the mesic and mesic-humic peats are base saturated, less acidic than fibric peats and have a much lower carbon-nitrogen ratio. The same relationship of degree of decomposition to chemical properties holds true in both northern (Mildred Lake) and southern central (Evansburg) Alberta.

The water holding capacity of the Kenzie Series is greater than 850% and the Eaglesham Series is 600% (Logan 1978). The bulk density of the peats is extremely low (0.04-0.1 g/cm^3) in comparison to cultivated soils (1.1-1.3 g/cm^3), mineral horizons of forest soils (1.0-1.3 g/cm^3), or tailings sand (1.3-1.5 g/cm^3).

.3 Tailings Sand

Oilsand tailings consist of the whole oilsand ore body plus net additions of water used in processing, less the recovered bitumen product (Camp 1976). Oilsand tailings can be subdivided into three categories:

i) screen oversize (these are often collected and disposed in mined-out areas and will be ignored in this report);
ii) sand tailings (the fraction that settles out of the water rapidly);
iii) dispersed fines (the fraction that settles slowly).

Although the procedures for handling and disposing of the oilsands tailings (either by dike building or overboarding) are simple, the volume of material imposes practical restraints on reclamation planning. An oilsands plant that produces 125,000 barrels of synthetic crude oil per day generates approximately 270,000 tonnes of tailings daily (Scott et at. 1979). Reclamation in the oilsands area is primarily concerned with the use of oilsands tailings because they represent huge volumes of fill materials.

A particle size distribution curve for an oilsand tailings stream (sand tailings and dispersal fines) is shown in Figure 2-6. Approximately 88% of the solids are above 0.05 mm in diameter (sand size) and settle rapidly. Over a short period of time, another 50% of the

TABLE 2-7

Chemical Properties of Peat from Mildred Lake and Evansburg Areas

Soil Series	Peat Classification	pH (H_2O)	Cation Exchange Capacity*						Total C	Total N	C/N
			Ca	Mg	K	Na	TEC**	Base Sat.			
			me/100g					%	%	%	
			Mildred Lake Area								
Kenzie	Fibric	3.7	21.90	14.30	0.38	1.19	116	33	46.75	0.61	77
Kenzie	Mesic	5.9	81.30	12.80	0.06	0.32	166	57	39.18	1.47	27
Eaglesham	Mesic-humic	6.6	94.22	10.94	0.13	0.38	110	96	46.49	2.80	17
			Evansburg Area								
Kenzie	Fibric	4.0	13.32	2.76	0.20	0.33	115	14	44.86	1.25	36
Kenzie	Mesic	5.6	53.10	16.90	0.13	1.08	142	50	44.73	1.48	30
Eaglesham	Mesic-humic	7.1	129.26	19.69	0.15	0.25	165	90	35.13	2.19	16

SOURCE: Adapted from Logan (1978)

* Extracted with NH_4OAc, 1 N solution.

** Total exchange capacity, extracted with NACl, 1 N solution.

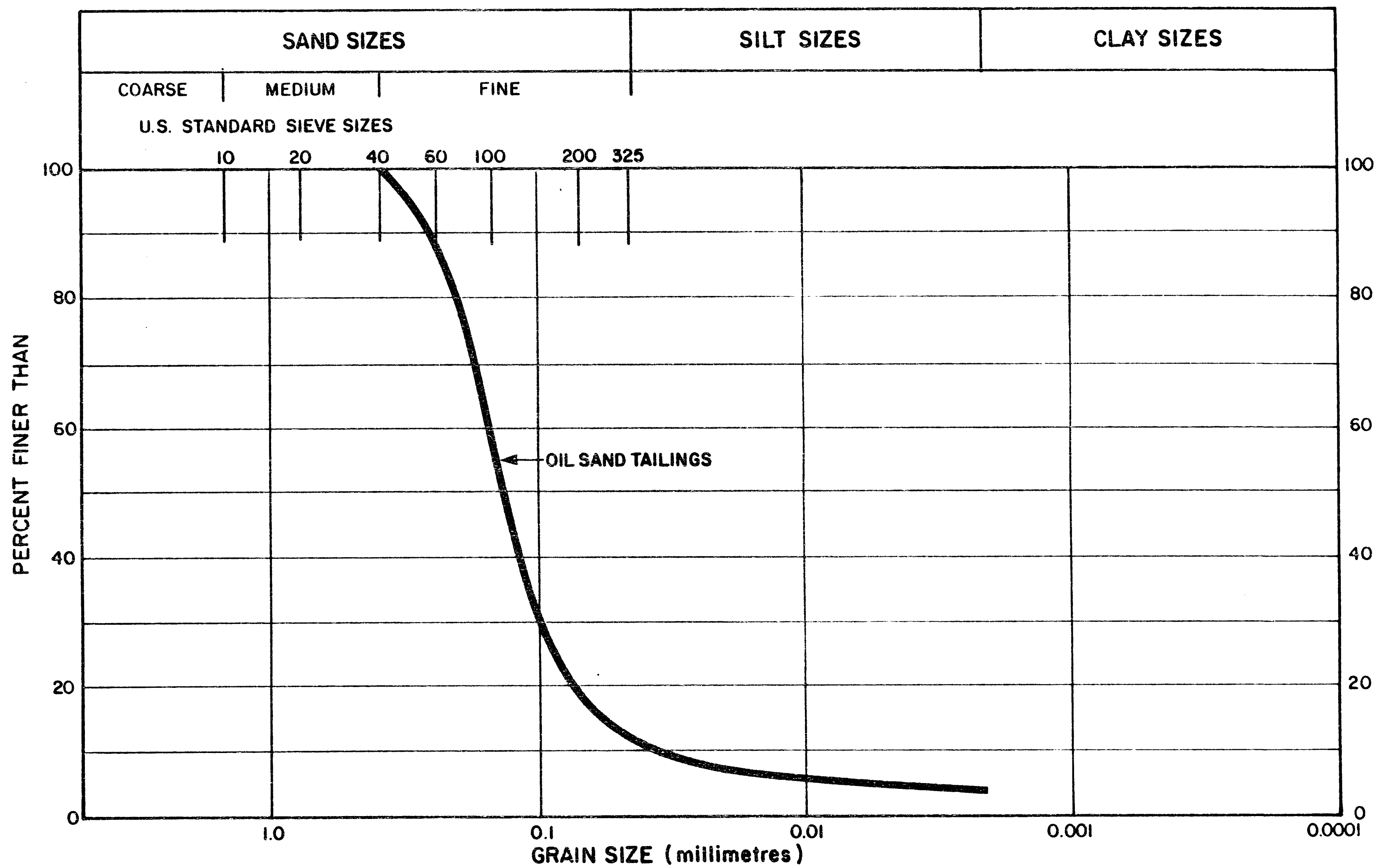


FIGURE 2-6
GRADATION OF TYPICAL TAILINGS FROM OILSAND PROCESSING
(ADAPTED FROM COOK 1977)

remaining fines are deposited in the voids between sand particles (Scott et al. 1979, Camp 1976). The remaining water and unsettled fines are handled apart from the deposited "tailings sand" and are not further considered in this report.

Tailings sands as defined in this report are the mineral deposits left after water and sludge removal. These deposits consist of approximately 97% sand and 3% silt and clay (Table 2-8). Since fine sand fractions (0.05-0.25 mm) behave somewhat like silt fractions in regard to the hydrological properties of soils (FAO 1975), the high content of fine sands (MacLean 1980, Scott et al. 1979, Logan 1978) is significant.

The water retention characteristics of tailing sands have been widely investigated (Table 2-9), however, no conclusive statement pertaining to available soil water can be made. Following the research done in soil material with a very high content of sand (MacLean 1980, Webster and Beckett 1971, Salter et al. 1967, Richards 1949), we have chosen -0.1 bars (100 mbars) as the tension that best represents field capacity of sands. The change in slope of the soil moisture characteristic curve for tailings sand between -0.3 bars and -0.1 bars (Figure 2-7) means that much of the water that would be considered lost to drainage if field capacity were -0.3 bars is thought to be retained for plant use using our evaluation. Estimates of available water in tailings sand with a particle size distribution similar to that described in Table 2-8 have ranged from 1% (Rowell 1977) to 10% (MacLean 1980). The authors of this study think that a reasonable estimate of available water in tailings sand is 7.5%, a figure close to that suggested by Takyi et al. (1977).

There has been only one investigation relating the change in hydraulic conductivity of tailings sand to changes in soil matric potential (Figure 2-7). There is a sharp change in hydraulic conductivity at 100 millibars or field capacity. A further decrease in soil moisture tension at this point is reflected in extremely large increases in hydraulic conductivity.

The chemical properties of tailings sand are reported in Table 2-10. Most of the tailings sands are near neutral in pH, but more alkaline values are encountered in fresh sand as a result of caustic traces left after processing. Although the exchange complex is represented by only two samples in Table 2-10, the total exchange capacity is normally very small (5 me/100 g sand). Calcium usually dominates the exchange complex, but residual sodium can appear. Total nitrogen is extremely low. Available nitrogen and phosphorus are also deficient, reflecting the low organic matter content of the tailing sands ($<1\%$).

TABLE 2-8

Physical Characteristics of Tailings Sand in Oilsands Region of Alberta

Source	Particle Size Distribution					
	fine sand	medium sand	coarse sand	total sand	silt	clay
			%			
MacLean 1977	77.4	16.3	4.5	98.9	1.1	0
Scott et al. 1979*	75	15	0	90.0	3.0	7.0
Logan 1978	93.3	3.3	0.4	97.0	3.0	0
Takyi et al. 1978	-	-	-	96.6	1.0	2.4
Takyi et al. 1977	-	-	-	96.2	0.6	3.2
McCoy et al. 1976	-	-	-	99.2	0	0.8
McCoy et al. 1976	-	-	-	97.2	0.6	2.2
McCoy 1981**	-	-	-	96.0	2.0	2.0
Rowell 1977	-	-	-	96	1.0	3.0
Rowell 1977	-	-	-	94	4.0	2.0
Rowell 1977	-	-	-	93	2.0	5.0

* Scott et al. (1979) report on a sample taken from the tailings stream before particle settlement; therefore up to 50% of silt and clay can be expected to be deposited in void space of the sand (see text for explanation).

** McCoy (1981) is an addendum of two pages of laboratory analyses to McCoy et al. (1976).

TABLE 2-9

Water Retention Characteristics of Tailings Sand
From the Oilsands Region of Alberta

Source	Moisture Content				
	0.06 bar	0.10 bar	0.33 bar	15 bar	Field Capacity Column Method*
			% dry weight		
Logan 1978	31	2.5	3	1	-
Takyi et al. 1977	-	-	14	-	-
Takyi et al. 1977	-	-	14	-	-
McCoy et al. 1976	-	3.8	1.8	0.5	25.5
McCoy et al. 1976	-	-	0.7	0.3	-
McCoy 1981**	-	-	2.7	0	20.7
Rowell 1977	-	-	1.8	0.8	-
MacLean 1980	14	-	-	-	-

* Column method of measuring water content at field capacity is outlined in Miller and McMurdie (1953).

** McCoy (1981) is an addendum of two pages of laboratory analyses to McCoy et al. (1976).

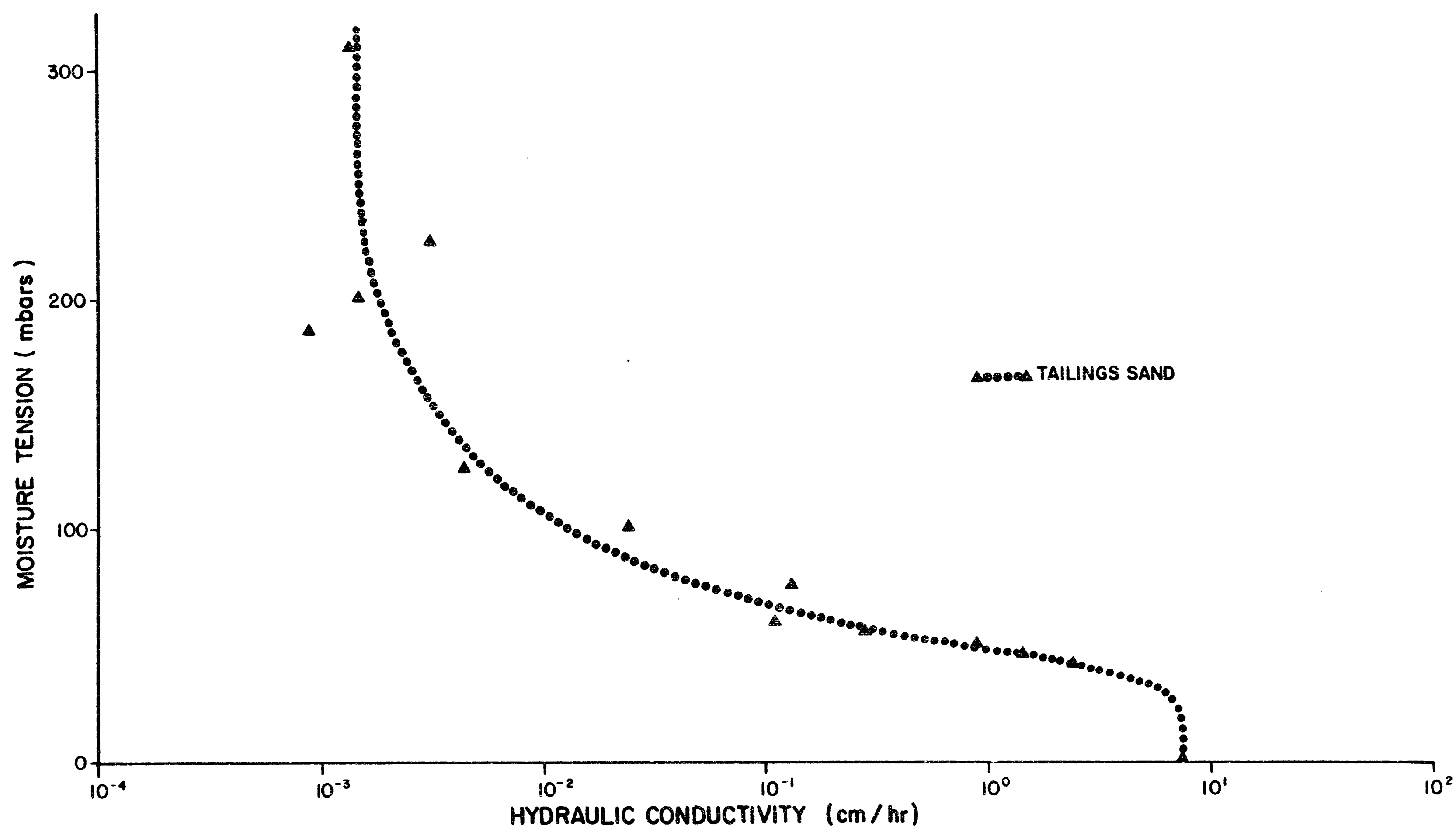


FIGURE 2-7

RELATIONSHIP BETWEEN HYDRAULIC CONDUCTIVITY AND MOISTURE TENSION FOR TAILINGS SAND FROM DIKE SLOPES

TABLE 2-10

Chemical Properties of Tailings Sand
from the Oilsands Area of Alberta

Source	pH	Conductivity	Exchange Complex					Total N	Nitrate N	Sulphates	Phosphorus
			CEC	Ca	Mg	K	Na				
		mS/cm	me/100 g					%	ppm	ppm	ppm
Takyi et al. 1977	7.89	0.55	2.9	0.25	0.48	0.26	0.43	0.005	0.5	11.4	3.5
Klym 1976*	8.5	0.6							0	-	0.3
Rowell 1977	6.23	0.46						0.03	1.3	1.0	2.3
McCoy et al. 1976	6.6	0.7						0.01	1.0	-	0.8
Turchenek and McGill 1977	9.2	0.6	-	0.5	0.3	0.03	0.5	0.003	-	0.05	-

* Klym (1976) is the average of 20 samples as reported in Hardy and Associates (1978a).

2.2 PLANT COMMUNITIES AND ASSOCIATED SOILS

221 INTRODUCTION

The correlation of soil type to plant cover is often strong enough to serve as a means of predicting the properties of one when only the characteristics of the second are known (Coile 1952). Although the variability of both soil and vegetative community affect the accuracy of the prediction, this method is used widely for comparing biological productivity on different sites with different plant species (Munn and Vimmersledt 1980).

The purpose of this section is to describe the relationship of vegetative cover to soil properties as they are presently found in the boreal forest of Canada. It is expected that a set of "minimal" values for various soil properties can be identified for each of three vegetative communities - grasslands on slopes, jack pine forests and mixedwood forest. The "minimum" in these cases will be the lowest level of each soil property that corresponds to a stable vegetative cover. It is presumed that these conditions have evolved over long periods of time and therefore represent "minimal" standards for similar soil-plant associations being established as a part of on-going reclamation programs.

This section includes an extensive survey of literature written with reference to areas outside the oilsands area. The study of forest soils in Alberta is recent, while the study of soils in Michigan, Minnesota, Wisconsin, Manitoba, Ontario and Saskatchewan that support the same tree species has been well documented. When climatic patterns, soils and vegetation types have been found to be similar to those of the oilsands area, the data have been utilized.

222 DIKE SLOPE VEGETATION

The dike slopes, composed primarily of fast-draining quartzitic sands, must support at all times a stable vegetation. A mixture of grasses and legumes is therefore recommended due to the speed with which these species may become established and the self-perpetuating nature of this type of community. It is possible that jack pine may invade and ultimately dominate the slopes due to the climatic conditions and the availability of seed from nearby trees, but the definition of a mature soil developed under similar conditions has assumed that the grass cover could be permanent.

223 DIKE SLOPE SOILS

The sandy soils developed under grass on stabilized dunes south of Athabasca Lake are analagous to the soils which will undergo pedogenesis near Fort McMurray. The two areas are geographically close and are subject to very similar climatic regimes. From a recently published study examining in detail the soils, geology and vegetation of the Athabasca sand dunes (Mackenzie River Basin Committee 1981), we have chosen a soil sampling site which seems to correspond texturally and topographically to constructed dike slope soils in the oilsands area. It is of some interest that the authors of the Mackenzie River Basin study think the soil described here has been developing without major disturbances for approximately 3000 years.

.1 Physical Properties

The particle size distribution is dominated by sand (Table 2-11), a fact that makes it a close analogy to dike slope soils. The silt and clay contents do not increase with depth and they are not substantially different from the parent material. Under these conditions, there is little to no soil particle translocation or transformation (Acton 1980). The increase in clay in the organic debris layer at the surface is probably due to aeolian deposits trapped by the vegetative cover.

The depth of profile development (120 to 150 cm) and the clear distinction of horizon boundaries (Table 2-11) are indications of a long period of stability. The horizons are uniformly structureless, reflecting the high content of sand and lack of biological activity. The sharp change in consistence at 35 cm is due to pedogenic deposition of iron and aluminum discussed under the chemistry of these soils.

The water table is found in excess of five metres at the site where this soil is found (Mackenzie River Basin Committee 1981). Moisture contents range from 4 to 6% in an active dune area where groundwater has no influence and moisture regimes originate from and are recharged by precipitation alone. As the dunes are stabilized - by groundwater, vegetation or both - the average soil moisture contents increase.

.2 Chemical Properties

Sandy soils supporting a grass cover in a boreal environment have chemical properties reflecting the dominance of coarse particle sizes and the accumulation of stable organic matter only in the uppermost horizons (Table 2-12).

The dithionate extractable iron and aluminum indicate the levels of oxides present in each horizon for each of these elements. A high concentration of iron and aluminum oxide in the surface horizons could create phosphorus deficiencies. In fact the LH horizon tends to have a very low bulk density, and 0.12% amorphous oxides do not represent a serious chemical problem. However the high concentration of aluminum oxide in the Bfj_1 horizon (35-82 cm) explains the hard consistency noted for this depth in Table 2-11. Furthermore, the oxide distribution is indicative of the period of profile development (more than 3000 years) and the nature of chemical transformation to be expected under similar conditions in the oilsands area.

Physical and Morphological Characteristics
of Mature Dune Sand Soils
Formed Under a Grass Association

Horizon	Depth	Structure	Horizon Distinctness	Consistence	Dry Colour	Particle Size Distribution		
						Sand	Silt	Clay
	cm					%	%	%
LH	2-0	structureless	clear	loose	10YR3/2	93	1	6
Ahe	0-15	structureless	clear	loose	10YR7/2	97	2	1
Ac	15-35	structureless	abrupt	soft	10YR7/3	97	2	1
Bfj_1	35-82	structureless	clear	hard	10YR7/4	96	1	3
Bfj_2	82-120	structureless	gradual	hard	10YR7/4	99	0	1
C	120-150	structureless	----	soft	10YR8/4	98	1	1

SOURCE: Mackenzie River Basin Committee (1981).

TABLE 2-12

Chemical Properties of Mature Dune Sand Soils
Formed Under a Grass Association

Horizon	Depth	Soil Texture	Dithionate[1] Fe	Dithionate[1] Al	pH[1]	Exchangeable Cations[2] CEC	Exchangeable Cations[2] Ca+Mg	Exchangeable Cations[2] K
	cm		%	%		me/100g		
LH	2-0	sand	0.07	0.05	4.4	-	-	-
Ahe	0-15	sand	0.01	0.02	4.4	7	5	1
Ae	15-35	sand	-	0.02	5.9	-	-	-
Bfj_1	35-82	sand	0.01	0.08	6.1	5	3	0.5
Bfj_2	82-120	sand	-	0.04	6.2	-	-	-
C	120-150	sand	-	0.03	6.4	6	-	-

Horizon	Organic C[1]	Total N[1]	Available Nutrients P_2O_5[3]	Available Nutrients K_2O[3]
	%	%	ppm	
LH	9.17	0.24	--	--
Ahe	0.17	0.01	<10	<10
Ae	0.12	0.01	--	--
Bfj_1	0.14	0.01	--	--
Bfj_2	0.02	-	--	--
C	-	-	--	--

1 Mackenzie River Basin Committee (1981)

2 Kjearsgaard (1972)

3 Cole *et al.* (1975)

Organic carbon distribution is confined mainly to the upper 35 cm and nitrogen is very low below the layer of organic debris on the surface.

The data reported on Table 2-12 for exchangeable cations and available nutrients are abstracted from other sandy soils (Kjearsgaard 1972, Cole et al. 1975) not directly comparable to the oilsands area. However, the amount and distribution of cations (<8 me/100 g soil) in each horizon reflect the coarse particle size and low surface area (Black 1968). Similarly, mature soils dominated by sand can be expected to have less than 10 ppm available phosphorus (P_2O_5) and potassium (K_2O).

224 JACK PINE FOREST

Jack pine (Pinus banksiana) is dominant in large areas of aeolian sand deposits in the northeast and southeast portions of the oilsands area, and represents a xerophytic vegetation type (Stringer 1976). Although jack pine can grow anywhere except on fen peats, it is most typical of well drained, sandy plains and hills (Rowe personal communication).

Due to the interrelationships of soil and water, the drainage of jack pine areas is as variable as the soil types. While drainage in these communities may range from excessive to restricted, growth at either extreme is slow (Cayford et al. 1967). Water tables under jack pine have been reported from 0.75 m to 30 m depth (Wilde 1958, Chrosciewicz 1963).

Several authors have indicated that the optimum sites for jack pine are moist upland soils of intermediate texture such as loams and clay loams, aeolian deposits and well drained loamy sands (Rowe personal communication, Kabzems et al. 1972, Sheldon and Bradshaw 1977). Good growth is also found on both coarser and finer materials, such as glacial till and silty sands respectively (Stringer 1976, Chrosciewicz 1963).

Jack pine is able to adapt to diverse conditions because of its flexible rooting habit. In sandy soils, the tree is very deep rooted and drought resistant; the taproot may descend more than 2.7 m in well drained, easily penetrated soils. Lateral roots can develop in conjunction with a taproot, and may extend horizontally from the taproot to 5-8.5 m (Cheyney 1932, cited by Fowells 1965, Rowe personal communication).

Vegetational patterns are best related to drainage and soil conditions (Thompson et al. 1978), and the variability of these factors will contribute to a diverse understory for the jack pine community. The poorest jack pine sites are typified by a very open structure with few tall shrubs and herbs. The understory is generally composed of lichens (Cladina spp.) and bearberry (Arctostaphylos uva-ursi) (Cayford et al. 1967). As moisture availability increases, so does the number of species. The intermediate jack pine producing sites contain some low and dwarf shrubs such as bog cranberry (Vaccinium vitis-idaea) and blueberry

(Vaccinium myrtilloides). A few herbs such as twin-flower (Linnaea borealis) and bunchberry (Cornus canadensis) can be present. Other trees may grow as site conditions allow. Areas which are too dry to support birch (Betula papyrifera) in conjunction with the pine might have aspen (Populus tremuloides) (Thompson et al. 1978). Very good jack pine sites are capable of supporting the above species as well as raspberry (Rubus idaeus), leather-leaf (Chamaedaphne calyculata), alder (Alnus crispa), dogwood (Cornus stolonifera), roses (Rosa spp.), honeysuckle (Lonicera dioica) and currant (Ribes spp.).

Sites with drainage and soil characteristics appropriate for jack pine tend to be susceptible to fire. As fire is propagated by the total geographic environment, it follows that jack pine must have evolved as a component of fire-prone ecosystems (Rowe and Scotter 1973). Characteristics of growth habit and reproductive adaptations enable jack pine to regenerate rapidly following a fire. The amounts of charcoal and fire-scarred trees show that fire has always played a prominent role in the boreal forests. The absence of fire can lead to the change from jack pine to mixedwood forests (Rowe and Scotter 1973, Fowells 1965).

225 JACK PINE SOILS

.1 Physical Properties

Jack pine forests are found throughout the oilsands environment under different site conditions. Factors such as aspect, elevation, soil temperature and day length do not appear to limit jack pine establishment within its ecological range. The range of site conditions supporting jack pine is presented in Table 2-13, developed from data obtained by Turchenek and Lindsay (1978, 1979).

Parent Material The range of parent material over which jack pine has been seen to occur in the oilsands area is divided into broad groupings based on their depositional history (Table 2-13). The parent materials, excepting the glacial till, are generally coarse textured and similar in physical and hydrological properties. Jack pine forms relatively productive stands on these materials, indicating a tolerance for low levels of available water and nutrients. The fines content of the tills can be much higher and drainage on these materials can be impeded. The fact that jack pine is productive also under these conditions indicates the wide soil tolerance of this species.

Topographic Position and Local Hydrology Jack pine is found on lower, mid and upper slope positions (Table 2-13). The relationship of forest type to regional topography and hydrology is illustrated in Plate 2-1. It would appear that jack pine forest stands are related to the localized hydrological characteristics, which are influenced by soil and geographical characteristics such as texture of parent material, depth to impermeable layer, topography and surface runoff conditions.

TABLE 2-13

Parent Materials and Topographical Conditions
Associated with Jack Pine

Parent Material	Understory	Slope Position	Slope	Aspect	Elevation	Drainage
			%		m	
Brown glacial till	lichen, blueberry, bearberry	Lower	2-30	South	350 - 650	Imperfect
Outwash deposits	aspen, bearberry, rose	Mid	0.5-5	North to East	250 - 350	Rapid
Aeolian deposits	lichen	Upper	2-15	South	400 - 500	Rapid
Meltwater channel deposits	bearberry, lichen	Lower	2-9	West	250 - 350	Rapid

SOURCE: Turchenek and Lindsay (1978, 1979)

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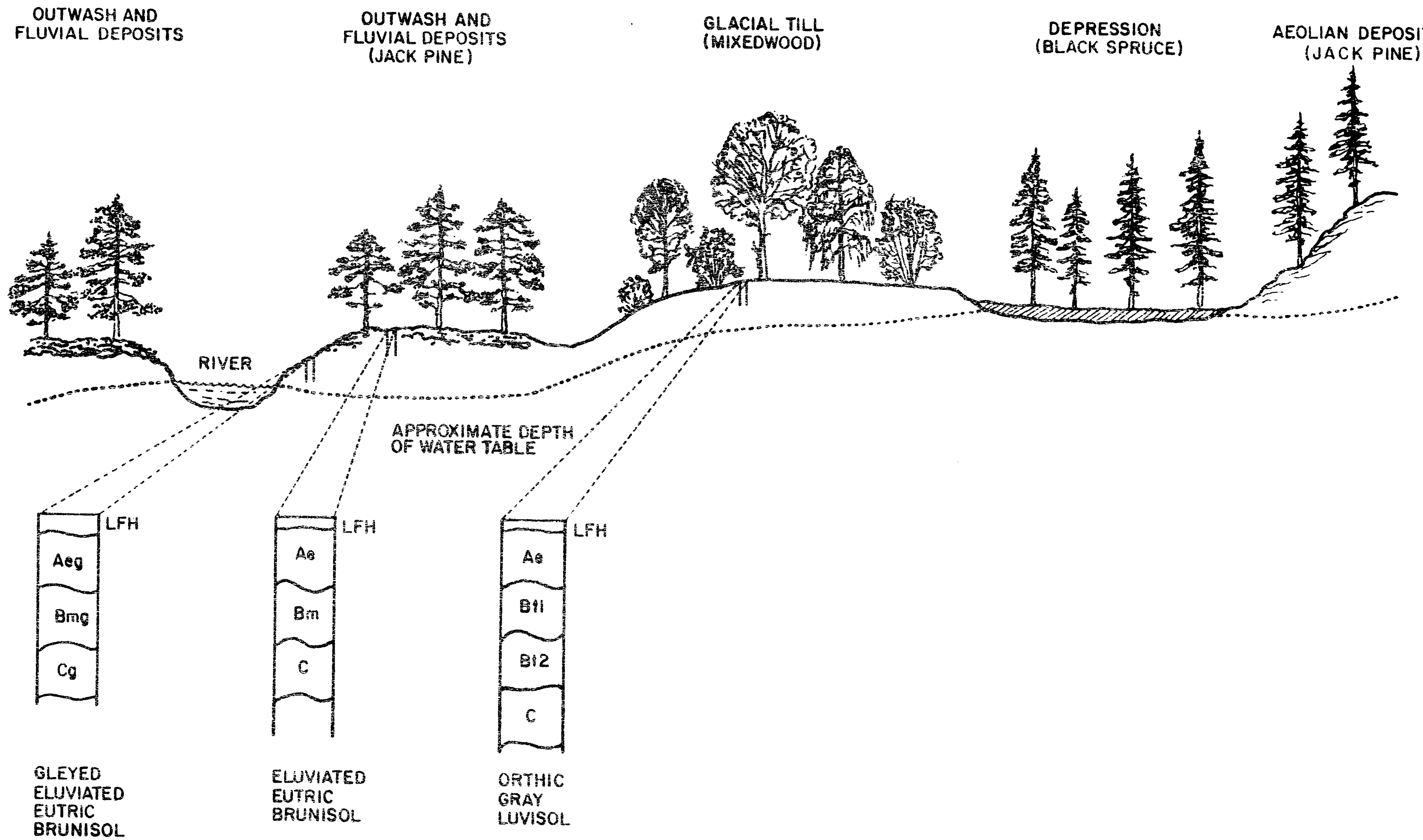

PLATE 2-1

SCHEMATIC CATERNARY SEQUENCE OF VARIOUS FOREST SOILS ON UNDULATING TOPOGRAPHY

Texture of Jack Pine Soils The silt and clay contents of soils supporting jack pine are highly dependent on the kind of parent material upon which they were formed (Table 2-14). The tills have significantly higher proportions of finer textured components than the outwash and meltwater deposits and the aeolian sands. Approximately the same proportion of silt and clay to sand exists in the A and B horizons for each parent material (Table 2-14). There are no major differences in the textural classes found under jack pine when comparing the oilsands area soils information with that of other areas in Canada and the USA. The textural ranges for outwash and meltwater channel deposits show that a silt and clay content of 5% in both the A and B horizons supports jack pine.

Soil Moisture The water contents of a jack pine soil at permanent wilting point and field capacity (measured at 0.06 bars) are shown in Table 2-15 (MacLean 1977). The measurements were made under laboratory conditions, but comparable field data are available (MacLean 1979). The C horizon has a lower water content at both measured suction pressures than either the A or B horizon. It can be assumed that a high water table is not present under these soils.

The moisture holding capacity of the forest floor was not measured by MacLean (1979, 1980). Because of the extremely high organic carbon content in relation to mineral soil, it is possible that forest litter could play an important part in the water regime. However, Mader and Lull (1968) found that the maximum water storage capacity of the forest floor was 10-11.7 mm, only 2-5% of the amount of total water required for optimum growth. Furthermore, even when a single rainfall exceeded the maximum storage capacity, the forest floor did not resaturate. The organic deposits on the surface provided improved infiltration to the mineral soil below, but did not function as an important soil moisture reservoir.

The saturated hydraulic conductivities of soils under jack pine are shown in Table 2-16 (MacLean 1980). Both sites, which are in the oilsands area, have high sand contents (95-97% in the A horizon) and support mature stands of jack pine. The hydraulic conductivity is high (10^{-2} cm/s) and typical of sandy soils (Gardner and Gardner 1950, Low and Deming 1953). However, as the moisture content declines, the hydraulic conductivity decreases rapidly, thus limiting the ability of these soils to transmit water to plant roots within the available moisture range (MacLean 1980).

MacLean (1980) estimates the water requirements of jack pine over the growing season at 130 mm. The amount of plant available water on jack pine sites is approximately 7.5% by volume.

Soil Structure Structural development of soils under jack pine tends to be single grain. The coarse texture, slow organic matter accumulation, and low amounts of moisture impede structural development. The

TABLE 2-14

Silt and Clay Contents
in Jack Pine Soils

Parent material	Silt and clay in A horizon		Silt and clay in B horizon	
	In Area[1]	Out of Area[2]	In Area[1]	Out of Area[2]
	%	%	%	%
Brown glacial till	8-70	10-42	27-50	30
Outwash deposits	3-30	6-30	2-30	14-20
Aeolian	5-18	5[3]	14[3]	5[3]
Meltwater channel deposits	5-9	5[3]	5	5[3]

[1] Reference in area: Turchenek and Lindsay (1978, 1979)

[2] References out of area: Morrison and Foster (1974)
Fowells (1965)
Wilde et al. (1948)

[3] Values estimated from literature

TABLE 2-15

Water Contents of a Jack Pine Soil
as Measured in a Laboratory

Horizon	Water content 15 bars (PWP)[1]	.06 bars (FC)[2]	Available Moisture
	%	%	%
Ae/AB	1.8	12.3	10.5
Bm	2.2	13.9	11.7
C	1.6	9.3	7.7

1. Permanent Wilting Point (-15 bars)
2. Field Capacity (-0.06 bars)

SOURCE: MacLean (1977)

TABLE 2-16

Saturated Hydraulic Conductivities
in Soil Horizons
from Sites Under Jack Pine Forest

Location	Horizon	Saturated Hydraulic Conductivity
		cm/s
Mildred Lake 2	Ae	0.9×10^{-2}
	Bm	0.9×10^{-2}
	C	0.3×10^{-2}
Richardson	C	1.2×10^{-2}

SOURCE: MacLean (1980)

soil forming processes of expansion and contraction, clay eluviation, and salt solution and deposition are not intensely expressed in jack pine soils. In particular, the B horizon of a jack pine soil is normally a Bm, Btj, or Bfj.

.2 Chemical Properties

The previous section has shown the wide range of parent materials which have evolved to support pure or mixed stands of jack pine. Table 2-17 has grouped all of the parent materials together and identified the chemical properties for common horizons of these soils. The average levels of total exchangeable bases are not minimum amounts needed to support a jack pine forest; they are averages for parent materials having very high contents of silt and clay, as well as those soils occurring on aeolian or deep sand formations.

There is a similarity of chemical properties associated with jack pine forests across a wide climatic and geological area (Table 2-17). Northern Wisconsin, for example, has forest species and soils similar to northern Alberta (Wilde 1953, Kaufman 1945, Turchenek and Lindsay 1978).

The higher CEC values associated with the B horizon in the oilsands area are probably part of the natural variability in silt and clay contents in a range of parent materials. The percentage of soils under each forest community is not reported and, consequently, heavier textured and higher base status soils can be disproportionately represented by these averages.

The pH status of jack pine soils tends to fall in a relatively narrow range (approximately 5-6) regardless of parent material or geographical location in North America. Furthermore, the surface horizons tend to be more acid, due to the immediate acidifying effect of decomposing organic debris, while the subsurface horizons are slightly more alkaline.

Table 2-17 includes a summary of the range of values found for organic carbon and total nitrogen under jack pine forests in the oilsands area and other parts of Canada and the U.S. The relationship of carbon and nitrogen to profile depth can vary with the nature of parent materials and productivity of the associated forest. On glacial till deposits in northern Wisconsin with highly productive jack pine, the organic matter can reach 7.8% in the Ahe horizon and have total nitrogen contents of 0.8% (Wilde and Patzer 1940). Aeolian deposits, consisting of very deep dune sands, seldom have an Ahe horizon and have relatively low contents of organic carbon and total nitrogen in the upper B horizon. Olson (1958) found that 80 year-old jack pine forests on dune sands in Wisconsin seldom accumulated more than 0.3% organic carbon in any part of the mineral profile.

TABLE 2-17

Selected Chemical Properties of Jack Pine Soils Found in the Oilsands Area and in Other Forested Areas of North America

Area	Parent Material	Horizon and Depth	CEC[3]	Exchangeable Cations			pH in H_2O
				Ca	Mg	K	
		cm	me/100g		me/100g		
Oilsands[1]	Glacial till, fluvial out- wash, channel deposits and aeolian sands	A:6	4.3	2.0	1.3	0.5	4.9
		B:45	9.0	4.8	1.8	2.0	5.8
		C:50	0.45	0.3	0.05	0.05	5.6
Other Parts of Canada and U.S.A.[2]	Glacial till, fluvial outwash and aeolian sands	A:7	4.0	2.0	0.5	1.0	5.3
		B:35	6.0	2.5	1.5	1.5	5.6
		C:45	2.1	0.8	0.5	0.7	5.9

Area	Horizon and Depth	Organic Carbon	Total Nitrogen	Carbon Nitrogen Ratio	Available Nutrients	
					P_2O_5	K_2O
	cm	%	%		ppm	
Oilsands[1]	LFH:2-14	22-47	0.61-1.4	23-95	-	-
	A:4-14	0.2-0.7	0.01-0.03	19-31	-	-
	B:6-45	0.4-1.6	0.003-0.40	10-43	-	-
	C:25-50	-	-	-		
Other Parts of Canada and U.S.A.	LFH:1-8	20-41	0.58-1.3	21-62	30	120
	A:2-30	0.6-8.0	0.02-0.04	-	40	150
	B:10-100	0.1-2.0	0.01-0.91	-	10	90
	C:30-300	-	-	-	-	-

1 Oilsands: Turchenek and Lindsay (1978), Twardy (1978).
2 Others: Wilde et al. (1948), Wilde (1953), Kaufman (1945), Fowells (1965), Swan and Dix (1966), Foster and Morrison (1976), Rudolf (1958), Alway and McMiller (1933).
3 CEC is reported in oilsands studies as total exchangeable bases (TEB).

Soils formed under forests in the boreal region often have an organic horizon above the mineral soil; the jack pine soils are not an exception. The litter layer, as described in the existing soil survey reports (Turchenek and Lindsay 1978, Twardy 1978) for northern Alberta has a high percentage of nitrogen, but it represents only a fraction of the total nitrogen pool because of low total weight and density of the organic layer. The high C/N ratio demonstrates the relative abundance of energy source for microbial degradation. One limiting factor is available nitrogen because the majority of the nitrogen pool is bound in an organic form.

In the event of the occurrence of an eluviated surficial horizon (Ae), total nitrogen and organic carbon tend to be lower than in the underlying B horizon. The eluviation of colloids from the Ae often includes a substantial portion of the stable organic matter associated with the mineral component. Upon reaching the subsurface portion of the profile, the organic colloids are physically stabilized by the finer textured materials in the B horizon having a higher exchange capacity and increased surface area.

The decreasing ratio of carbon to nitrogen in the lower horizons is a direct measure of organic matter stability. Newly added litter has C/N ratios of 25 to 100 while very stable humic and fulvic components are usually between 8 and 15 (Lowe 1974). Cation exchange capacity also increases with organic matter stability.

226 MIXEDWOOD FOREST

The mixedwood forest is composed of varying proportions of coniferous and deciduous trees, principally white spruce (*Picea glauca*) and aspen. Other trees found in the area on specific microsites are jack pine, black spruce (*Picea mariana*), larch (*Larix laricina*), birch, balsam poplar (*Populus balsamifera*) and balsam fir (*Abies balsamea*) (Thompson *et al*. 1978).

The mixedwood forest may be found over most of the southern and western portions of the study area. Optimum growth is achieved on medium to fine textured loams and clay loams on well drained uplands (Rowe 1972). This forest type may also exist however on alluvial lacustrine materials, tills, aeolian deposits and muskeg.

It would appear that drainage is largely responsible for determining which of the two main species is to be dominant in each microsite. The drier, better drained sites usually support a dense white spruce community; the more moist regions are normally dominated by aspen.

White spruce has a very flexible rooting habit which enables the tree to exist under diverse conditions. White spruce and aspen typically have adventitious roots and well developed lateral root systems in conjunction with a taproot.

The mixedwood forest is floristically richer than the jack pine forest. Generally, mixedwood sites with a high proportion of conifers tend to have a high species diversity (Thompson et al. 1978). As the associated vegetation is dependent upon a number of factors including moisture, soil type, texture, nutrient availability, light, litter accumulation and root competition, the structure of the understory is variable. The dry areas are often characterized by the presence of jack pine and bog cranberry; birch, larch and balsam fir are uncommon occupants. Areas which are well drained have many shrubs and herbs including blueberry, twin-flower, alder, wild sarsaparilla (Aralia nudicaulis), roses and willow-herb (Chamaenerion spicatum). The moist to moderately drained sites are populated by several of the above species in conjunction with hazelnut (Corylus cornuta), cranberry (Viburnum trilobum) and goldenrod (Solidago lepida). Willows (Salix spp.) become evident in the very moist, imperfectly drained areas (Rowe 1956). The details of understory relationships are presented in Table 2-18.

Like jack pine stands, mixedwood forests are influenced by external factors such as fire. After fire, aspen usually dominates in areas formerly occupied by mixedwood, due to its ability to reproduce by suckering (Fowells 1965, Heinselman 1971). Other means by which fire influences tree reproduction and productivity include: the reduction of competition for moisture, nutrients, heat, and light by temporarily eliminating the overstory and understory vegetation; creation of suitable seedbeds by exposing mineral soil or dense ashes; the elimination and consequent sanitization of old stands which provide breeding grounds for such pests as spruce budworm and dwarf mistletoe (Heinselman 1971).

Aspen poplar can prepare a site for invasion by other species, such as white spruce, by the deposition of leaf litter which redistributes nitrogen to the surface soil layers (Fowells 1965). A sufficiently developed canopy can provide partial shade, decreasing the ground temperature and moisture loss, or resulting in a frost protective cover (Fessenden personal communication). Consequently, lack of disturbance in the mixedwood forest allows white spruce, often in association with balsam fir, to become the dominant tree species (Quirk and Sykes 1971).

227 MIXEDWOOD SOILS

.1 Physical Properties

The range of conditions in the oilsands environment that support mixedwood are presented in Table 2-19. This table has been developed from field data obtained from Turchenek and Lindsay (1979).

Parent Material and Topographical Position The parent material which gives rise to soils supporting mixedwood forests is predominantly till or glaciolacustrine (Table 2-19). The modes of deposition of these parent materials are ice and extremely slow moving water. The glaciola-

TABLE 2-18

Vegetation Table for the Southern Boreal Forest
The species are arranged by strata in the vertical dimension and by moisture reference in the horizontal dimension.

	VERY DRY AND DRY FOREST xerophytic species	FRESH FOREST xero-mesophytic species	MOIST FOREST mesophytic species	VERY MOIST FOREST meso-hydrophytic species	WET FOREST hydrophytic species
ATION A	Pinus banksiana Picea glauca Betula papyrifera Populus balsamifera Picea mariana Populus tremuloides Abies balsamea				Larix laricina
SHRUBS plus)	Alnus crispa Elaeagnus commutata Salix humilis Shepherdia canadensis	Amelanchier alnifolia Corylus cornuta Prunus pensylvanica Prunus virginiana	Acer spicatum Sorbus decora Viburnum trilobum	Acer negundo Cornus stolonifera Salix bebbiana Salix discolor	Alnus rugosa Salix petiolaris Salix pyrifolia
M SHRUBS m - 1 m)	*Hudsonia tomentosa Juniperus communis	Diervilla lonicera °Rosa acicularis Symphoricarpos albus Symphoricarpos occidentalis *Vaccinium myrtilloides	Lonicera dioica var. glaucescens	*Ledum groenlandieum Lonicera involucrata Lonicera villosa var. solonis Ribes glandulosum Ribes hirtellum Ribes triste Rubus idaeus Viburnum edule	*Andromeda polifolia Betula glandulosa *Chamaedaphne calyculata *Kalmia polifolia Rhamnus alnifolia Ribes hudsonianum Ribes lacustre Spiraea alba
HERBS RASSES m plus)	Agastache foeniculum Anemone cylindrica Hedysarum alpinum var. americanum Hieracium canadense Lathyrus venosus Lillium umbellatum Potentilla arguta	Agropyron subsecundum Anemone riparia Apocynum androsaemifolium °Aralia nudicaulis Chamaenerion spicatum Disporum tracycarpum Lathyrus ochroleucus Sanicula marilandica Thalictrum venulosum	Achillea sibirica Aquilegia canadensis Osmorhiza longistylis Solidago lepida	Anemone canadensis Aster umbellatus var. pubens Calamagrostis canadensis Cinna latifolia Heracleum maximum Pteretis pensylvanica Solidago gigantea Thalictrum dasycarpum Urtica gracilis	Arnica chamissonis Aster junciformis Aster puniceus Cirsium muticum Eupatorium maculatum Glyceria borealis Impatiens capensis Petasites sagittatus Petasites vitifolius Sium suave
M HERBS RASSES 0 cm)	Achillea millefolium Aster laevis Astragalus alpinus Astragalus striatus Erigeron glabellus Castilleja rhexifolia Comandra pallida Elymus innovatus Equisetum hyemale Gentianella amarella Habenaria bracteata Heuchera richardsonii Melampyrum lineare Oryzopsis asperifolia Poa interior Polygala senega Rudbeckia hirta Solidago nemoralis Zizia aptera	Aquilegia brevistyla °Aster ciliolatus Corallorhiza maculata Corallorhiza striata °Galium septentrionale Prenanthes alba °Schizachne purpurascens °Smilacina stellata Vicia americana Viola rugulosa	Bromus ciliatus Mertensia paniculata Osmorhiza obtusa Petasites palmatus	Dryopteris cristata Dryopteris disjuncta Dryopteris spinulosa *Geocaulon lividum Habenaria hyperborea Lysimachia ciliata Poa palustris Valeriana septentrionalis	Caltha palustris Equisetum arvense Equisetum pratense Geum macrophyllum Geum rivale Lathyrus palustris Mentha arvensis Parnassia palustris var. neogaea Senecio pauperculus Stachys palustris
ERBS RASSES HRUBS than tall)	Antennaria campestris Antennaria petaloidea *Arctostaphylos uva-ursi Danthonia spicata Houstonia longifolia Festuca ovina Juniperus horizontalis *Lycopodium complanatum Oryzopsis pungens Polygala paucifolia *Sibbaldiopsis tridentata Solidago hispida Spiranthes gracilis Vaccinium caespitosum Viola adunca	Anemone quinquefolia Corallorhiza trifida °Fragaria virginiana *Lycopodium obscurum °Maianthemum canadense var. interius Pyrola asarifolia Pyrola secunda	Carex deweyana *Coptis groenlandica Corallorhiza trifida Cornus canadensis Fragaria vesca *Goodyera repens *Linnaea borealis var. americana Lycopodium annotinum Moehringia lateriflora Monotropa uniflora *Pyrola virens Rubus pubescens *Trientalis borealis *Vaccinium vitis-idaea var. minus *Viola renifolia	Circaea alpina *Equisetum scirpoides Galium triflorum *Gaultheria hispidula *Habenaria obtusata *Habenaria orbiculata *Listera cordata Mitella nuda *Moneses uniflora *Ranunculus lapponicus	Carex capillaris *Carex disperma Carex gynocrates Chrysoplenium ioense *Drosera rotundifolia Galium trifidum Ranunculus abortivus *Rubus acaulis *Rubus chamaemorus *Smilacina trifolia Stellaria longifolia *Vaccinium oxycoccus Viola nephrophylla Viola palustris
AND S	Ceratodon purpureus *Cladonia rangiferina Polytrichum piliferum	Brachythecium salebrosum Polytrichum juniperinum Rhytidiadelphus triquetrus	*Calliergonella schreberi *Dicranum rugosum Eurhynchium strigosum Eurhynchium diversifolium Peltigera spp.	*Hylocomium splendens *Hypnum crista-castrensis Thuidium recognitum	Aulacomnium palustre Camptothecium nitens Climacium americanum Drepanoecladus uncinatus Mnium cuspidatum *Sphagnum spp.

ies characteristic of coniferous types

° Species having little indicator value so far as moisture is concerned.

CE: Rowe (1956)

TABLE 2-19

Topographic Conditions Associated with Mixedwood Forests

Parent material	Understory Vegetation	Slope Position	Slope	Aspect	Elevation	Drainage
			%		m	
Bedded glaciolacustrine	Aspen, white spruce, buffalo berry, rose, bunchberry	Upper, Mid, Bottom	0.5-5	North to West	300 - 500	Imperfect to moderately well
Brown glacial till	Aspen, white spruce, rose, bearberry	Upper	2-15	North	450 - 500	Moderately well
Mixed till	Aspen, balsam fir, rose, grasses	Mid	2-30	South to East	350 - 800	Well
Meltwater channel deposits	White spruce, aspen, blueberry bunchberry, feathermoss, club moss	Upper	2-9	North	250 - 350	Moderately well

SOURCE: Adapted from data of Turchenek and Lindsay (1979) custrine deposits are heavier textured and much more uniform than till deposits. The latter may include well mixed layers of fines, gravels and large rocks.

Mixedwood forests can grow on any slope position, lower, mid or upper, and on slopes ranging from 0.5% to 30%. Aspect, elevation and understory do not apparently influence the development of mixedwood forests.

The drainage characteristics of mixedwood sites reflect the characteristics of the parent material. In general, the mixedwood forests are located on materials less well drained than those under jack pine. Excess water or very poor drainage, however, impedes development of a mixedwood community (Jarvis et al. 1966).

Texture A mixedwood forest soil in the oilsands area normally contains large amounts of fine textured materials in both the A and B horizons. Glacial till and lacustrine materials under mixedwood have up to 60% silt and clay in each horizon (Turchenek and Lindsay 1978). Melt-water channel deposits have less fines, but an average silt and clay content of several horizons is seldom less than 20% (Stoeckler 1938). In any case, mixedwood forest soils are normally characterized by more silt and clay than jack pine soils (Wilde 1966).

Soil Moisture The available moisture in soils under a mixedwood stand is higher than that under jack pine probably because of the higher proportions of silt and clay in the mixedwood soils. Table 2-20 compares the available moisture of "C" horizon material for the two forest types (MacLean 1980). The jack pine site has approximately half the amount of available water of the mixedwood site.

A water volume study (MacLean 1980) shows that the annual uptake of water by mixedwood forest is approximately 325 mm. Although the presence of a perched water table at 100 cm could have distorted the value, the wide difference between water use by mixedwood and jack pine (130 mm per growing season) indicates that different soil physical properties may be necessary for each forest type.

.2 Chemical Properties

The mixedwood forest soils of North America are more varied in their chemical properties than jack pine soils. A major part of the variation is due to the wide range of tree species and understory commonly associated with mixedwood, and the different requirements or tolerances of each. Table 2-21 divides the typical soil profile found under mixedwood into the eluviated A (Ae), illuviated B (Bm,t) and underlying C horizons. The Ae horizon is somewhat less pronounced than that found in the jack pine soils. The reason is twofold: the parent materials under a mixedwood forest are usually heavier textured and less susceptible to eluviation, and the influence of biotic weathering is less pronounced due to slightly higher pH and a qualitative change in microflora communities.

TABLE 2-20

Water Characteristics Measured Under Field Conditions
of Soils Supporting Mixedwood and Jack Pine

Material 'C' Horizon	Water Content		Available Water
	24 hours after rain	15 bars	
	---------- % by volume ----------		
Mixedwood	12	2	10
Jack pine	5	0.2	4.8

SOURCE: MacLean (1980)

TABLE 2-21

Chemical Properties of Mixedwood Soils in the Oilsands Area and Other Forest Areas of North America

Area	Horizon and Depth	CEC	Exchangeable Cations Ca	Mg	K	pH in H_2O
	cm	me/100g	me/100g			
Oilsands area[1]	Ae:10	6.5	3.0	1.5	1.0	5.1
	Bm, Bt:30	14.0	8.0	2.5	1.5	5.3
	C:40	3.0	2.0	0.3	0.3	6.5
Other Parts	Ae:7	6.7	3.0	1.0	1.0	5.6
of Canada	Bm, Bt:25	12.5	7.2	3.0	1.0	5.8
and U.S.A.[2]	C:35	2.0	0.9	0.5	0.3	6.0

Area	Horizon and Depth	Organic Carbon	Total Nitrogen	Carbon Nitrogen Ratio	Available Nutrients P_2O_5	K_2O
	cm	%	%		ppm	
Oilsands[1]	LFH:5-15	8-47	0.6-1.8	14-34	-	-
	Ae:7-12	0.4-0.9	0.01-0.07	12-20	-	-
	B:15-50	0.3-1.3	0.02-0.07	12-40	-	-
Other Parts	LFH:2-17	22-39	0.2-2.5	-	60	170
of Canada	Ae:3-11	0.1-0.8	0.01-0.5	-	80	240
and U.S.A.	B:8-40	0.5-1.6	0.02-1.3	-	20	120

[1] Oilsands: Turchenek and Lindsay (1978), Twardy (1978), Takyi et al. (1977).

[2] Others: Wilde (1953), Wilde and Patzer (1940), Nienstadt (1940), Dix and Swan (1971), Alway and McMiller (1933).

Cation exchange capacities are consistently higher for both A and B horizons under mixedwood than those under jack pine. Part of the increased capacity is due to higher levels of clay and silt in both horizons and concomitant increases in organic matter. Table 2-21 shows an average cation exchange capacity of 6.6 me/100 g soil in the A horizon for both in-area and out-of-area studies. The cation exchange capacity also increases in the B horizon, and can reach values of 25 me/100 g soil (Fowells 1965).

The level of exchangeable bases varies in accordance with cation exchange capacity. In all cases, there is more calcium than magnesium or potassium on the exchange complex. The mixedwood soil contains higher levels of both cations than the jack pine soil. The C horizon under mixedwood, however, is often similar to jack pine in exchangeable bases. The implication is that the major nutritional needs of white spruce and aspen are met from supplies located in the A and B horizons. The observation that the majority of roots in a mixedwood forest are found in these two horizons provides further support for this argument.

The pH of a mixedwood soil varies from strongly acidic (4.5) to neutral (7.0). The uppermost horizons are normally slightly more acidic than the B and C. In many cases, the mixedwood soil as a whole is slightly more basic than that of jack pine. This could be due to the chemical composition of the litter (higher in bases), the lower permeability of the mineral soil (less leaching), or a less acidic leachate from tree roots.

Studies outside the oilsands area have shown that levels of phosphorus and potassium (Table 2-21) are higher for mixedwood soils than for jack pine. It is on this basis that nutrient element levels have been assigned an essential role in determining a site index for mixedwood forests (Wilde 1953, Jameson 1965).

A typical soil profile under a mixedwood forest shows a decrease in organic carbon and total nitrogen from the LFH to the Ae horizon and an increase in the Bm or Bn horizons. The influence of higher clay contents on the change in subsoil carbon and nitrogen contents was discussed for jack pine soils and is equally true for mixedwood soils.

Organic carbon contents can vary from 0.1% to more than 10% in an Ahe horizon under a mixedwood cover. The lacustrine deposits associated with white spruce, white pine (Pinus monticola) and white birch in Wisconsin and Minnesota have very high organic matter levels in the Ah horizon (Wilde and Patzer 1940). The mixedwood soils in the oilsand area in northern Alberta very seldom have more than 1.3% organic matter (Table 2-21).

Total nitrogen levels in soils under mixedwood may be slightly higher than similar soils under jack pine, but on oilsands sites the difference is small. Nitrogen levels decrease more rapidly with depth than organic carbon; the C/N ratios in the Ae (12-20) and Bm (12-40) horizons reflect the anomaly of more carbon and less nitrogen.

228 SUMMARY OF SOIL PROPERTIES ASSOCIATED WITH THREE MATURE PLANT COMMUNITIES

The minimal values for the physical and chemical properties of sand slopes supporting grasses and jack pine and mixedwood soils are summarized in Table 2-22. These values coincide with vegetative cover on soils containing the coarsest materials and least fertile profiles; however, all values are found within the published literature as cited throughout the report.

Grassland soils in the boreal forest region are anomalous by definition. The reasons why grasses form permanent cover in an area which receives sufficient rain to grow pine, spruce and many other trees and shrubs are numerous, but the primary factors are probably water supply in the soil, nutritional requirements and fire, whether managed or unmanaged. The purpose of outlining the status of soil properties of stable dune sands is to identify the physical and chemical properties associated with minimum water supply and minimum fertility requirements on grass covered slopes.

The available water holding capacity of sand dunes is extremely low - approximately 5% by weight - and there is a very low content of fine particles in the mineral soil. The parent materials of grassland soils in the boreal forest can vary from wind blown sands to fluvial deposits resulting from departing glaciers. Drainage is rapid because particle sizes are large.

The cation exchange capacity, the levels of exchangeable cations, the total nitrogen content, and amounts of available nutrients all reflect the accumulation of small amounts of humified organic matter in the upper horizons, particularly in the A horizon. Soil development under the physical and chemical conditions imposed by the properties outlined for grassland dune soils in Table 2-22 is slow. Over long periods of time, however, one can expect significant accumulations of aluminum and iron oxides in subsurface horizons. These may eventually lead to modified hydrological characteristics.

Jack pine soils are highly variable because the tree species is adapted to extremes in regard to water and nutrients. Jack pine will grow on a wide range of parent materials with very little silt and clay in any horizon, and it can tolerate poor drainage or drought. A minimum level of 7.5% available water is taken from a comparative study on jack pine, Norway pine, and hardwoods in Minnesota (Alway and McMiller 1933). The level of silt and clay contents (5%) for jack pine soils represents a concensus of various studies done by Wilde and co-workers in Minnesota, Michigan and Wisconsin. The data are supported by Turchenek and Lindsay (1978) in the oilsands area and Fowells (1965) in a North American synthesis of jack pine soil properties.

TABLE 2-22

Summary of the Minimal Physical and Chemical Characteristics of Soils Associated with Three Mature Vegetation Types

Soil Property	Horizon	Vegetation Type: Grasslands	Jack Pine	Mixedwood
PHYSICAL				
- Parent materials		aeolian, deltaic, fluvial sands and silts	till, outwash sand, aeolian sand	lacustrine, till
- Silt + clay: (%)	A	2	5	15
	B	2	5	12
- Drainage		moderate-excessive	impervious-excessive	impervious-moderate
- Available water (%)	A	5	7.5	10
	B	4	4	7
	C	4	4	7
CHEMICAL				
- CEC (me/100g)	A	7.0	4.0	7.0
	B	5.0	6.0	12.0
	C	2.0	2.0	2.0
- Exch. cations (me/100g) Ca+Mg/k	A	5.0/1.0	2.5/0.5	4.0/1.0
Ca+Mg/k	B	3.0/0.5	4.0/1.5	10.1/1.0
Ca+Mg/k	C	2.0/0.5	0.5/0.1	1.5/0.3
- pH (mineral soil)		4.5-8.0	4.5-6.0	4.5-7.0
- Nutrients (ppm) P_2O_5		10	10	20
K_2O		10	90	120
- Org. C (%)	LFH	9.0	2.0	2.0
	A	0.20	0.2	0.1
	B	0.10	0.01	0.3
- Total N (%)	LFH	0.25	0.6	0.2
	A	0.01	0.01	0.01
	B	0.01	0.003	0.02

Jack pine soils are characterized often by a detectable, but unremarkable, accumulation of fines and organic colloids in the B horizon. The chemical properties associated with this change from surficial to subsurface horizons are outlined in Table 2-22. Cation exchange capacity values increase from 4-6 me/100 g soil, and the sum of exchangeable calcium and magnesium increases slightly.

The mixedwood soils have different characteristics than those associated with jack pine. The increased contents of silt and clay in the A and B horizons (12-30%) are important in making correct inferences about water and nutrient relations in these soils. The available water contents of mixedwood soils are in the range of 10%, almost double that for jack pine. Available water requirements are reflected in the total water requirements as calculated by MacLean (1980): mixedwood - 300-350 mm/yr and jack pine - 120-150 mm/yr.

The chemical and physical characteristics of mixedwood soils - cation exchange capacity, exchangeable cations and available nutrients - are higher than those of jack pine soils. The physical properties are more variable. Organic carbon and total nitrogen contents under mixedwood and jack pine are approximately equal.

CHAPTER 3

THE DESIGN OF SOILS FOR THE REVEGETATION OF THE OILSANDS

CHAPTER 3 - THE DESIGN OF SOILS FOR THE REVEGETATION OF THE OILSANDS

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FIGURES

3.1 INTRODUCTION

There are three primary processes characteristic of the ecology in the Canadian boreal forest that interrelate soil type to vegetative community: soil moisture status, nutrient supply, and physical stability. The purpose of this section is to identify the minimal levels of each soil property necessary for the establishment and initial growth of all three vegetative communities. The properties and their degree of expression are selected so that each soil can "evolve" or "mature" into a stable, representative unit capable of continual support of the chosen plant community. Chapter 3 is structured to answer the following questions:

- What properties are most critical in determining moisture, nutrient and erosion "function" in soils?
- What is the quantitative relationship of each of the selected properties to each of the three "functions"?
- What is the minimally acceptable degree of expression of each "function" for each vegetation community?
- What level of each soil property is needed to create each "function"?

3.2 THE ESTABLISHMENT OF PRE-SELECTED PLANT COMMUNITIES

It was pointed out in the introduction to this report that a revegetation strategy had to be formulated in order to define the soil-plant community type and the minimal properties acceptable for physical stability, nutrient supply and water balance. The strategy was discussed in Chapter 1; the purpose of this section is to provide the details of seed and seedling mixtures and establishment practices for each plant community.

321 DIKE SLOPE COMMUNITY

The most important role of the vegetative cover on dike slopes is to aid in permanent soil stabilization. The relatively steep slopes (25-50%) will have a prepared soil mixture laid down over deep tailings sand. The recommended vegetative mixture is a combination of grasses and legumes because of its rapid establishment and fast growth to complete ground cover. Other reasons for choosing a grass-legume mixture for dike slopes were outlined in detail in the revegetation strategy in Chapter 1.

The grass component will include sod forming (caespitose) and bunch grasses. The sod forming species form a continuous mat at ground level. The best results in the oilsands area to date have been obtained from pubescent wheat grass (Agropyron trichophorum), stream bank wheat grass (A. riparium) and redtop (Agrostis alba) (Lesko 1974). Bunch grasses tend to establish even more rapidly than sod formers, and thereby provide good cover initially. Crested wheat grass (Agropyron cristatum) has shown best results in the preliminary experiments in the oilsands area (Lesko 1974).

Legumes are used in combination with grasses on dike slopes to reduce nutrient deficiencies. The fixation of dinitrogen (N_2) by bacterial symbionts provides an inexpensive source of nitrogen in the root zone. Recommended legumes for conditions in the oilsands area are cicer milk vetch (Astragalus cicer), sainfoin (Onobrychis viciaefolia), alfalfa (Medicago sativa) and alsike clover (Trifolium hybridum).

Fertilizer used during the establishment of the grass-legume seed mixture should have a relatively low nitrogen content. Excessive nitrogen favours the growth of grasses in competition with the legumes and inhibits the formation of effective, nitrogen-fixing nodules on the legume roots.

322 JACK PINE COMMUNITY

Jack pine forests of low productivity are to be established in the study area. To provide interim stabilization and to prevent runoff related erosion between the seedlings, the area should be seeded to grasses and legumes in the first year and tree seedlings introduced in the second. Spot applications of herbicides could be administered prior to tree planting to reduce the competition between the grasses and tree seedlings.

Seed Mixture

In order to minimize the competition between the grass community and tree seedlings, a mixture of bunch grasses and open-sod grasses and legumes is recommended. Therefore, the seed mixture should consist of the following species: hairy wild rye (Elymus innovatus), smooth brome (Bromus inermis "Carleton"), slender wheat grass (Agropyron trachycaulum), late yellow loco-weed (Oxytropis campestris), common sainfoin (Onobrychis viciaefolia) and alsike clover (Trifolium hybridum). This mixture contains perennials of varying life spans with differing growth habits. With the exception of alsike clover, the nutrient requirements of these species are low. All of these species exhibit fair to good growth on sandy soils and have been used in reclamation trials in Alberta and the tarsands region with varying success rates (Watson et al. 1980, Rowell 1978, Fedkenheuer and Langevin 1978, Takyi et al. 1977). A seeding rate of 3-5 kg/ha is recommended to reduce tree/grass moisture competition (Fedkenheuer 1979). Used in conjunction with spot herbicide applications, this seed mix should result in sufficient interim cover for soil stabilization while minimizing grass/tree seedling competition.

Tree Seedling Densities

To produce jack pine of reasonably good tree form, a spacing of 2 to 2.5 m is recommended (Bella and DeFranceschi 1980, Benzie 1977). This results in approximately 1480 trees/ha.

Unless mortality rates in the first few years exceed 50%, seedlings should not be planted after the initial phase. Three year old bare root stock is recommended (Keller personal communication).

Although jack pine stands in the study area have an understory (Chapter 2), they are not included in this revegetative strategy. Once the jack pine plantations have been established and conditions become suitable, it is probable the understory components will invade.

323 MIXEDWOOD COMMUNITY

Due to the variable composition of a mixedwood forest (Chapter 2), a wide range of materials is capable of providing a suitable growth medium. As the required texture of this rooting substrate is generally medium to fine with a higher silt and clay content than jack pine soils, the erosion potential is minimally lower. Consequently, initial soil stabilization with grasses should not be required and the area can be planted directly to woody species. The trees and shrub considered in this strategy are aspen poplar, white spruce and rose (Rosa acicularis).

Trees

The differing growth rates and shade tolerances of aspen poplar and white spruce contribute to the variable nature of the mixedwood forest. Due to its growth and regenerative properties, aspen poplar generally forms the forest canopy with white spruce providing a tall understory (Nienstadt 1957, Rowe 1972). When the poplar dies canopy openings are created which encourage white spruce growth.

Therefore, depending on a variety of factors such as stand age, location and soils, either species can dominate the stand as noted in the study area by Stringer (1976). For this reason, a planting ratio of white spruce to aspen has been arbitrarily set at approximately 1.75 to 1 (Keller, personal communication). White spruce has been selected as the dominant species due to its commercial desirability relative to aspen poplar, and to aid in obtaining the required productivity of 1.4 m^3/ha/yr.

According to the Timber Management Regulations (Alberta Energy and Natural Resources 1978), a fully stocked stand is defined as containing "one or more established seedling trees in at least 80% of the 2.5

milacre units it includes" (~800 seedlings/ha). Therefore, allowing for a mortality rate of approximately 25%, the recommended mixedwood planting density is 1100 seedlings/ha, consisting of 700 white spruce and 400 aspen poplar. These trees should be planted on a three metre grid.

Shrubs

Shrubs are planted in conjunction with the tree seedlings to aid in the control of erosion.

A shrub species which has performed well in trials in the study area (Fedkenheuer 1979, Stringer 1976, Rowe 1956) and which is found in dry mixedwood areas is prickly rose (*Rosa acicularis*). Rose is a low to medium shrub (0.5 - 1 m height). The rose shrubs should be randomly planted amongst the tree seedlings wherever necessary. Unless there is a very high mortality rate (>60%) and/or erosion problems, the shrubs should not be replanted. As the trees become established, the understory should develop accordingly.

3.3 SOIL MOISTURE STATUS

The amount of water held in the soil available for plant use (available water content) and the rate at which water moves through the soil (hydraulic conductivity) are two components of soil moisture status directly related to vegetation establishment and performance. Although a thorough study of water relations in soils covers the interrelationships of soil water content, energy differences (as in matric or osmotic potential) and hydraulic conductivity, the scope of this study imposes a small restriction: we will use available water content capacity as the primary indicator of soil moisture status. A more complex and detailed study of the water relations of various soils in the oilsands area has been done by Maclean (1980).

331 SOIL PROPERTIES AFFECTING SOIL AVAILABLE WATER

Available water is defined as the difference in water content (% by weight) of a soil at 0.1 bars pressure (field capacity of sandy soils, see Chapter 2) and 15 bars pressure (permanent wilting point).

The soil properties which have the most influence on available water are texture (particle size distribution), organic matter content, bulk density, soil depth, depth of wetting and the chemical environment. Other expressions of soil water relations, such as pore size distribution total porosity and hydraulic conductivity at varying moisture contents, are generally predictable from a knowledge of other soil properties (Salter *et al*. 1967).

The chemical properties which are influential in modifying soil water characteristics are related to the aggregation of particles, the boundary conditions surrounding each particle and the osmotic potential in the soil solution. Generally, the oilsands materials have a low sodium adsorption ratio (SAR), a low content of exchangeable sodium versus other cations and a low electrical conductivity. Therefore, in the analysis of the present oilsands environment, the chemical influence on water relations is ignored.

.1 Particle Size Distribution

The effect of soil particle size on available water content is most obvious when comparing coarse textured (loamy sands) and medium textured materials (loams and silt loams). Figure 3-1, modified from a more complex histogram in Russell (1973), gives the scatter of available water content for over 100 samples of surface soils collected in England and Wales. It shows that the highest volumes of available water are in the loams (sand $< 60\%$, clay $< 25\%$, silt $> 15\%$). The same trend has been evaluated and confirmed by Salter and Berry (1966). There is a rapid rise in available water content when sand contents are decreased and silt and clay contents increase. However, when clay contents reach a level of approximately 20% (loams), the permanent wilting percentages tend to increase at the same rate as field capacity percentages, thereby stabilizing available water contents (Russell 1973).

.2 Bulk Density

Bulk density is defined as the soil mass per unit volume and thus reflects both the density of the soil particles and the total pore space (Hausenbuiller 1978). There is a reasonably good relationship between texture and the bulk density of mineral soils. Bulk density is generally highest in coarse textured soils where there is a low porosity in spite of a high proportion of large diameter pores. Conversely, the total pore space volume of fine textured soils tends to be large and bulk density values are low (Table 3-1). Hydraulic conductivity under unsaturated conditions is higher in soils with more total porosity and smaller diameter pores (Klute 1973). Therefore, mineral soils with lower bulk density values can supply water to plant roots at faster rates than those with higher bulk densities.

The bulk densities of the materials in the oilsands area of northern Alberta were reported in Chapter 2. Tailings sand has an extremely high bulk density value at 1.5-1.6 g/cm^3; values for overburden vary according to type from 1.1-1.4 g/cm^3; and peat has an exceptionally low value of 0.1 g/cm^3.

.3 Organic Matter Content

The available water content of a soil can be raised somewhat by increasing the organic matter content, although the largest increases are a result of massive organic matter additions to coarse sands (Feustel 1938).

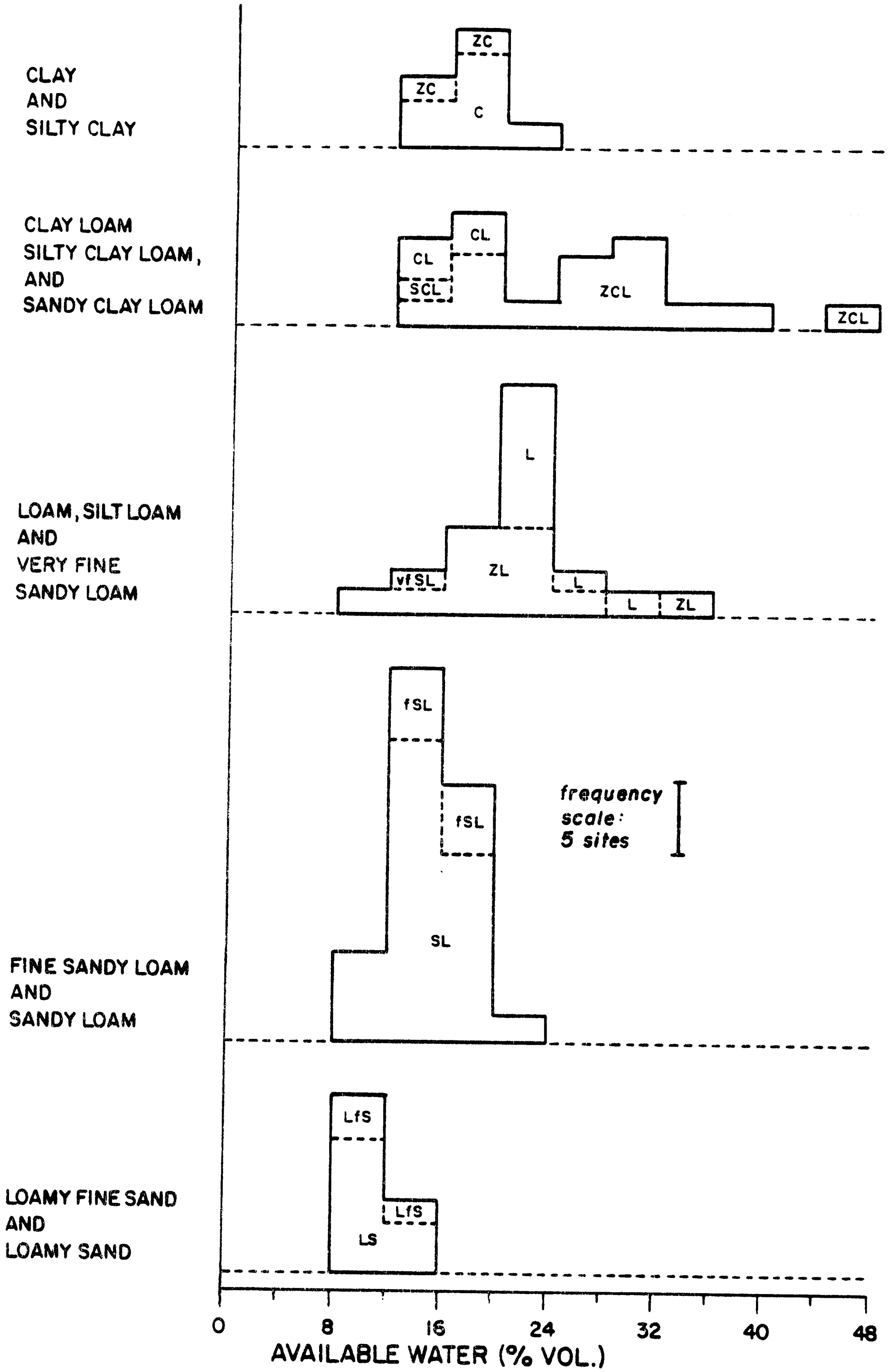

FIGURE 3-1

HISTOGRAMS OF AVAILABLE WATER CONTENT IN MINERAL SURFACE (A) HORIZONS OF FIVE TEXTURE GROUPS

SOURCE: RUSSELL 1973

TABLE 3-1

General Relationship Among Texture, Bulk Density, and Porosity of Soils

Textural Class	Bulk Density	Porosity
	g/cc	%
Sand	1.55	42
Sandy loam	1.40	48
Fine sandy loam	1.30	51
Loam	1.20	55
Silt loam	1.15	56
Clay loam	1.10	59
Clay	1.05	60
Aggregated clay	1.00	62

SOURCE: Hausenbuiller 1978.

.4 Soil Depth

Soil depth and depth of rooting are both important influences on available moisture content. They are interrelated in that fine textured soil and impermeable layers can impede moisture movement and restruct rooting to very small soil volumes.

332 SOIL AVAILABLE WATER AND VEGETATION COMMUNITY

The amount of available soil water needed for each vegetation community type depends on prevailing climatic conditions, the water holding capacity of the soil materials and the type of plant community. All of these factors are reviewed in depth in Chapter 2; it is the purpose of this section to combine the sources of information into an individual recommendation of water availability for each of the three vegetation communities. Furthermore, we will recommend a means of combining soil materials (sands, overburden and peat) such that the water requirements of each vegetation type are met.

.1 Available Soil Water and Rooting Depth for Dike Slope Vegetation

Reconstructed soils on dike slopes require an available water capacity of approximately 15% to a depth of 30 cm. The reasoning behind this recommendation can be outlined as follows:

1. There is a strong possibility of recurring seasonal water deficits for vegetation on deep tailings sand (having a 7.5% available water content over a vertical distance of one metre), as shown in the evapotranspiration calculations in Chapter 2.

2. Measurements on existing dike slopes in the oilsands area (with 7.5% available water) have shown that the total water potential in the top 15 cm frequently reaches -9 bars (MacLean 1977, 1980). Furthermore, there are several studies which show that seed germination and seedling emergence of grasses and legumes are severely (> 50%) reduced at -9 bars soil water potential (Wright et al. 1978, Hughes et al. 1966).

3. Increases in plant performance as estimated by productivity and percent of plant cover are related directly to increases in soil moisture, especially in the minimal moisture ranges found in sandy soils (Rowell 1978, Logan 1978). Since dike slope stabilization depends on a stable, complete ground cover (as will be shown later in this chapter), an increase in available water content in the surface horizons will result in long-term physical stabilization.

4. The major portion of root biomass accumulation of grasses and legumes on dike slopes corresponds directly to the depth of maximum available water storage (Takyi et al. 1977, Rowell

1978). Therefore, an increase in available water storage to 30 cm will result in deeper rooting patterns and enhanced physical stability.

.2 Minimal Soil Properties for Water Supply on Dike Slopes

Chapter 2 presented information on the physical characteristics of oilsands tailings, mineral overburden and peat types found in northern Alberta. These materials were shown to have available water contents of 7.5%, 23-39% and 15-30% respectively. The differences in available water content of these materials are due mostly to differences in particle size composition and organic matter content. By selecting the right combination of characteristics, therefore, it should be possible to reconstruct a soil capable of achieving an available water capacity of 15% to a depth of 30 cm.

The textural classes of soil (determined on the basis of particle size distribution) which correspond best to 15% available water capacities are sandy loam, fine sandy loam, silty loam and loam (Figure 3-1). By means of a textural diagram (Figure 3-2), these classes can be converted to specific ranges of sand, silt and clay. Since the limitation pertinent to this discussion of water supply is the allowable percentage of sand in relation to that of silt and clay, the coarsest acceptable textural class will serve as the limit to sand content. A sandy loam contains maximally 70% sand to 30% silt and clay. Therefore, the dike slope soils should contain at least 30% silt and clay in order to have 15% available water, unless the organic matter content or bulk density ratings replace some portion of the influence of particle size.

Available soil water in sandy materials can be increased by approximately 1% for each percentage point of well-humified organic matter stabilized in the soil (Allison 1973). Since only 30% of organic material added to soil is finally stabilized (Rowell 1978, McGill and Paul 1977), available water is increased by 0.33% for each unit dry weight of added organic matter. A 30 cm slice of topsoil weighs approximately 4×10^6 kg/ha. One would need to add 120,000 kilograms (dry weight) of organic residues per hectare to increase the available soil water by 1%.

In summary, a reconstructed dike soil in the oilsands area needs an available water supply capacity of about 15% in the top 30 cm in order to support a full stand of grass and legumes during the initial revegetation period. This soil water supply status can be achieved by manipulating particle size contents (minimum 30% silt plus clay) or organic matter contents (1% increase in available water per 1% stabilized organic matter) or both.

.3 Available Soil Water and Rooting Depth for Jack Pine

Mature jack pine forests have been shown to have an available water holding capacity as low as 7.5% and support the low levels of productivity required for reclamation of the oilsands (Chapter 2). The

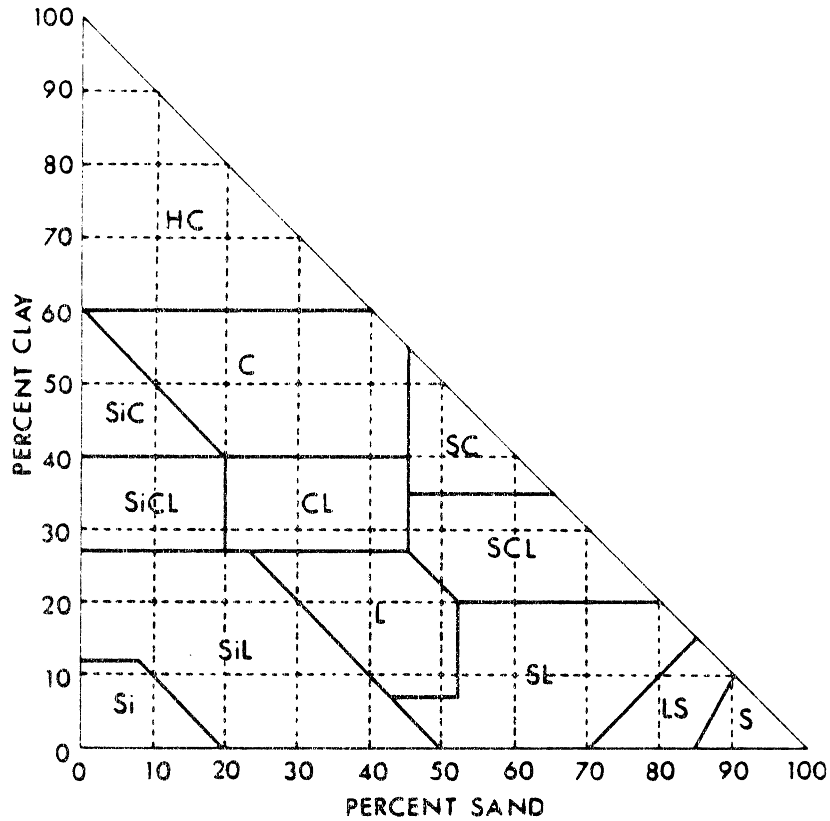

FIGURE 3-2

Soil Texture Classes Percentages of Clay and Sand in the Main Textural Classes of Soil ; the Remainder of Each Class is Silt (Canada Soil Survey Committee 1978).

soils that have low available water contents and support jack pine and associated understories are deep - often more than two metres of relatively uniform sand - and do not have restricting layers. Therefore, as much as 150 mm (200 cm x 7.5%) available water can be stored in the soil, ready to satisfy the evapotranspirative demands of climate and plant cover.

There are two basic reasons why the available water capacity of reclaimed soils to be seeded to jack pine should be higher than 7.5%:

1. The soil volume exploited by the roots of jack pine seedlings is very small in the first few years after establishment. Therefore, the water required during vegetative growth is extracted from a relatively small reservoir.

2. Jack pine establishment will occur a year after the seeding of a grass-legume cover which will compete with the jack pine seedlings for available water.

On the other hand, there are several factors which lessen the severity of a water imbalance of a jack pine stand on tailings sand: first, water deficits in a grass-legume and jack pine stand will not reach maximum values if the grass-legume cover is controlled in those areas where force seedlings are set out; second, the transpiration potential of very young seedlings is much less than that of a mature tree.

In order to maximize the possibility of a successful establishment of a grass-legume cover and jack pine seedlings a year later, we recommend that the available water holding capacity of the surficial 15 cm of soil average 15%. Even though the underlying material may have a much lower water holding capacity, it is assumed the soil horizon boundary will not affect tree root penetration into the subsurface.

The reduction in soil depth requirement from 30 cm for dike slopes to 15 cm for jack pine soils is justified by the decrease in erosion sensitivity. Unlike the situation on relatively steep dike slopes, the jack pine soils are relatively immune to water erosion when a full vegetative cover is established.

.4 Minimal Soil Properties for Moisture Supply to Young Jack Pine Stands

Using the same information and reasoning as described in dike slope soils, newly reconstructed jack pine soils can best meet the minimum requirements of water balance by having a surficial (15 cm) layer with 30% silt and clay or large amounts of organic matter. The trade-offs between the fines fraction in the mineral soil and organic matter were explained in the previous section; in short, approximately 60 tonnes (dry weight) of peat are needed per hectare to raise the available water capacity of the top 15 cm by 1%.

.5 Available Soil Water and Rooting Depth for Mixedwood

A mature mixedwood forest has a minimal available water holding capacity of 10% to at least 50 cm depth under climatic conditions such as those of the oilsands area (Chapter 2). A reconstructed soil which is to be planted to a mixedwood stand will need more available water in the surficial layer and possibly less available water at depths exceeding 50 cm for the following reasons:

1. The surficial layer (15 cm) will provide the necessary water requirements for the young trees and shrubs for the first one or two years while larger root systems are being established.

2. The uppermost subsoil layer (15-50 cm) is a zone of maximum root concentration for most mixedwood species and, therefore, plays an important role in providing adequate moisture for developing mixedwood stands.

3. The bottom soil layers (>50 cm), if constructed from unamended tailings sand, may not contain large amounts of available water, but these horizons should be relatively uniform and offer no critical impediment to root growth. Therefore, although available water capacity may be low (<7.5%), an increased volume of soil can be used to supply moisture requirements.

We recommend that the mixedwood forest soils have an available water capacity of 15% in the surficial 15 cm. In the soil layer from 15-50 cm, 10% available water is probably sufficient. And, finally, the 7.5% available water in the unamended tailings sand is sufficient for mixedwood soils below the 50 cm depth.

.6 Minimal Soil Properties for Moisture Supply to Young Mixedwood Stands

The rationale for selecting minimum properties to supply the recommended water contents for mixedwood stands is predicated on two kinds of evidence:

1. The relationship of soil property (fines content and organic matter) to available soil water. The support for this evidence has been cited before for dike slopes and jack pine soils, and need not be repeated here. It results in a justification of 30% fines content in the surficial 15 cm, 10% fines content in the layer from 15-50 cm, and unamended tailings sand to the bottom of the root zone. These levels can be decreased by adding large amounts of organic matter.

2. The mixedwood forest must achieve a given level of productivity (mean annual increment), and there are several studies which relate forest productivity to site index which can be related in turn to the fines content of the root zone (Perala 1977).

The reclaimed soils to be planted to mixedwood are designed to support a minimally productive stand, defined as a mean annual increment of 1.4 m^3/ha/yr. The yields of bigtooth aspen in northern Michigan can be used to represent the relationship of minimum fines content to site index to mean annual increment (Table 3-2). The site index in this example is defined on the basis of silt and clay content in the top 36 inches (100 cm) of soil profile and the dominant drainage pattern. Site index 40 signifies 10% silt and clay or less in the upper 100 cm and an excessively well drained profile. Mean annual increment is slightly above the minimum 20 ft^3/acre/yr (1.4 m^3/ha/yr).

In the oilsands we recommend that the mixedwood forest soils be composed of 30% silt and clay in the surficial 15 cm, 10% silt and clay in the 15 - 50 cm layer, and 50 - 100 cm of unamended tailings sand (3% silt and clay). A soil reconstructed in this way has a minimum of 9.5% silt and clay in the upper 100 cm, a value sufficiently close to the 10% silt and clay content of the soil with a site index of 40 to ensure the minimum productivity needed in northeastern Alberta.

3.4 SOIL FERTILITY

Soil fertility is of major importance in regulating plant growth on reconstructed soils. In addition to providing mineral elements necessary for plant development, the correct management of nutrient regimes can also greatly increase the efficiency with which water is used (Power et al. 1978). Although there are 16 elements needed for plant growth and reproduction (Barber 1981), this report will discuss only those elements, major or minor, which have been shown to be important in the oilsands area. The primary factors affecting the availability of nutrients are related to the physical, chemical and biochemical status of the soil; we examine total nutrient contents, organic matter content, pH and cation exchange capacity as soil properties which account for the largest part of the nutrient supplying capacity. Finally, a recommended amount of each element for each soil-vegetation type is established, and an appropriate mixture of soil properties is outlined to meet these requirements.

341 FACTORS AFFECTING SOIL NUTRIENT SUPPLY

Nutrient supply is used in this report to mean the capacity of the soil to store and make available to plants adequate quantities of major and minor nutrient elements. The majority of nutrients absorbed by plants enter through the root system in water and, therefore, the concentration of nutrients in the soil solution is the amount immediately available for plant uptake. However, only a relatively small fraction of nutrients contained in a soil are in solution; the ions in solution are in equilibrium with those held in solid or nonactive forms by several mechanisms (MacLean 1977). Each mechanism which inactivates

TABLE 3-2*

Normal Yield Table for Bigtooth Aspen in Northern Lower Michigan; All Trees 0.6 Inch d.b.h. and Larger (Perala 1977)

Age[1]	Dominant Height[1]	Number Trees/Acre	Stand Basal Area[1]	Gross Yield/Acre 4-inch Top	
years	feet		ft^2/acre	Cords[2]	MAI[3]
			SITE INDEX 40[4]		
30	36	540	48	6.88	21.1
40	39	407	71	11.35	26.1
50	40	357	76	12.40	22.8
60	41	313	65	10.98	16.8

[1] Data extracted from Table 11, page 26 (Perala 1977)

[2] Data is interpolated from Table 7, page 23 (Perala 1977)

[3] Calculation by Dr. R. Fessenden (personal communication): Mean annual increment (MAI) = cords x 92 (ft^3/cord) ÷ age (in years)

[4] Site index 40 was chosen on basis of Table 1, page 51 (Perala 1977): excessively well drained, silt and clay in top 36 inches is 10% or less.

ions, but gradually releases a fraction of them into the soil solution as their concentration is lowered, can be regarded as an ionic reservoir (Figure 3-3). The stronger an ion is held (bonded) in a given reservoir (mechanism), the lesser its tendency to go into solution, and the lower its availability to plants. The relationship of a reservoir and an ion is determined by (i) the size of the reservoir in relation to the amounts of ion, and (ii) the relative strength of bonding between ion and reservoir. For example, due to the relatively large magnitude of cation exchange capacity (CEC) of most soils compared to other mechanisms, and of existing amounts of exchangeable calcium, the CEC mechanism is most often involved in regulating the availability of calcium to plants (MacLean 1977). A cation such as copper may be regulated more by chelation than by cation exchange capacity because of the smaller amount and stronger bonding by chelation.

The reservoirs or mechanisms responsible for the supply of nutrients of most interest in the oilsands are: cation exchange capacity, microorganism absorption and solubility-insolubility capacity. Cation exchange capacity is a relatively easily measured soil property which influences the availability of potassium, calcium and magnesium. The absorption of ions by microorganisms is a complex process in soils regulated by many soil factors. Although this process will be discussed in more detail in Chapter 4, we will use soil organic matter content and quality to evaluate the status of microbial activity. In addition to a knowledge of the total nutrient pool, a measurement of soil pH and buffering capacity is needed to estimate the solubility-insolubility capacity.

.1 Cation Exchange Capacity

Cation exchange capacity is the capacity of the soil to hold cations and to exchange species of these ions in reversible, chemical reactions (Buol *et al.* 1973). The ion exchange property of a soil is due almost entirely to the clay and silt fractions (<20 µm) and the organic matter, the colloidal material of the soil being most important (Sandoval and Gould 1978). Cation exchange is particularly important to soil fertility studies because of the following inferences which can be made (Buol *et al.* 1973):

- The prescence of given clay mineral species:

CEC (me/100 g)	Clay mineral
3 - 15	kaolinite
80 - 150	smectite (including montmorillonite)
10 - 40	illite
100 - 150	vermiculite
10 - 40	chlorite

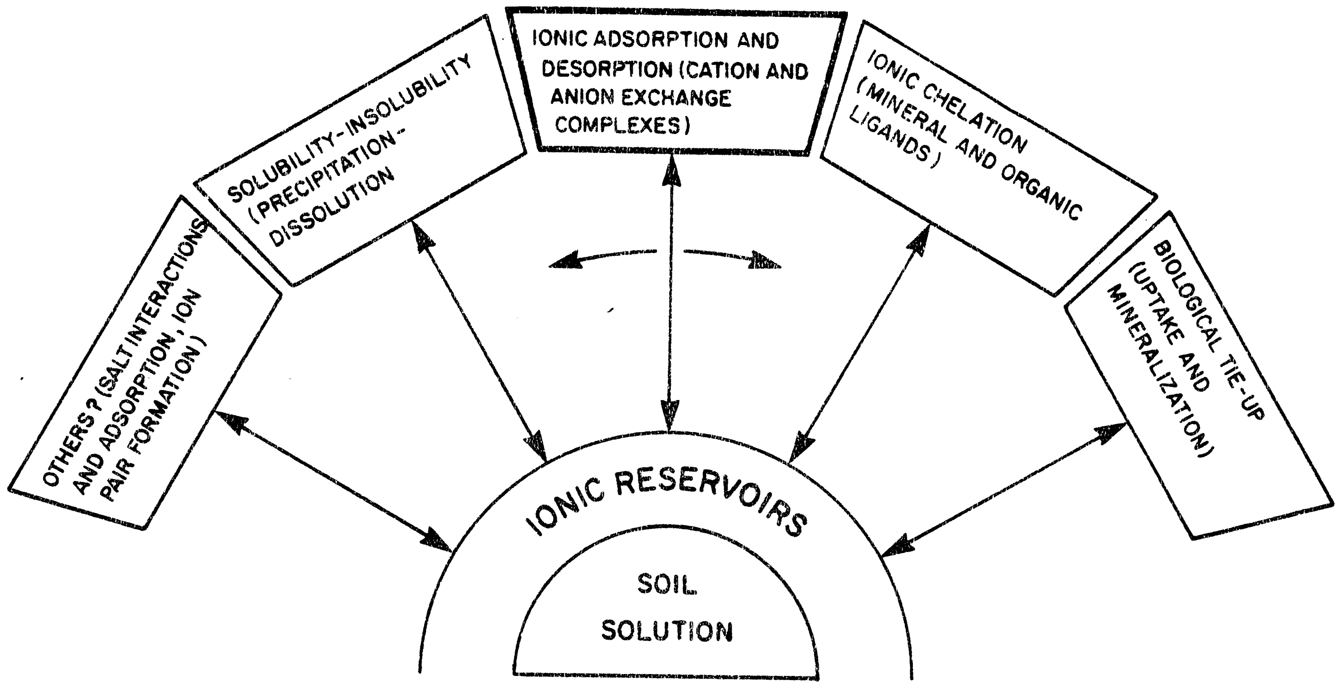

FIGURE 3 - 3

SCHEMATIC DIAGRAM OF THE IONIC RESERVOIRS (MECHANISMS) REMOVING IONS FROM AND RETURNING IONS TO THE SOIL SOLUTION (MacLEAN 1977)

- Relative degree of weathering of the soil: Low cation exchange capacity indicates low amounts of primary weatherable minerals. High cation exchange capacity indicates higher amounts of primary minerals with higher nutrient supplying capacity.

- Agronomic/forest nutrition: High CEC in a mineral soil indicates a high plant nutrient storage capacity. In cases where high CEC and low pH co-exist, there may be a problem with aluminum toxicity.

- Percent base saturation: The cations countering negative charges on soil clays and organic matter can be placed in two groups: (1) exchangeable bases - Ca, Mg, K, Na; and (2) exchangeable acid-generating cations - H, Al. Both H and Al are ordinarily present and are termed the exchangeable acidity.

The two components of total cation exchange capacity in soils - the mineral and organic colloids - are not equally represented in a developing soil profile. The contribution of the mineral fraction is less because only intense mineral weathering can affect it (Birkeland 1974). The organic component, on the other hand, is a result of the biological activity in the soil and, as such, can increase rapidly.

The cation exchange capacities of the materials located in the oilsands area range from a low of 3.0 me/100 g for tailings sand (Table 2-10), 25 - 30 me/100 g for overburden (Table 2-6), and 150 me/100 g for peat (Table 2-7). In all cases the calcium is the dominant cation, although sodium is present in large amounts in some overburden materials (Fessenden personal communication).

For each percentage point increase in silt and clay content in the reconstructed soil, there will be an approximate increase of 0.27 me/100 g in cation exchange capacity.* Each 1% increase in organic matter (assume CEC equal to 150 me/100 g) will result in an increase of 1.47 me/100 g in the cation exchange capacity of the reconstructed soil. This latter calculation coincides almost perfectly with results on a variety of agricultural soils showing a decrease in cation exchange capacity of 1.50 me/100 g for each 1% soil organic matter removed (Coleman and Thomas 1967).

.2 Soil Organic Matter

Soil organic matter includes the soil biomass (microflora and microfauna), partially degraded plant, animal and microbial components, and the soil humic constituents. The soil humus is that portion which is

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* This calculation assumes that CEC of silt and clay = 30 me/100 g and CEC of sand = 3 me/100 g.

associated intimately with the clay and sequioxide fractions; it represents 75 - 85% of the total soil carbon (Kononova 1966, Paul 1970). The humus acts as a major reservoir of nitrogen and a secondary, but important, source of phosphorus, sulphur and potassium (Witcamp 1971, Campbell 1978).

The degree of maturation, stability or quality of soil organic matter is characterized by the total nutrient content and the ratio of carbon to individual nutrients like nitrogen (C:N), phosphorus (C:P) or sulphur (C:S). The reason for measuring total nutrient content in organic matter is because the available nutrient supply is dependent on the size of the reservoirs containing the nutrient ion in question. The reason for measuring the carbon-nutrient ion ratio is that this ratio is indicative of the strength with which the ion is held in the reservoir (and consequently not released into solution for plant absorption). The higher the carbon-nutrient ion ratio, the less likely the ion will be made available to the plant.

Freshly incorporated plant debris often has a C:N ratio of 60:1 (Paul 1970). Under these circumstances nitrogen will be strongly held in the organic matter reservoir (immobilized) until enough carbon has been released to lower the ratio to 15:1. Well stabilized humus in temperate soils has a C:N ratio of 10:1, a C:P ratio of 100:1 and a C:S ratio similar to that of carbon and phosphorus.

The organic matter content of the materials available for soil reconstruction in the oilsands area varies from nearly zero for oilsands tailings (Takyi *et al.* 1977, Logan 1978), less than one to five percent, depending on horizon, for overburden materials to 75% for peat (Table 2-7)*. The carbon-nitrogen ratio for organic matter in overburden is low, approximately 15:1, but the C:N ratio for peat is 30:1.

.3 pH and Buffering Capacity

pH is defined as the negative logarithm of hydrogen ion activity. As a measurement of soil acidity or alkalinity, pH values can lead to a number of inferences in reference to soil fertility (Buol *et al.* 1973):

- pH <4.5. At these pH values significant amounts of exchangeable hydrogen and aluminum are present due to the disassociation of strongly acid functional groups in the organic fraction, the chemical transformation of free acid sulphur compounds to sulphates, the hydrolysis of fertilizer salts, or to the increased solubility of $Al(OH)_3$.

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* Organic matter equals organic carbon multiplied by 1.72.

- pH 4.5 - 5.8. In this range, there exists sufficient exchangeable aluminum to adversely affect plant growth.

- pH 5.8 - 6.5. The acidity present is sufficient to adversely affect acid-sensitive crops, such as alfalfa. The soil is 70-90% base saturated.

- pH 6.5 - 8.0. In this pH range, the soil is fully base saturated. There is no exchangeable aluminum present. Free calcium carbonate may be present inside soil aggregates that have restricted diffusion.

- pH 8.0 - 8.5. The soil is fully base saturated, with most of the exchangeable bases being calcium and magnesium. Free carbonates are present.

- pH 8.5 - 10. pH levels in this range indicate the presence of high amounts of soluble salts, especially sodium, although sodic horizons may not be present.

- pH >10. The soil is highly saturated with sodium and may be termed an alkali soil.

The range of pH values appropriate for the establishment of forest stands reflects the interrelationship of pH and nutrient availability. Figure 3-4 demonstrates the effect of pH on major and minor nutrients in both mineral and organic soils. In mineral soils, nitrate, nitrogen, phosphorus and potassium are most available at pH values between 5.5 and 7.5. Magnesium, sulphur, copper and boron show a similar relationship. Alkaline pH levels allow calcium and molybdenum to dominate, while acidity promotes the availability of aluminum, iron, manganese and zinc.

In shifting from an inorganic to an organic soil, optimum pH ranges for most nutrients are expanded and shifted slightly toward more acid conditions.

Sudden changes in pH can negatively affect nutrient availability and render trees susceptible to pathogen attack (Wilde 1958). It has been found that soils with high and low pH values can be corrected by proper silvicultural practices, but care must be taken not to destroy the natural equilibrium of exchange acidity (Lutz and Chandler 1942).

The oilsands tailings are not buffered naturally against wide swings in pH (Figure 3-5). The addition of one milliequivalent of hydrogen or hydroxide per 100 g sand results in a change of 1.5 to 3 pH units. The addition of equal volumes of peat and tailings sand reduces the pH of the material to 4.4 and increases the buffering capacity. However, the pH and buffering capacity are most dramatically improved by mixing equal volumes of tailings sand and overburden. Unpublished comparisons have shown that a three part mixture (equal volumes) of peat,

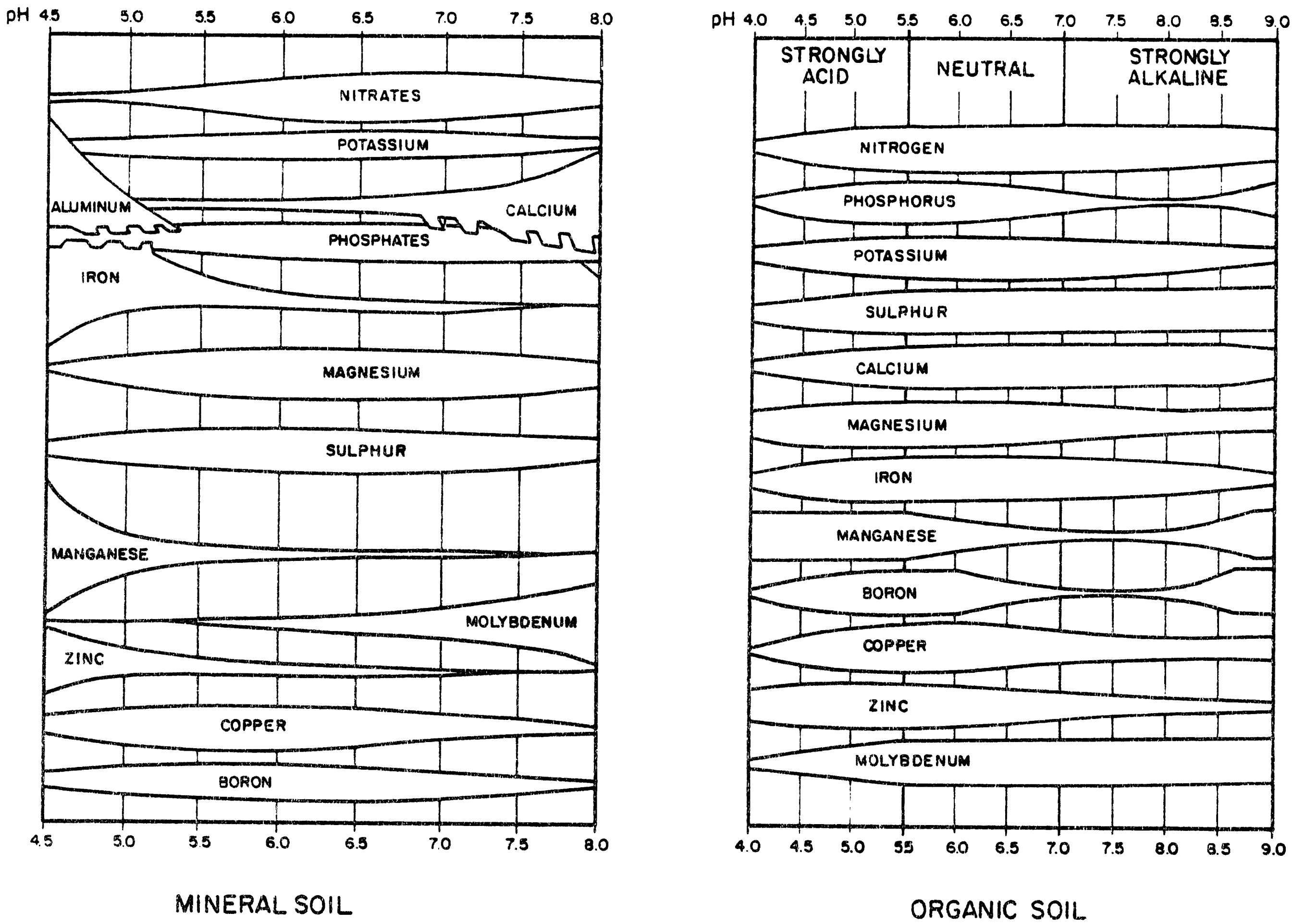

FIGURE 3-4

THE EFFECT OF pH ON NUTRIENT AVAILABILITY IN MINERAL AND ORGANIC SOILS (HINISH 1980)

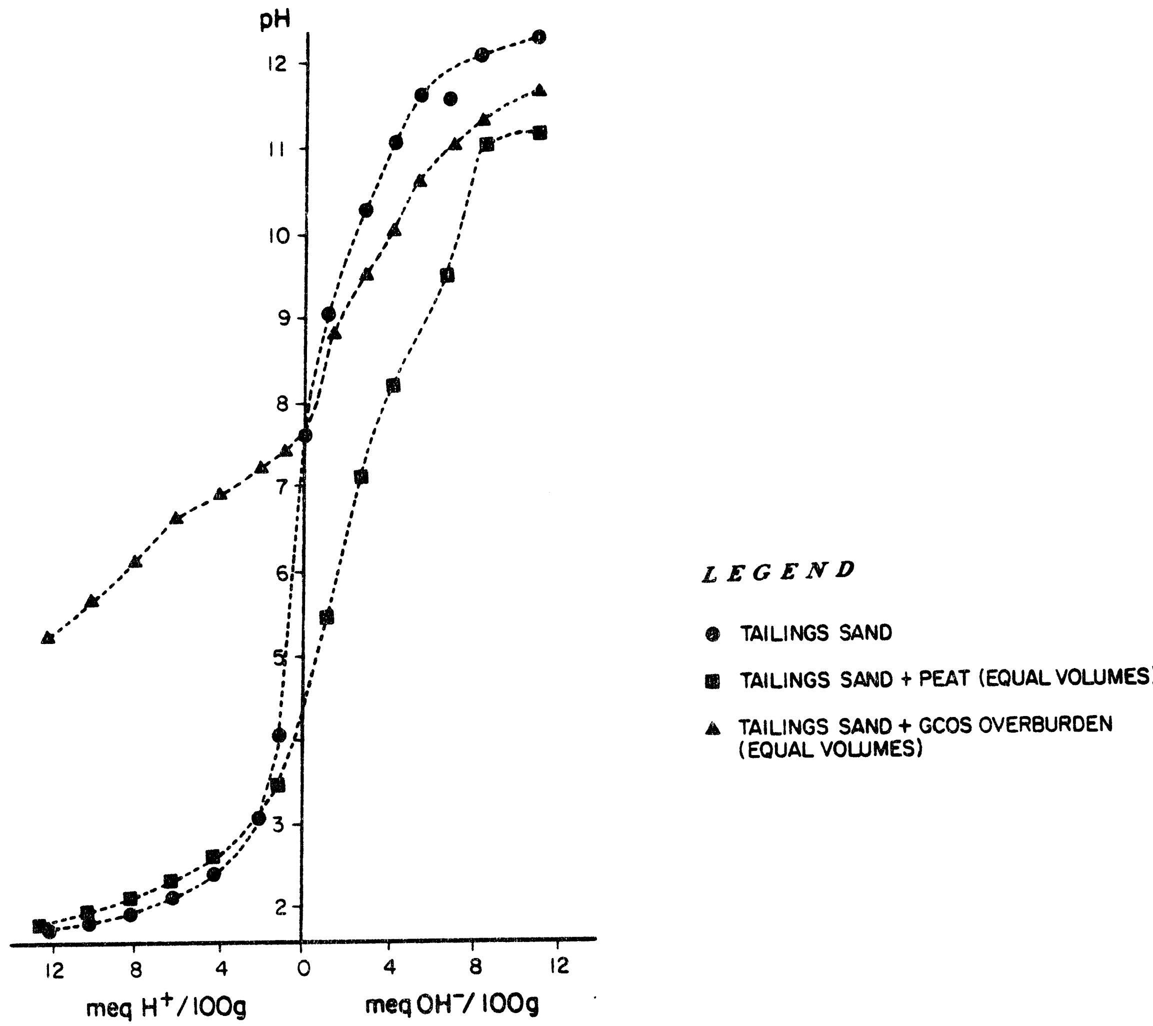

FIGURE 3-5

THE BUFFERING CAPACITY OF TAILINGS SAND & TAILINGS SAND - SOIL MIXTURES (TAKYI ET AL 1977) overburden and tailings sand results in a curve very similar to the overburden - sand example in Figure 3-5 (Takyi *et al.* 1977).

342 ESSENTIAL NUTRIENT ELEMENTS

Essential elements are divided somewhat arbitrarily into those required by the plant in large or small quantities. Nitrogen, phosphorus, potassium, sulphur, calcium and magnesium are used in tens or hundreds of kilograms per hectare; the micronutrients or trace elements may be used in kilograms or grams per hectare per year (Table 3-3).

.1 Nitrogen

The soil organic matter is the largest and most important reservoir of potentially available nitrogen in any plant-soil association. It is common to find total nitrogen contents of 6,000 to 10,000 kilograms per hectare in the surficial 15 cm of soil. Not all the reservoir is biologically active (organic nitrogen is synthesized and decomposed by the action of soil microorganisms), and only a minor fraction of the total nitrogen pool is released (mineralized) in an inorganic form each year. Studies carried out on grassland soils immediately south of the boreal forest have shown that the net annual release of nitrogen is approximately 1% of the total nitrogen reservoir (Paul personal communication). This fraction represents the amount of nitrogen available for plant absorption.

Analytical determination of available nitrogen is useful in predicting nutrient requirements of plants only when levels are above 15-20 ppm. Available nitrogen contents below this amount are indicative of a small reservoir and low turnover (Berg 1980).

Except for the peat deposits, the materials available for soil reconstruction in the oilsands area are virtually devoid of biologically active, organic nitrogen. The tailings sand has less than 0.03% total nitrogen (Table 2-10) and only the leaf litter layer and surficial cap, representing a minor proportion of the overburden, have nitrogen contents above 0.01% (Tables 2-17 and 2-21). Peat, on the other hand, is rich in nitrogen (1.5%, Table 2-7), even though the high carbon-nitrogen ratio (30:1) may mean that the annual net release of nitrogen is much less than the 1% identified for prairie soils.

In general it can be shown that available nitrogen is increased by 12 kg/ha/yr for every 1% increase in stable organic matter (humus) per 15 cm soil depth. The assumptions and calculations underlying this estimate are as follows:

Assumptions:

- 15 cm depth per hectare = 2×10^6 kg
- organic carbon = 58% organic matter

TABLE 3-3

Essential Nutrients Absorbed from Soil and Representative Roles in the Plant

Element	Absorption Form	Total kg/ha (elemental form) present in soil (general value)*	Available kg/ha (general value)*	Representative Role in Plant
Nitrogen (N)	NO_3^- NH_4^+	6,000	1-50	Amino acid; protein synthesis; nucleic acids
Phosphorus (P)	$H_2PO_4^-$ HPO_4^{2-}	1,300	0.01-0.10	Utilizing energy from photo-synthesis
Sulphur (S)	SO_4^{2-}	900	1-10	Sulfhydryl groups
Potassium (K)	K^{+}	55,000	5-15	Hexokinase
Calcium (Ca)	Ca^{2+}	16,500	10-100	Calcium pectate
Magnesium (Mg)	Mg^{2+}	6,600	5-50	Chlorophyll; respiration
Iron (Fe)	Fe^{2+}	55,000	Trace	Cytochromes; ferredoxin
Manganese (Mn)	Mn^{2+}	1,360	Trace	Formation of amino acids
Boron (B)	BO_3^{2-}	100	Trace	Possibly in sugar translocation
Copper (Cu)	Cu^{2+}	55	Trace	Nitrate reduction
Zinc (Zn)	Zn^{2+}	55	Trace	Dehydrogenases
Molybdenum (Mo)	MoO_4^{2-}	Trace	Trace	Nitrate reductase
Chlorine (Cl)	Cl^-	Trace	Trace	Phososynthetic phosphorylation

* Adapted from Mitchell (1970)

- carbon-nitrogen ratio of stable organic matter = 10:1
- 1% total nitrogen in 15 cm depth is made available ("net mineralization") per year

Calculations:

- 1% organic matter per ha (15 cm) = $2x10^4$ kg
- organic carbon (58%) = 11,628 kg
- total nitrogen (10%) = 1,163 kg
- available nitrogen (1%/yr) = 11.6 or 12 kg/ha/yr

.2 Phosphorus

Phosphorus is an example of a nutrient ion regulated by the ionic adsorption-desorption and solubility-insolubility mechanisms as shown in Figure 3-3. The amount of phosphorus in the soil solution at any one time is very small because it forms sparingly soluble compounds with aluminum, iron and calcium (MacLean 1977). These cations may be part of compounds on which phosphate is adsorbed (clay edges, calcium or iron oxides and organic moities for example) or they may be contained in the soil solution and react with phosphates to form slightly soluble precipitates (Lindsay 1981).

By convention, the solution phosphorus is known as the "intensity" factor, while the phosphorus adsorbed on the clay particles and amorphous materials or precipitated as an iron, aluminum or calcium complex - the solid phase - is known as the "capacity" factor (Fox 1981). Plants growing in soil absorb phosphorus only from the soil solution and simple calculations show that in order for normal plant growth and phosphorus uptake to occur, the soil solution must be renewed several times each day during the growing season. As nutrients are removed from the soil solution, there is a tendency to replace the deficit from solid phase sources. It is this ability (or "capacity") to replace phosphorus in the soil solution that results in a soil judged to be high or low in available phosphorus. Another term commonly used to describe the capacity factor is "labile" phosphorus or that portion of total soil phosphorus that is relatively loosely bound onto or associated with soil minerals or amorphous materials. Labile phosphorus is normally a small percentage of total phosphorus.

The clay content of soil is a property closely related to the level of available phosphorus. Clay increases the adsorption surface available to phosphorus. Although more phosphorus is required by a soil high in clay than one high in sand to reach a given phosphorus level, the clay soil can satisfy the plant requirement at a lower soil test level because it has the ability to supply phosphorus continuously from its extensive surface (Thomas 1967). This is shown in Figure 3-6 where an increase in clay content lowers the equilibrium phosphate concentration necessary for good plant growth. Most soil tests measure a combination of the intensity factor and the capacity factor. Soils high in clay have been shown to have a high capacity for supplying phosphorus and a rapid rate of renewal (Thomas 1967).

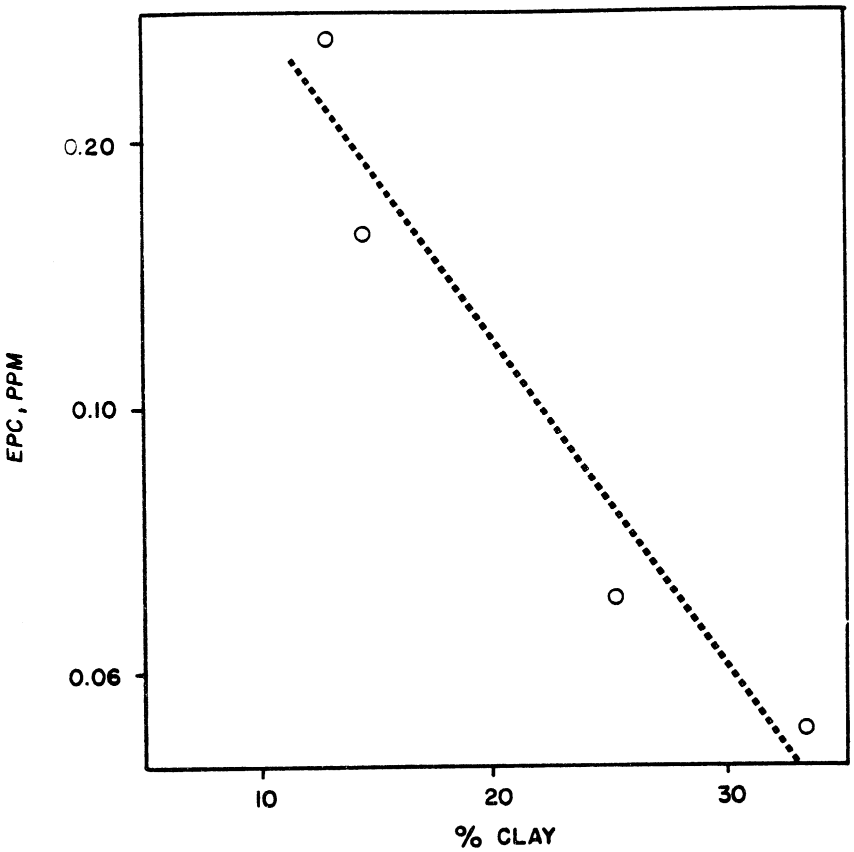

FIGURE 3-6

THE RELATIONSHIP BETWEEN PERCENT CLAY CONTENT OF FOUR SOILS AND THE EQUILIBRIUM PHOSPHATE CONCENTRATION (EPC) THAT SUPPORTED GOOD PLANT GROWTH (KUNISHI AND VICKERS 1980)

The soil pH value is another property which regulates the availability of phosphorus. Figure 3-4 shows that the range of pH values between 5.5 and 7.0 is optimum for phosphorus supply. Below pH 5.5, aluminum and iron adsorption and precipitation negatively affect phosphorus availability. Above pH 7.0, calcium-phosphorus complexes are formed which decrease available phosphorus levels.

The mineral based materials available for soil reconstruction in the oilsands area, like most geological materials in western North America (Power et al. 1978), are low in available phosphorus. Tailings sand, for example, has less than 5 ppm available phosphorus (Table 2-10), and overburden materials without topsoils have similarly low contents (Table 2-6). Although there is very little information on the phosphorus concentrations in jack pine and mixedwood soils in the oilsands area, studies published in the United States on similar soils with jack pine, aspen poplar and white spruce show that available phosphorus ranges from 5 to 80 ppm in the surficial horizons.

The peat deposits in the oilsands area can contain up to 55 ppm of available phosphorus (Table 2-7). However, it is also common to find phosphorus concentrations as low as 4 ppm (Logan 1978).

.3 Potassium

Together with nitrogen and phosphorus, potassium completes the group of major nutrients most often deficient in soils. Plants contain more potassium than any other nutrient except nitrogen (Doll and Lucus 1977).

Like phosphorus, potassium availability is a function of the capacity and intensity factors and the rate of renewal (Thomas 1967). Soils normally contain between 1-2% total potassium by weight, but usually less than 1% of this total is in exchangeable form (capacity), and much smaller amounts are in the soil solution (intensity). Much of the non-exchangeable potassium is a component of some of the primary minerals in the soil, such as potassium laden feldspars, muscovite and biotite micas. Another part of the non-exchangeable soil potassium is found in secondary clay minerals such as illite, vermiculite and chlorite. The primary minerals tend to release potassium very slowly through weathering; potassium in secondary clays is released more rapidly to the exchange complex and soluble pools as potassium levels in the soil are decreased during plant growth (Black 1968).

The procedure used in determining exchangeable potassium often includes the potassium in the soil solution. However, the amount of water soluble potassium is usually so small in comparison to potassium on the exchange complex that the two pools determined together are commonly called "available" potassium (Doll and Lucus 1977).

Newer methods for characterizing available potassium use the ratio of exchangeable bases (MacLean 1977), the potassium buffer power -

a ratio of exchangeable potassium to solution potassium - (Mengel and Busch 1982) and "readily available" non-exchangeable potassium by strong acids and sodium tetraphenylboron (Schulte and Corey 1965). There seems to be little justification at the present time for using an analysis different from exchangeable plus water soluble potassium for soil testing.

As could be expected from the foregoing discussion, the principal soil properties which influence available potassium are texture (mostly clay content) and the kinds of secondary clay minerals. Although exchangeable potassium is more available in coarse textured than in fine textured soils (Doll and Lucus 1977), the latter have a greater supplying power for potassium. Overall, the higher the exchange capacity and the greater the amounts of potassium on the exchange, the larger are the pools of available potassium in soil.

The overburden material in the oilsands has very high contents of available potassiun as estimated by the amount on the exchange complex (Table 2-6): 0.5 to 1.0 me/100 g material is equal to 195 to 390 ppm of potassium*. Tailings sand is somewhat lower in available potassium, ranging from 12 to 120 ppm. Peat is very low in potassium; the concentration is 100 ppm (Table 2-7), similar to that of tailings sand, but the weight of peat in equal volume is 10 to 20 times less.

.4 Calcium and Magnesium

Soils usually contain less total calcium than total potassium or magnesium (Doll and Lucus 1977), but the exchangeable calcium concentration is usually much higher than either of the other nutrients. Most of the non-exchangeable calcium is in the form of primary minerals such as calcite or dolomite, and the calcareous soils of western Canada often have substantial amounts of lime ($CaCO_3$) or gypsum ($CaSO_4$).

Exchangeable calcium ranges from 250 to 5,000 ppm with no apparent evidence of deficiency in plants (Doll and Lucus 1977). It is the one nutrient element which can be supplied to plants in sufficient quantity by mass flow.

Magnesium, like calcium and potassium, is an important ion on the exchange complex. The total content of magnesium in soil is often similar to potassium, but a much greater percentage of magnesium is located on the exchange. A determination of exchangeable plus water soluble magnesium is the most practical indicator of magnesium availability.

Calcium contents of the overburden and peat materials in the oilsands area range from a low of 1000 ppm in the most calcium deficient sample of overburden (Table 2-6) to 26,000 ppm (0.26%) in one of the peat soils reported in Table 2-7. In both cases, the calcium and magnesium

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* me/100 g x equivalent weight x 10 = ppm

contents easily meet the requirements for optimum plant growth, and the balance of calcium to magnesium is well within acceptable limits. Although the tailings sand has lower contents of exchangeable calcium and magnesium (<1.0 me/100 g), it is highly unlikely that these levels will cause plant deficiencies.

.5 Sulphur

Like phosphorus, sulphur is a major nutrient element for plants and animals, but a relatively minor constituent of soils (Table 3-3). Sulphur has received much less recognition as an essential element in soil fertility than phosphorus; it is only now achieving status as a primary nutrient in some Canadian soils (Beaton 1980).

The plant available sulphur fraction of soils (labile sulphur) includes: (a) the readily soluble inorganic sulphate; (b) the adsorbed sulphate; and (c) part of the organic sulphur which is mineralized over the growing season. While reactions a and b can be easily assessed using chemical extractants, no satisfactorily simple and rapid procedure has been proposed for the estimation of fraction c.

The quantity and nature of the labile sulphur in soils is variable, and frequently the inorganic sulphate pool is large enough that contributions from the mineralization of organic sulphur can be neglected. However, when soils contain low amounts of inorganic sulphate, mineralized sulphur may be critical in preventing sulphur deficiency in plants.

Soils in areas near exploitable reserves of hydrocarbons - gas, oil or coal - often receive sulphur from the atmosphere as sulphur dioxide (SO_2) and hydrogen sulphide (H_2S) in amounts more than adequate to meet plant needs.

Due to the large sulphur emissions associated with oil extraction and preliminary processing in the oilsands area, this study will assume that no sulphur deficiencies are likely to appear in reclaimed soils of the area. Furthermore, in accordance with the terms of reference stated in the introductory chapter, we have not included a discussion of problems of excess sulphur accumulation in soils.

.6 Trace Elements

There have been very few recognized deficiencies of trace elements in reclaimed land of western Canada or the western United States. Micronutrient deficiencies - boron, copper, iron, manganese, zinc and molybdenum - probably occur, but they are invariably limited to a small portion of a given field (Bauer et al. 1978). Some micronutrients have been found to exist at toxic concentrations (Cu, Zn, Mn, B), but these cases too, are restricted to a very small portion of the total mined land (Doubleday 1971, Power et al. 1978). Monenco Consultants Pacific Ltd. (1982) has prepared an extensive assessment of trace element deficiency and toxicity levels, with special reference to the reclamation of disturbed mine lands.

Some reports indicate the molybdenum levels in plants may occasionally be high enough to interfere with copper nutrition of livestock. No selenium deficiencies or toxicities have been detected (Power et al. 1978).

343 SOIL FERTILITY AND VEGETATION COMMUNITY

The purpose of this section is to outline the initial nutrient requirements of each vegetative community, and show how the soil properties can be manipulated to provide for these requirements. Since nutrient content is most often expressd as a concentration - parts per million, kilograms per hectare - the information pertaining to soil depths is important in this section. To recapitulate: the recommended depths of reconstructed soil* for each vegetative community are as follows:

Dike slope soils	30 cm
Jack pine soils	15 cm
Mixedwood soils	50 cm

Therefore, the recommendations made in regard to nutrient concentration will reflect the soil depths listed above, unless specific exceptions are made.

.1 Nutrient Levels for Dike Slope Vegetation

Using the performance and nutritional standards of grass and legume forage crops as a guide, the dike slope vegetation can be expected to absorb annually the following nutrient amounts (Western Canada Fertilizer Association 1978):

Nitrogen	125 kg/ha
Phosphorus	35 kg/ha
Potassium	160 kg/ha
Calcium	50 kg/ha
Magnesium	50 kg/ha

Although these levels are associated with a highly productive forage stand (>6.0 tonnes dry matter/ha), they do not take into account the nutrient absorption necessary for root system growth. Therefore, we will use these nutrient requirements as a basis for planning the soil fertility levels necessary on dike slopes in the boreal forest.

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* The term reconstructed soil is used to designate surficial soils designed to serve as primary zones of plant establishment and growth as opposed to underlying mixtures of tailings sand and other materials deposited at random. Even though root penetration will occur into these subsurface layers, they are not considered here as reconstructed soils.

Nutrients can be supplied from existing pools of soil nutrients or in exceptional cases, like nitrogen, from biological fixation from the atmosphere. Fertilizers are a commonly used third option.

The efficiency with which the plant takes up the soil nutrients or added fertilizer is another factor that determines the amount of nutrients needed to meet plant requirements. It is common to assume that agricultural species, including forage crops, absorb approximately 60% of the available nitrogen, 30% of the available phosphorus and 55% of the available potassium (Hinish 1980). Although calcium and magnesium absorption efficiencies are not known for sure, it is likely they would be similar to potassium. We will assume a 50% efficiency for these two elements.

Combining the annual nutrient requirement for each element and the uptake efficiency, the pools of available nutrients necessary for dike slope vegetation on an annual basis are the following*:

Nitrogen	210 kg/ha
Phosphorus	115 kg/ha
Potassium	290 kg/ha
Calcium	100 kg/ha
Magnesium	100 kg/ha

When these amounts of available nutrients are converted into concentrations to a 30 cm depth, the nitrogen is approximately 50 ppm, the phosphorus is 30 ppm and the potassium is 75 ppm (or 0.2 me K/100 g); the calcium and magnesium are 25 ppm each or 0.125 me Ca/100 g and 0.216 me Mg/100 g).**

.2 <u>Minimal Soil Properties for Nutrient Supply on Dike Slopes</u>

The supply of 210 kg available nitrogen per hectare per year (from the surficial 30 cm of soil) necessitates a stable organic matter content of 9%, an extremely efficient nitrogen fixing symbiosis (e.g. alfalfa and *Rhizobium meliloti*), the application of large amounts of nitrogen fertilizer annually or a combination of these factors. In practical terms it will be difficult to find overburden with more than 4 or 5% humus or nitrogen fixing plants in the boreal forest that contribute more than 50 kg nitrogen per hectare per year. Therefore, the soil management regime during the first year or two will probably include a minimum fertilizer application of 50 kg N per hectare.

Although available phosphorus levels are highly variable between materials, a mixture of tailings sand, overburden and peat will probably not result in an average of more than 10 ppm, or approximately one third of the recommended level for dike slopes. There are several

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* Calculated to the nearest 5 kg/ha.

** me/100 g x equivalent weight x 10 = ppm means of increasing the concentration of available phosphorus to 30 ppm: soil, overburden and peat materials richer in phosphorus can be added in higher amounts, or phosphorus can be added as fertilizer. Unlike nitrogen, phosphorus is not lost due to leaching or volatilization; large amounts of phosphorus can be added during soil reconstruction and fertilization does not need to be done annually. Phosphorus is one of the elements most sensitive to changes in soil pH; in this case reconstructed soils with a pH value from 5.5 to 7.5 should show few signs of phosphorus fixation.

The annual requirement for potassium by dike slope vegetation is large - approximately 290 kg/ha. However, the amount of exchangeable potassium needed to meet that demand is low - 0.19 me/100 g soil. Since potassium normally represents about 5% of the total exchangeable basic cations (MacLean 1977) and the percentage of base saturation in these materials is usually above 80%, a total cation exchange capacity of 5.0 me/100 g in the surficial 30 cm will satisfy the potassium requirements.

A soil with 19% silt and clay (0.27 me/100 g soil per 1% silt and clay) or 3.5% stable organic matter (1.5 me/100 g soil per 1% organic matter) or a modified combination of the two will result in a cation exchange capacity of 5 me/100 g and an exchangeable potassium level of at least 0.19 me/100 g.

Recommended calcium and magnesium levels (0.125 me Ca and 0.216 me Mg/100 g soil) are approximately equal to that of potassium, but because these cations normally represent a much higher proportion of the total exchangeable bases, a cation exchange capacity of 5 me/100 g will easily provide for sufficient amounts of both.

.3 Nutrient Levels for Jack Pine Establishment

The level of essential nutrients in each horizon for mature jack pine stands is outlined in Table 2-17. The following list summarizes the averages over the profile:

Nitrogen (total)	0.08 %
Phosphorus (available)	25 ppm
Potassium (available)	120 ppm
Calcium (exchangeable)	2.5 me/100 g
Magnesium (exchangeable	1.0 me/100 g

The level of nutrients necessary for the establishment of a young stand of jack pine within a pre-established grass and legume cover will vary from the list above for several reasons:

- Even though the individual pine seedlings will occupy a herbicide treated space, on a hectare basis the grass cover must also be supplied with sufficient nutrients;

- A young jack pine stand has a shallow root system capable of exploiting only the surficial horizons, so available nutrients may need to be higher in the surficial horizons;

- Jack pine seedlings represent very little biomass and therefore need less nutrients per hectare than a mature stand.

Overall, it follows that soils supporting a grass and legume cover along with newly planted jack pine seedlings will need more nutrients in the surficial horizons and less fertility at depth than the mature stands.

We recommend that the jack pine areas be reconstructed and managed for the first two years such that the surficial 15 cm of soil have the same nutrient concentration as the dike slope soils. Thus, available nutrient contents will be reduced by approximately 50%, but surficial concentrations will remain the same. Although jack pine soils will be expected to support a vegetation cover structurally more complex than dike slopes - in addition to grasses and legumes, jack pine seedlings will be introduced - the nutrient demands are less stringent because the completeness of cover and areal productivity are less crucial to physical stability.

The recommended levels of nutrients for reconstructed jack pine soils are summarized in Table 3-4. The last column outlines the minimum nutrient concentrations for jack pine establishment as suggested by Wilde and co-workers (Wilde 1958, 1964, 1966, Wilde and Patzer 1940) working mainly in the north-central United States on similar soils and under similar climatic conditions.

.4 Minimal Soil Properties for Nutrient Supply for Jack Pine Establishment

The supply of sufficient quantities of available nitrogen (110 kg N/ha/yr) for jack pine establishment and grass and legume maintenance is the most difficult of the nutrient problems. The legume component is expected to fix symbiotically a maximum of 50 kg/ha/yr; the remaining 60 kg/ha/yr must result from the mineralization of organic nitrogen or fertilizer applications. If the organic or total nitrogen pool is reconstructed to supply all of the available nitrogen, the surficial 15 cm of soil need contain approximately 0.3% nitrogen. At a carbon-nitrogen ratio of 15:1, this would mean stable organic matter levels of approximately 4.5%. If, on the other hand, this nitrogen pool need supply only 60 kg N/ha/yr, the humified organic matter need only be 2.5%. Similar to fertility management on dike slopes, a mix of organic matter additions, legume cultivation and fertilizers can be used to optimize nitrogen supplies.

TABLE 3-4

Nutrient Levels Recommended for Jack Pine Soils in Northeastern Alberta

Nutrient	Recommended Amounts[1] per Hectare		Comparative Recommendations[2] per hectare
	Concentration	Content	Concentration
Nitrogen			
Available	55 ppm	110 kg	
Total[3]	0.275%	5,500 kg	0.04%
Phosphorus (available)	30 ppm	60 kg	15 ppm
Potassium (available)	0.19 me/100 g	145kg	0.15 me/100 g
Calcium (exchangeable)	0.5 me/100 g	200 kg	0.5 me/100 g
Magnesium (exchangeable)	0.216 me/100 g	50 kg	0.25 me/100 g

1 The recommendations of this report; for explanation see text.

2 The recommendations of Wilde and co-workers as per: Wilde (1958), Wilde (1964) Wilde (1966) Wilde and Patzer (1940).

3 Calculation of total nitrogen assumes that available nitrogen equals approximately 1% of total.

The calculation of phosphorus supply in jack pine soils will follow the guidelines outlined for dike slope soils. The available geological materials probably will not contain more than 10 ppm available phosphorus; fertilization will be needed to raise these levels to 30 ppm. Jack pine soils with pH values ranging from 4.8 to 7.0 do not present problems in phosphorus supply (Wilde 1964).

A total cation exchange capacity of 5.0 me/100 g with a minimum 80% base saturation in the surficial 15 cm of soil will contain enough available potassium (145 kg/ha), calcium (200 kg/ha) and magnesium (50 kg/ha) to meet the requirements of jack pine establishment and grass and legume growth. Soils that have a fines content of 19% or an organic matter content of 3.5% will have a cation exchange capacity of 5.0 me/100 g.

.5 Nutrient Levels for Mixedwood Establishment

The recommended levels of available nutrients for the establishment of a mixedwood stand are based on the reconstruction of a soil with two horizons - a surficial 0-15 cm layer and a subsurficial 15-50 cm layer. The surface horizon will have a higher concentration of nutrients than the subsurface, but due to the increased soil volume in the latter horizon, the nutrient content will be approximately equal (Table 3-5).

The amount of available nitrogen necessary for the establishment of a mixedwood stand (100 kg N/ha/yr) is less than the amounts needed for dike slope vegetation or jack pine forests because the mixedwood does not include a grass component.

In order to supply 265 ppm of available potassium, the surface soil must have an exchangeable potassium content of 0.7 me/100 g. The subsurface horizon will contain approximately 0.37 me exchangeable potassium per 100 g soil.

If sufficient cation exchange capacity is incorporated to meet the requirements of available potassium, there will be no problem in the supply of sufficient calcium or magnesium in either soil layer.

.6 Minimal Soil Properties for Nutrient Supply for Mixedwood Establishment

The sources of available nitrogen in mixedwood soils in the initial years are limited to mineralized organic nitrogen and fertilizers. Fifty kilograms of available nitrogen per hectare per year in the top 15 cm of soil will require slightly less than 4% organic carbon (at a C:N ratio of 15:1) or 7% organic matter. These amounts are reduced by 50% when the 15 to 50 cm depths are considered.

The demand for available phosphorus is high enough at both soil depths (80 and 45 ppm) to warrant the use of large fertilizer applications in the initial year. During soil placement and construction, the

TABLE 3-5

Recommended Concentrations and Contents of Nutrients for Two Horizons in Reconstructed Mixedwood Soils

Nutrient	Horizon	Concentration	Content	Source of Recommendations
			kg/ha	
Total Nitrogen	Surface	0.25%	5000	Table 2-21[1]
	Subsurface	0.12%	4800	Wilde 1966
Available Nitrogen[2]	Surface	25 ppm	50	- - - - -
	Subsurface	12 ppm	48	- - - - -
Available Phosphorus	Surface	80 ppm	160	Wilde 1966
	Subsurface	45 ppm	180	Table 2-21
Available Potassium	Surface	265 ppm	530	Table 2-21
	Subsurface	145 ppm	580	Table 2-21
Exchangeable Calcium	Surface	5 me/100 g	2000	Wilde 1958
	Subsurface	3 me/100 g	1200	Wilde 1966
Exchangeable Magnesium	Surface	1 me/100 g	240	Wilde 1966
	Subsurface	0.6 me/100 g	145	Table 2-21

1 Recommendations formulated on basis of Table 2-21 are approximations of LFH and A horizon values for surface and B horizon value for subsurface.

2 Available nitrogen is considered to be 1% of total nitrogen.

phosphorus requirements for several years (up to 10) could be included in the mixture for each layer. Mixedwood stands show highest productivity when pH values are above 4.7 and below 7.3 (Wilde 1966), therefore phosphorus availability is assumed also to be optimal between these pH values.

Exchangeable potassium levels of 0.7 and 0.37 me K/100 g soil are best ensured by incorporating cation exchange capacities of 14 and 9 me/100 g in surface and subsurface layers respectively. This estimate assumes that approximately 5% of the exchangeable bases will be potassium and 80% of the exchange capacity will be base saturated.

It will take slightly more than 50% fines content (silt and clay) in the surficial 15 cm or 9% organic matter to reach an exchange capacity of 14 me/100 g. If 30% fines are used in this layer to meet the water supply requirements (Chapter 2), there need be only 4% organic matter to fill out the exchange capacity requirements.

In the subsurface layer, an exchange capacity of 9 me/100 g can be achieved by incorporating 33% fines or 6% organic matter. A combination of fines and organic matter would lower the minimum levels of each.

The calculations used in this study have assumed a base saturation of 80%; under these circumstances calcium levels of 5 me/100 g and magnesium levels of 1 me/100 g should be achieved without any problems.

3.5 SOIL EROSION CONTROL

Wind and water erosion are problems in northeastern Alberta in the vicinity of Lake Athabasca. The dominant particle sizes of the soils and geological overburden - silts and fine sands - make these materials highly susceptible to wind erosion. The Athabasca sand dune area, a nearby region of Saskatchewan, attests to the influence and extent of wind erosion in this part of the world. The occurrence of water erosion, on the other hand, is related to the construction of dike slopes, earth barriers designed to contain a mixture of tailings sand and water for sufficient time to allow settling. Although the possibility of wind erosion is widespread, almost regional, reclamation practices such as peat mulching and rapid revegetation of open areas are effective in checking wind erosion in the oilsands area (Hardy and Associates 1978b). This section therefore concentrates on the control of soil erosion by water.

351 ACCEPTABLE LIMITS OF SOIL EROSION

Soil loss tolerances are defined as the maximum rate of annual soil erosion that will permit a high level of plant productivity to be obtained economically and indefinitely (Cook 1982). In other words, there should be no loss in the long-term productive capacity of the soil.

The loss of five tons* soil per acre per year is considered to be a limit to maintaining soil productivity (U.S. Department of Agriculture 1978). This limit or tolerance reflects two important aspects of soil formation: first, the rate of formation for the surficial soil layer, the A horizon, is estimated to be five tons per acre per year; and secondly, losses above this limit are said to lead to gully formation (Cook 1982).

The 5 t/acre/yr tolerance is now questioned because there are new soil management techniques in use that lead to equal productivity levels under less favourable conditions; examples in western Canada include fertilization programs, selective weed control and reduced tillage systems. Furthermore, it has been shown that no single erosion rate can be related to gully formation for all kinds of soils, climate, crops or tillage methods. It is generally accepted now that erosion rates of seven (Moore et al. 1980) to ten tons per acre per year (Cook 1982) can be permitted without a serious loss in productivity.

Even though there is probably a loss of productivity at erosion rates of more than 10 t/acre/yr, land is not designated as "critically erosive" until losses are more than 25 t/acre/year (Ogg et al. 1982). Skidmore (1980) has proposed that a soil loss of more than 17 t/acre/yr represents serious environmental damage.

For purposes of this report, we recommend that single year erosion rates in the oilsands area do not exceed 20 t/acre/yr, and that productivity can be maintained over a long period of time by reducing erosion rates to less than 10 t/acre/yr.

352 THE UNIVERSAL SOIL LOSS EQUATION

Forty years of research by the United States Department of Agriculture has produced an empirical calculation, known as the Universal Soil Loss Equation (USLE), that describes the potential loss of soil due to water erosion in any area where factors affecting rainfall and soil stability have been measured or can be estimated. The USLE has been used extensively for sediment prediction and erosion control planning for agricultural soils, and during recent years it has been adapted for use on construction and mining sites (Farmer and Fletcher 1976, King 1977, McKenzie and Studlick 1978, Wischmeier and Meyer 1973). The following paragraphs define the various factors of the USLE.

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* In this section on soil erosion the more commonly accepted metric measurement (e.g. tonnes or 1000 kg) is replaced by the U.S. measurement (e.g. tons or 2000 lbs) because of the pioneering work in soil conservation carried out by the U.S. Soil Conservation Service.

The USLE (Wischmeier and Smith 1965) is:

$$A = RKLSCP \quad \text{(Equation 3-1)}$$

where, A = computed soil loss, expressed in tons per acre per year or per storm,

R = rainfall factor which is a measurement of the erosive power of a specific rainfall or an average year's rainfall,

K = soil erodibility factor,

L = slope length factor,

S = slope gradient factor,

C = cover or cropping management factor, and

P = erosion control practice factor.

The rainfall factor (R) may be defined as the total kinetic energy of a given storm in foot-tons per acre (metre-kilograms per square metre) multiplied by the rainfall intensity. The following equations (Ateshian 1974) are used to calculate the rainfall factor for:

a) an individual 24 hour storm:

$$R = 4.365\,(P_{24hr})^{2.2} \quad \text{(Equation 3-2)}$$

where, P_{24hr} = precipitation in inches for 24 hours

b) an average annual rainfall:

$$R = 27.0\,P^{2.2} \quad \text{(Equation 3-3)}$$

where, P = precipitation in inches for a storm that has a return period of 2 years and a duration of 6 hours.

The erodibility of a soil (K) may be determined best by setting test plots of the soil under investigation and measuring sediment loss during simulated rainfalls. In addition to the simulation techniques, an equation has been developed which can be used to predict the soil properties that influence erodibility. This equation (Wischmeier and Meyer 1973) is:

$$2.1(10^{-4})\,(12-G)M^{1.14} + 3.25(S-2) + 2.5(P-3) = 100K$$

(Equation 3-4)

where, G = % organic matter

M = particle size diameter
(% of 0.002 to 0.10 mm) x (% of 0.002 to 2.0 mm)

S = structural index

1 - very fine granular
2 - fine granular
3 - medium or coarse granular
4 - blocky, platy or massive

P = permeability class

1 - rapid
2 - moderate to rapid
3 - moderate
4 - slow to moderate
5 - slow
6 - very slow

The calculated probability of error for K indicates that 68% would be within ± 0.02 of the true values and 95% within ± 0.04. Observed K values range from 0.03 to 0.69 (Wischmeier et al. 1971). The properties measured by this equation are:

- those that affect the infiltration rate, permeability and total water capacity, and

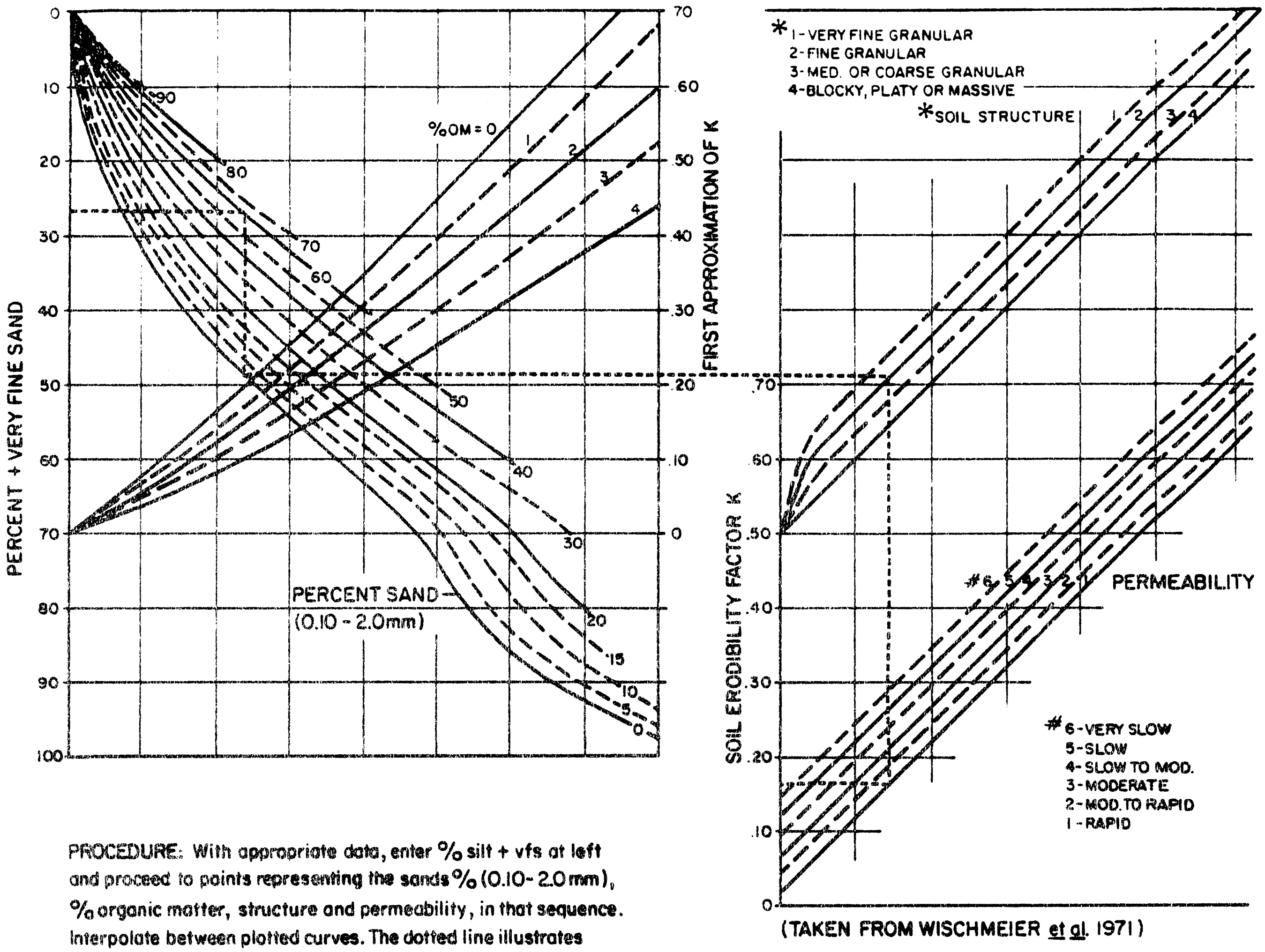
- those that resist the dispersion, splashing, abrasion and transporting forces of the rainfall and runoff (Wischmeier and Smith 1965).

A nomograph for Equation 3-4 is shown in Figure 3-7 (Wischmeier et al. 1971).

As the runoff velocity increases, the capability of runoff to detach and transport soil increases. The runoff velocity is determined by runoff rate, flow and slope angle; thus as the length and gradient of a slope increases, the erosive power of runoff water increases. The erosive power (LS) is calculated using the following equation (Farmer and Fletcher 1976):

$$LS = \frac{(0.43 + 0.3s + 0.043s^2)}{6.613} \quad \frac{t}{72.6}^{0.5} x \cos^2\left(\tan^{-1} \frac{s}{100}\right)$$

(Equation 3-5)



PROCEDURE: With appropriate data, enter % silt + vfs at left and proceed to points representing the sands % (0.10 - 2.0 mm), % organic matter, structure and permeability, in that sequence. Interpolate between plotted curves. The dotted line illustrates procedure for soil having si + vfs 27%, sand 70%, OM 0.90%, structure 2, permeability 1, solution = .17

(TAKEN FROM WISCHMEIER et al. 1971)

FIGURE 3-7

NOMOGRAPH FOR DETERMINING SOIL ERODIBILITY (K) where, s = gradient in %

t = length of slope in feet

For the purposes of this report, the cover factor (C) shall represent both the amount of erosion protection due to the vegetation and to erosion control practices (P). Vegetation provides protection against soil loss by shielding the soil from direct raindrop impact via its foliage, by impeding runoff, and by binding the soil with its root system.

In spite of the USLE's general applicability and performance, several limitations, as discussed by Farmer and Fletcher (1976), should be noted:

- The equation is semi-empirical and does not necessarily express its several factors in their correct mathematical relationships. This limitation is overcome by the use of empirical coefficients.
- As the slope gradient increases past 20%, the LS equation (Equation 3-5) loses accuracy in the estimation of the erosive power of water flow on slopes. The maximum slope length for the equation is 300 feet.
- The rainfall-erosion index measures the erosivity of rainfall and associated runoff only; it does not predict soil losses due to thaw, snowmelt or wind.
- The USLE accounts for rill and sheet erosion, not gully erosion.
- Soil loss predictions on a storm-by-storm basis often result in error because the equation was developed for an average annual basis.
- There is increased erodibility of soils that have been removed, stockpiled and redistributed (King 1977).

353 QUANTIFYING THE USLE FACTORS IN THE OILSANDS AREA

The following paragraphs use climatic, topographic and soils information from northeastern Alberta to calculate the factor values of the USLE. In all cases, at least two values are calculated for each factor to fit specific conditions or possibilities during reclamation.

.1 Rainfall Factor (R)

The annual rainfall factor is calculated (Equation 3-3) from the average annual rainfall - two year return, six hour storm - for the Fort McMurray area. In this case, an average of 28 mm (Langley and Janz 1978) results in an R factor of 32.

For purposes of estimating a plant cover - erosion control factor for northeastern Alberta, data on soil loss from actual erosion experiments during 1976 are substituted into the generalized USLE equation. The R factor in these examples is calculated from 24 hour rainfall measurements made at the experimental site, rather than from long-term averages. The R factor for the first period, June 30 - July 8, is 1.1; for the August 1 to August 8 period, R is equal to 6.9.

.2 Slope Length and Gradient Factor (LS)

The combination of slope length and gradient is limited in the oilsands area to a maximum vertical drop of 50 feet (Berry and Klym 1974). Three commonly proposed combinations of slope gradient and length and the resulting LS factors (Equation 3-5) are listed below. The fourth combination is included to represent the LS value for an erosion experiment conducted in the oilsands area in 1976:

Slope	Gradient %	Slope Length ft.	LS
2:1	50	100	17.3
3:1	33	150	11.2
4:1	25	200	8.2
4:1	27	50	4.6

.3 Soil Erodibility Factor (K)

The erodibility of mineral materials used in soil reconstruction in the oilsands is estimated from Figure 3-7, using the following examples:

(1) Tailings Sand:

Medium to coarse sand	(> 0.1 mm)	70%
Very fine sand and silt	(.002-0.1 mm)	25%
Clay	(< .002 mm)	5%
Stable organic matter		1%
Soil erodibility factor K_1		0.17

(2) Soil - Tailings Sand Mixture*:

Medium to coarse sand	(> 0.1 mm)	50%
Very fine sand and silt	(.002-0.1 mm)	35%
Clay	(< .002 mm)	15%
Stable organic matter		4%
Soil erodibility factor K_2		0.14

---

* This mixture results in the correct proportion of silt and clay (25%) and organic matter (4%) to satisfy the water and nutrient requirements of all three vegetative communities as described previously.

.4 Plant Cover and Conservation Practice Factor (C-P)

By rearranging the Universal Soil Loss Equation, we can solve for C-P:

$$C\text{-}P = \frac{A}{R\ LS\ K}$$

Logan (1978) conducted an erosion experiment in the oilsands area in 1975 - 76. Using rainfall measurements made by personnel (Great Canadian Oil Sands/Suncor) at the plant site and Logan's information on soils, slopes and erosion losses, we can derive second year C-P values for tailings sand without peat (0.63) and tailings sand with peat (0.09) (Table 3-6). In other words, unamended mineral soils (tailings sand or soil) planted to grass and legumes reduce potential erosion by 37% in the second year; mineral soils amended with peat (approximately 15 cm mixed to a depth of 30 cm) and planted to grass and legumes reduce potential erosion by 91% in the second year.

Although no data are shown in Table 3-6, Logan (1978) found that 15 cm of peat laid on the surface of the mineral component prevented as much erosion as peat mulches.

The first year erosion experiments set up by Logan in 1975 encountered problems of highly erosive rainfalls during plot establishment and equipment malfunction. Reliable erosion results were not collected on the effect of first year vegetation establishment and peat mulching. However, photographs of plant cover and discussion by Logan (1978) allow an estimate of C-P factors for each treatment in that year. Tailings sand without peat had a sparse plant cover and probably prevented less than 20% of potential erosion (C-P = 0.80). Plots with tailings sand, peat mulch and a first year cover are estimated to have reduced erosion by a lesser amount than year two, but in similar proportion to unamended treatments (C-P = 0.26).

In summary, estimated C-P values for two years with and without peat amendments are as follows:

	Without Peat	With Peat
Year 1	C-P = 0.80	C-P = 0.26
Year 2	C-P = 0.67	C-P = 0.09

354 CONTROL OF EROSION IN THE OILSANDS AREA

Erosion rates of more than 20 t/acre are not acceptable in any year or in any reclaimed soil because fast developing gully formation can destroy entire plant communities. Erosion rates more than 10 t/acre/yr and less than 20 t/acre/yr are acceptable for one or two years during initial plant establishment, but these rates must be reduced to less than 10 t/acre/yr in order to maintain productivity.

TABLE 3-6

The Use of Measured Soil Loss on Dike Slopes in the Oilsands Area to Calculate the Effect of Peat Mixed in the Soil Surface as an Erosion Control Factor

Erosion Control Measure	Date of Experiment	Soil Loss[1]	USLE Factors			
			R[2]	LS	K	C-P[3]
		t/acre				
None	June-July/1976	0.52	1.1	4.6	0.17	0.60[4]
	Aug/1976	3.52	6.9	4.6	0.17	0.65[4]
Peat Mixed in Surface	June-July/1976	0.13	1.1	4.6	0.17	0.15[5]
	Aug/1976	0.13	6.9	4.6	0.17	0.02[5]

[1] Soil loss data from Table 33, page 125 in Logan's (1978) thesis, reporting on runoff in 1976 experiment.

[2] R factor is calculated from rainfall information from Appendix 3, Table B in Logan's (1978) thesis: average 24 hr precipitation 30/6/76-08/7/76 = 12.4 mm; 01/08/76-08/08/76 = 32.4 mm.

[3] P factor is calculated from reported data: $P = \frac{A}{R\ LS\ K\ C}$

[4] C factor for bare tailings sand is estimated from pictures and discussion in Logan's (1978) thesis.

[5] C factor for plots with peat follows estimate for second year in this study.

All soil, plant and topographic factors contributing to erosion potential can be manipulated; rainfall is the one uncontrollable variable. This section outlines the details of several hypothetical situations in the oilsands area whereby the properties and management of soils and plants can be optimized to limit erosion rates to the acceptable tolerances as discussed above. After presenting the hypothetical cases, the minimum soil properties necessary for each vegetative community are evaluated.

.1 Predicting Erosion in the Oilsands Area

Four hypothetical cases of soil reconstruction are presented below. It is assumed that grass and legumes are seeded immediately after soils are reconstructed. A prediction of the erosion rate for two years is then calculated for each case (Figure 3-8).

(i) Tailings sand This soil reconstruction scheme assumes no soil or peat additions to tailings sand. Predicted erosion rates range from 28 t/acre/yr for 4:1 slopes in year 2 to 75 t/acre/yr for 2:1 slopes in year 1 (Figure 3-8). These rates exceed maximum tolerances for both years. If slopes were reduced to 5% or less on any slope length less than 2000 ft., erosion rates would be less than 10 t/acre/yr even during the establishment period (Water Erosion Calculator (WEC))*.

(ii) Tailings Sand Plus Peat This amendment strategy assumes that approximately 15 cm of peat is mixed into 15 cm of tailings sand. The predicted erosion on 2:1 slopes during the first year (25 t/acre/yr) is the only unacceptable rate. Even though erosion on lesser slopes during the first year is predicted to be above 10 t/acre/yr, the rates will be less than maximum limits by year two (Figure 3-8).

(iii) Soil Plus Tailings Sand By mixing soil with a high fines content (25% silt and clay) and 4% organic matter into tailings sand, the soil erodibility index can be reduced to 0.14 from 0.17. However, even with this reduction, predicted erosion rates exceed acceptable limits for all slopes during all years (Figure 3-8). If slopes were reduced to 7% or less, irrespective of slope length, to a maximum of 2000 ft., the erosion rates for the first year would be less than 20 t/acre and less than 10 t/acre for the second and succeeding years (WEC 1980).

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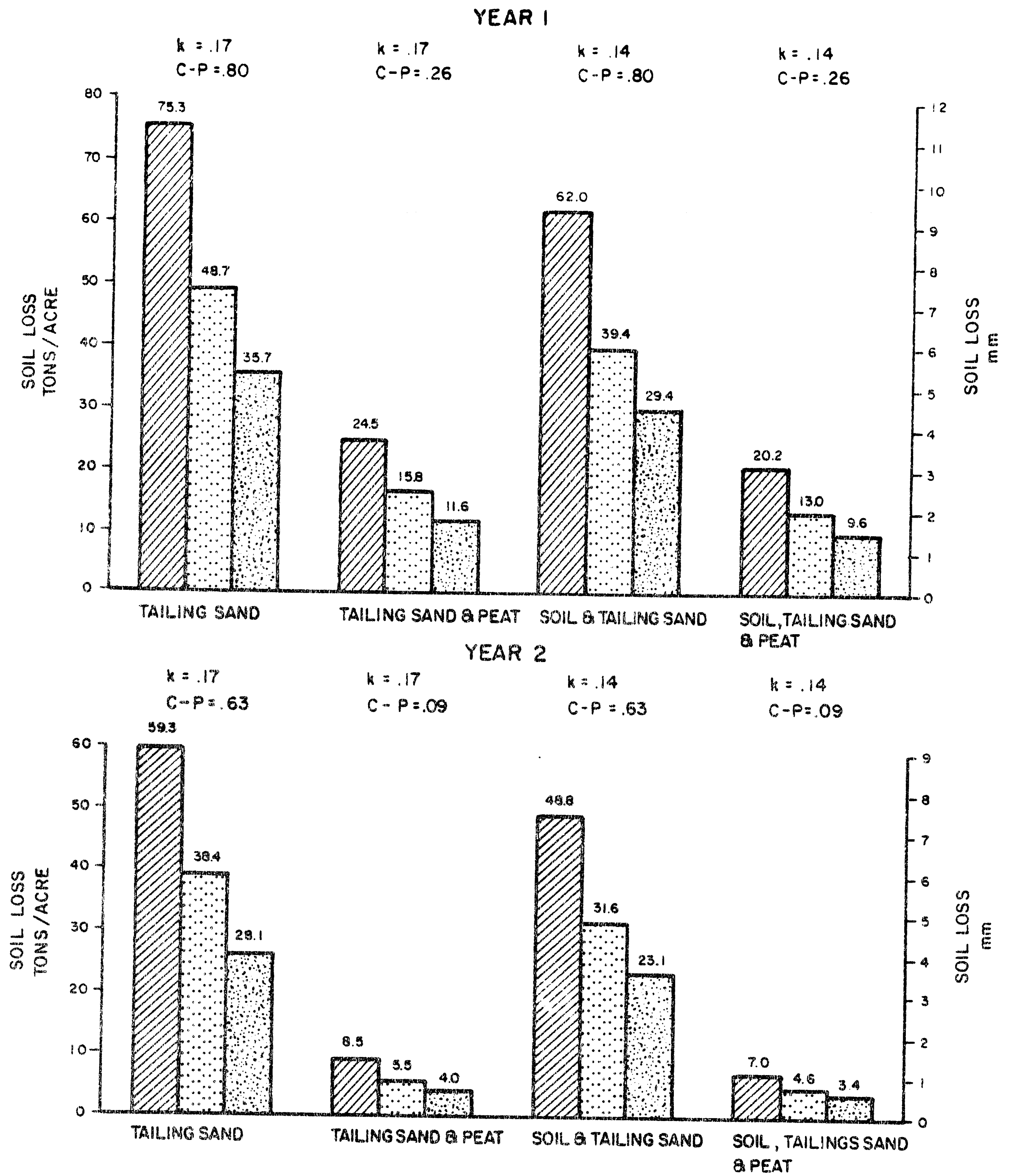
* All predictions and calculations cited by reference to WEC (1980) have been carried out using the water erosion calculator and the same factor values cited in the text.



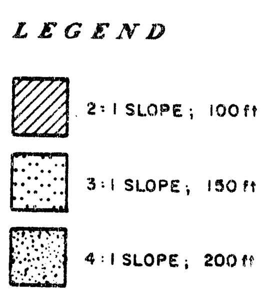


FIGURE 3-8

A TWO YEAR PREDICTION OF SOIL LOSS DUE TO WATER EROSION ON DIKE SLOPES WITH VARIOUS TREATMENTS

(iv) Soil Plus Tailings Sand Plus Peat A combination of these three materials results in a prediction of acceptable erosion rates for all slope categories in both years (Figure 3-8). However, a 100 foot, 2:1 slope might exceed 20 t/acre in the first year. Caution would suggest a slight decrease from this maximum in slope gradient or slope length.

.2 Erosion Control on Dike Slopes

Dike slopes are by definition the steepest sites in the reclaimed oilsands. Preliminary calculations suggest that dike slopes less than 25% (4:1) are neither cost nor space effective (Panek personal communication). Dike slopes that are steeper than 50% (2:1) are not geotechnically stable (Hardy and Associates 1978a). Therefore, the examples shown in Figure 3-8, which have slopes from 25% to 50% and lengths between berms from 50 to 200 feet, are accurate representations of potential dike slope construction practices.

Under these circumstances, the only acceptable soil reconstruction strategy is the design of dike slopes that contain peat mixed into the mineral component. It does not make a great deal of difference from the point of view of erosion control whether the mineral component is tailings sand or a soil and tailings sand mixture. Slopes should be less than 40% and 150 feet in length (WEC 1980). If the slopes are reduced, the distance between berms can be lengthened without affecting erosion potential.

.3 Erosion Control on Jack Pine Soils

The same principles developed for dike slopes apply to jack pine soils because the first introduced vegetation in both cases will be a grass-legume mixture. If tailings sand or tailings sand and soil are used without peat amendments, the slopes should be less than 5% for any length up to 2000 feet. On the other hand, if peat is used, any slope up to 40% can be planted and erosion rates are predicted to be less than 20 t/acre in the first year and less than 10 t/acre in the second year. If steep slopes (>5%) are used for jack pine establishment, permissible slope lengths should be progressively reduced (from 2000 feet) with increasing gradient to lessen the risk of excess erosion.

.4 Erosion Control on Mixedwood Soils

The mixedwood forests will be set out as seedlings without the prior establishment of grasses and legumes. The contribution of the trees to the cover-erosion control factor (C-P) is assumed to be zero. If we further assume the C-P factor without plant cover and without peat to be more than 0.99, the slopes for mixedwood stands should be less than 5% to prevent excess erosion (WEC 1980). However, if peat were mixed into the mineral component (tailings sand with or without soil), slopes could increase to 8% without risk of excessive erosion.

CHAPTER 4

THE DEVELOPMENT OF PLANT COMMUNITIES AND RECLAIMED SOILS OVER TIME

CHAPTER 4 - THE DEVELOPMENT OF PLANT COMMUNITIES AND RECLAIMED SOILS OVER TIME

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Figure

4.1 INTRODUCTION

The soil-vegetation complexes designed in Chapter 3 are dynamic - they will change over time. The objective of this chapter is to predict what properties will change and how the changes in these properties will affect the fundamental soil processes necessary to support self-maintaining plant communities.

The predictions offered here are based on inferences from the development of similar plant communities and natural pedogenesis in the boreal regions of North America. The proposed vegetation scenarios are simple, lacking many of the relevant details needed to justify their inclusion at the expense of other alternatives. The reason for this succinctness is that the central question of the entire study revolves around the appropriate design of the underlying soils, rather than an accurate interpretation of vegetational structure and ecology.

The choice of soil properties most likely to change in less than 80 years is relatively straightforward. The estimation of rates of change, however, is less simple and is left open to question in those areas where information is deficient.

The final sections of this chapter outline the most probable effects that changes in soil properties and maturation of plant community will have on soil erodibility, soil moisture status and nutrient supply. It is the latter soil process which is the most complex and least predictable. This chapter has identified, however, the one element which may present a nutritional bottleneck in the future and has shown why the others will not likely be in short supply.

4.2 CHANGES IN PLANT COMMUNITIES

The development of stable vegetative communities under natural conditions can be expected to conform to Odum's (1969) three principles of ecological succession:

1. It is an orderly process of community development that is reasonably directional and, therefore, predictable.

2. It results from modifications of the physical environment by the community; that is, succession is community controlled even though the physical environment, the pattern and the rate of change often set limits as to how far development can go.

3. It culminates in an ecosystem in which maximized biomass and symbiotic function between organisms are maintained per unit of available energy flow.

The essential aspect of principles (1) and (2) is that the directional character of succession results from a modification of the physical environment. The physical environment can be manipulated and therefore succession and ecosystem stability are predictable within the limits of understanding the interchange of energy between plant, soil and climate. A review of the existing literature pertaining to succession and ecosystem stability in the boreal regions aids in choosing the direction of change for each plant community and the prediction of rates at which changes will occur. It is the intent of the whole of this document to ensure that principle (3) results in a state that maximizes productivity and physical stability for each vegetation community in the least possible time and at the lowest possible cost.

421 MIXEDWOOD FORESTS

The distinguishing characteristics of a mixedwood forest are: (1) the inclusion of both coniferous and deciduous species, (2) a high level of biomass productivity and (3) underlying soils with relatively high contents of available moisture and nutrients. Since glacial action results in an extremely high proportion of landscape components having the soil attributes described above, contemporary research on plant succession following glacial retreat offers a preview of how the changes in mixedwood forests on reclaimed lands will probably occur.

Detailed studies on succession and soil genesis in northern areas recently exposed by glacial retreat show a definite physiognomic developmental sequence in vegetation (Crocker and Major 1955, Crocker and Dickson 1957). The actual plant communities correspond to an area of very high rainfall (2000 mm per year), but the functional role of the vegetation is applicable to broad areas of the boreal forest. Crocker and Major (1955) identified three stages of community development occurring over 80 years:

- pioneer vegetation (mosses, fireweed, shrubs - Equisetum, Epilobium, and Dryas);
- shrub and thicket vegetation (Salix and Alnus); and
- climax or transitional climax vegetation (Picea, Tsuga).

It is the recommendation of this document that representative individuals of all three stages be seeded in the initial year following soil reconstruction for mixedwood sites. The soils have been designed to support (supply nutrients and water and not erode) the most advanced vegetational types without needing the changes in physical or chemical characteristics normally associated with succession. However, it is likely that the pioneer species will thrive in the beginning (zero to five years), until they are restricted by rapidly growing shrubs (five to ten years) which will then have to compete with well-established trees (10-80 years).

422 GRASSES AND LEGUMES ON DIKE SLOPES

Tailings dikes are designed so that a grass-legume mixture will occupy these slopes for at least the first five years following reclamation. A model of community development for very sandy materials is outlined by Olson (1958) in a major ecological study of sand dune colonization in the Great Lakes area of the northern U.S.A. He finds that the initial colonization period is dominated by mixed or pure stands of marram grass (Ammophila breviligulata), sand reed (Calamovilfa longifolia) and little blue stem grass (Andropogon scoparius). These species are then replaced by poplar, chokecherry (Prunus) or jack pine. In all cases the water table is a minimum of three metres below the rooting zone.

The exclusion of marram grass is associated with the depletion of nutrient elements through leaching or a decrease in the available nutrient pools due to tie-up in rapidly increasing contents of organic matter (Olson 1958). Some shrubs, Prunus for example, precede tree invasion and are able to exploit the organic layers deposited during grass decomposition. Bearberry, identified as an excellent invader of bunch grass communities, survives well when sand deposits do not erode rapidly. The majority of shrubs establish themselves after jack pine but before canopies are dense enough to radically decrease light penetration. The exception to this rule on sand dunes is chokecherry which is most successful when a full canopy is present.

From the above information, it seems reasonable to predict that after the introduction of grasses and legumes on slopes which will ultimately return to jack pine, there will probably be a transitional stage. This stage will involve the natural invasion of fast-growing herbs and shrubs such as Arctostaphylus, Salix or Prunus. These, in turn, will encourage a further modification of soils, water balance and light penetration to permit the establishment of jack pine.

423 JACK PINE FORESTS

Jack pine is adapted to both primary (colonizer) and secondary (as described above) succession because of its low requirements for many nutrients and water (Olson 1958). Jack pine can most certainly invade stabilized sands, if seed is available. In the case of the oilsands and those areas designated as jack pine forests, the initiation of tree seedlings and shrubs in grass communities will result in a relatively rapid transition to jack pine communities (including the traditionally associated understory species). As competition for light, water and nutrients increases the less adaptable grasses and herbaceous legumes will disappear.

4.3 CHANGES IN SOIL PROPERTIES

The constructed soils will differ from naturally derived soils in one important aspect: after the first 15, 30 or 50 cm depending on soil type, there will be no variation with depth. In this sense they resemble closely the material left in Canada after glacial retreat some 10,000 to 12,000 years ago. Crocker and Major (1955) describe recent glacial moraine as "disorganized accumulations of ice deposited debris whose properties show no variation with depth". In the strict definition of soils as "natural bodies of geological material acted on by the soil forming factors of topography, vegetation, climate and time" (Buckman and Brady 1969), neither the glacial moraine nor the recently engineered mixtures of sand, peat and overburden are soils. However, the more functional definition of soils as "a mineral-organic media capable of supporting plant growth" includes both groups of materials.

The purpose of this section is to predict which soil properties will change within the first 80 years following revegetation and to estimate the direction and rate of those changes.

431 ORGANIC MATTER CONTENTS

The fundamental role that organic matter plays in the genesis of all soils may be illustrated by the following quotes from two well-known pedologists:

> "There is now sufficient evidence to state that when pedologists brushed off the 'dead litter' they removed with it not only the practical interests of silviculture but also the scientific foundation of soil genesis. The geological substratum is dead and sterile; it cannot be 'parent' to anything, least of all to the animated entity called soil". (Wilde 1958).

> "All cyclic processes of soil formation are kept in motion by the living matter which controls migration of the elements and energy that are involved in these processes. This is the principal determining characteristic of all strictly pedogenic processes. The dynamics of weathering depend upon the organic world". (Nikoforoff 1949).

.1 Organic Matter on Dike Slopes

The natural rate of organic matter increase in sands is not high. Salisbury (1925) showed that coastal sand dunes in California accumulated 2% organic matter in 200 years.

Organic matter increase is a balance of rates of organic additions and rates of organic composition. Rowell (1977, 1978) has calculated that a grass cover on dike slopes in northern Alberta can produce between 4 and 15 tonnes dry matter per hectare (assuming a root/shoot ratio between 4 and 7). Measured decomposition rates of organic matter in tailings sand, with and without soil amendments and fertilizers, have shown a half life of one year (that is, 50% weight loss of added organic residues each year). There seems to be no relation between the nutrient concentration, soil amendment, and decomposition rate of organic matter produced *in situ* (Rowell 1979).

However, when pure cellulose was added to tailings sand alone and tailings sand with peat and overburden, the decomposition over one year was 60-90% (Figure 4-1). The soil amendments affected the rate of cellulose decomposition within the year but not the total amount decomposed in one year. Only the peat overburden treatment, which had low fertilizer rates from 1976-77 and no fertilizer in 1978 (Treatment 6A, Figure 4-1), and tailings sand without peat or fertilizer (☆in Figure 4-1) showed a significant decrease in the amount of cellulose decomposed over a one year period. The data suggest that the decomposition of cellulose (a much simpler carbon polymer than plant material) is dependent on nutrient availability and the contribution of a peat/overburden amendment to a change in the soil properties.

.2 Organic Matter Under Forests

The organic matter under forests is conveniently considered as litter and mineral organic matter. Litter is that part of the vegetative production which accumulates above the mineral soil (horizon A_0 or layers L, F and H) while mineral organic matter is the mixture of organic and inorganic colloids in the surface soil (A_1).

Organic matter accumulates in the mineral soil and on the forest floor at varying rates (Figure 4-2). The lag phase for the first 20 years is due to the very low dry matter production associated with *Dryas* mats under natural soil forming conditions. After the first 20 years, the rates of dry matter accumulation in both the mineral soil and on the floor increase rapidly. Crocker and Major (1955) estimated that *Dryas* produces from 0.9 to 1.4 kg organic matter (D.W.)/m^2 during the initial 20 years. Alder, on the other hand, will provide 5-6 kg/m^2 in the following 40 - 50 years. When the forest type changes from an alder dominant community to spruce, the rates of organic carbon accumulation drop sharply. Alder thickets have been designated as effective traps of annual litter fall and organic matter builds up rapidly on the surface beneath them (Figure 4-3).

Organic matter accumulation is a function of vegetation, climate, soil type and time. The unique combination of these factors results in different equilibrium values for soil organic carbon and dry

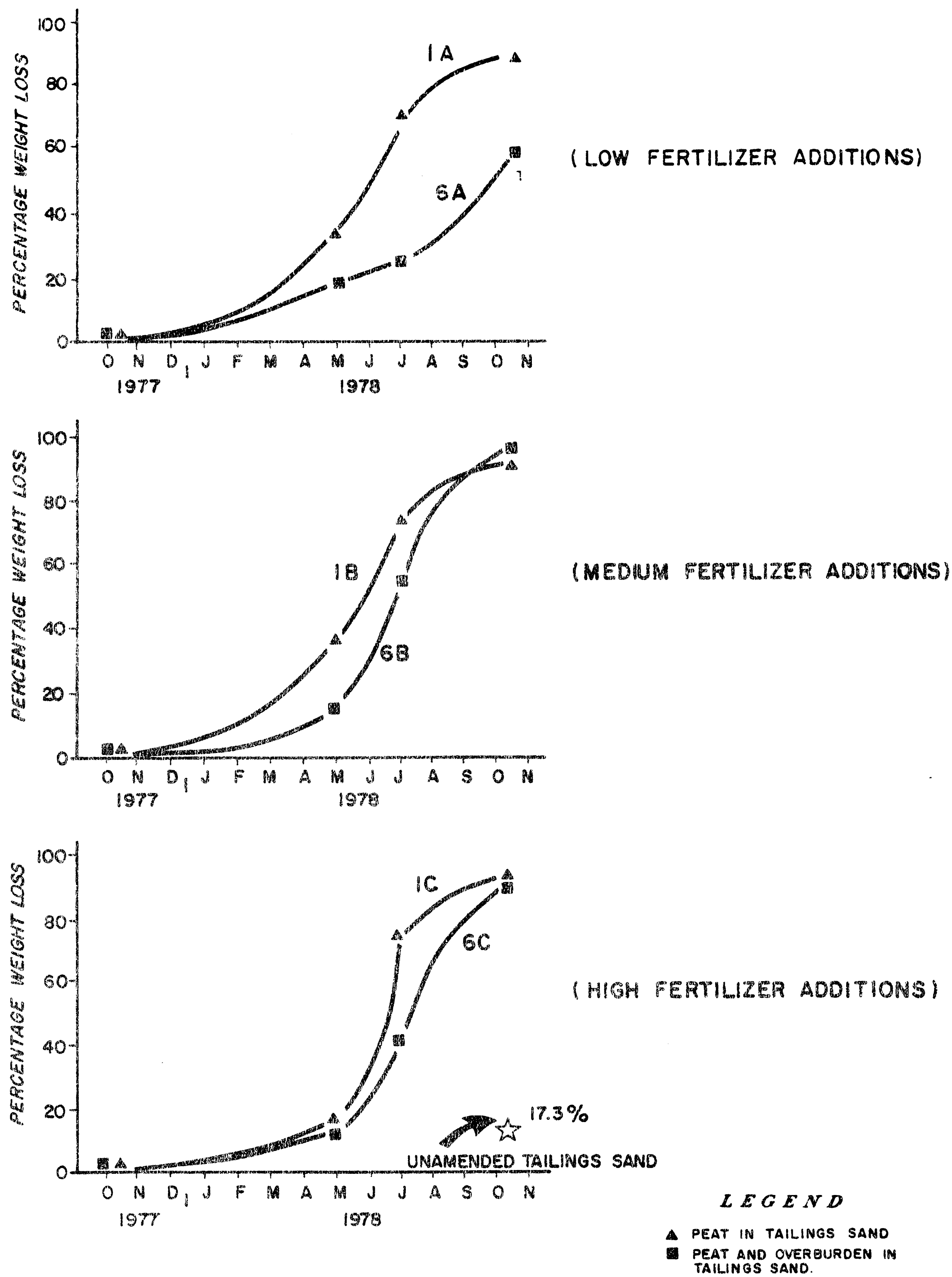


FIGURE 4-1

DECOMPOSITION OF CELLULOSE STRIPS BURIED TO A DEPTH OF 15 cm ON SELECTED TREATMENTS IN EXPERIMENT II DURING OCTOBER 1977 TO OCTOBER 1978 (ROWELL 1979).

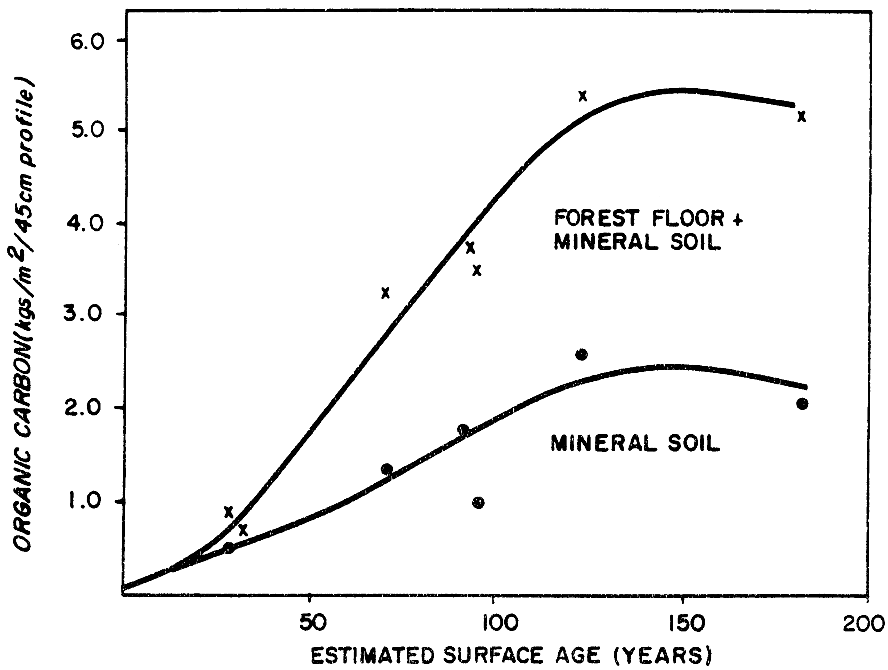


FIGURE 4-2
ORGANIC CARBON ACCUMULATION WITHIN THE MINERAL SOIL AND FOREST FLOOR (CROCKER AND MAJOR 1955)

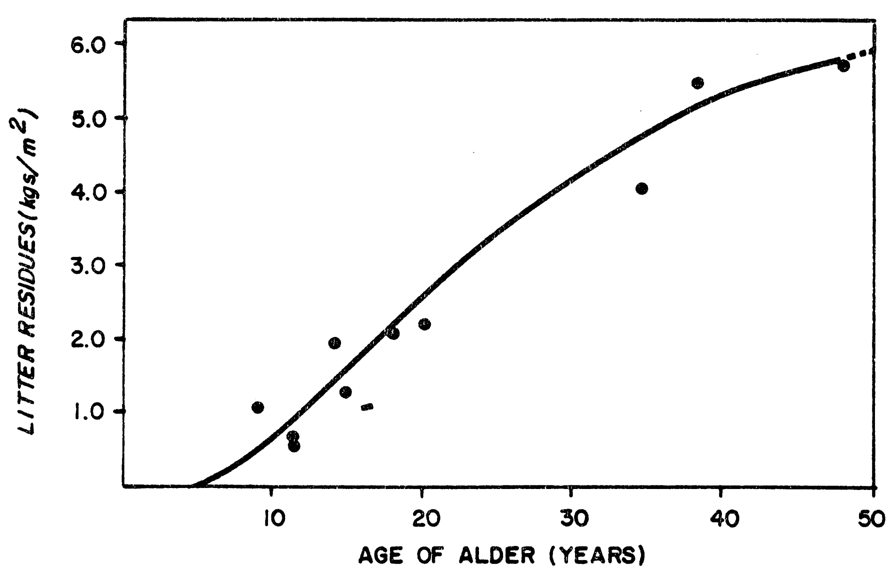


FIGURE 4-3
THE ACCUMULATION OF ORGANIC RESIDUES ON THE MINERAL SOIL UNDER DEVELOPING ALDER THICKETS (CROCKER AND MAJOR 1955)

matter on the forest floor. Table 4-1 is a synthesis of values for each of these components taken from Canada and the United States under different forest types. A jack pine forest floor of approximately 30,000 kg/ha (D.W.) corresponds closely to those values listed for lodgepole and red pine. The amount of organic matter in the mineral soil under a pine forest is about twice that on the forest floor.

The weight of the litter layers under a mature mixedwood forest with aspen or spruce can vary from 17,000 to 141,000 kg/ha. The mineral soil can contain 50,000 kg/ha (as in the only reported example on Table 4-1 (Alban et al. 1978)). The differences reported for organic matter contents under mixedwood vegetation correspond to different vegetation communities and extremely different climatic and soil conditions.

Yellow birch and oak forests are included in Table 4-1 to give a basis of comparison for radically different kinds of vegetative cover. These eastern deciduous communities are expected to produce high amounts of dry matter and have an associated soil-floor organic component of extremely high weight.

The oilsands area planted to jack pine and mixedwood will begin with very low contents of organic carbon in the soil and no litter layer. However, natural development of forest and soil in this area should result in values comparable to those in Table 4-1 within 50-100 years.

432 SOIL TEXTURE

Textural differentiation attributable to the pedogenic processes probably will not occur in the reconstructed soils for hundreds or thousands of years. The formation and illuviation of significant quantities of clay required much more than 200 years in Alaska, even where rainfall exceeded 2,000 mm/yr (Crocker and Major 1955, Crocker and Dickson 1957). Olson (1958) was able to quantify the increase in silt and clay by thousand year intervals in the dune sands of Illinois and Wisconsin (Table 4-2). Olson (1958) suggests that quartz will weather over 1000 years to yield a 1% increase in clay content. Factors such as the winnowing of sand, the deposition of dust and erosion might account for the more rapid changes in texture shown in Table 4-3 (Chandler 1942).

433 BULK DENSITY

The bulk density of soil (mass per unit volume) is dependent on the quantity of pore space as well as the mass of soil solids.

TABLE 4-1

Total Organic Matter Contents of the Forest Floor and Mineral Soil Under Various Forest Types

Forest Type	Organic matter ($x10^3$ kg/ha) Forest floor	Soil	Reference
Jack pine	33	66	Alban *et al.* 1978
Lodgepole Pine	28	-	Stottlemeyer & Ralston 1970
Red pine	30	78	Alban *et al.* 1978
Aspen	27	50	Alban *et al.* 1978
Aspen (Canada)	91-141	-	Lousier & Parkinson 1979
Aspen (Alaska)	28-76	-	Lousier & Parkinson 1979
Spruce	33	72	Alban *et al.* 1978
Spruce-fir	17	-	Stottlemeyer & Ralston 1970
Spruce-fir	91	368	Weaver & DeSelmo 1973
Yellow birch	60	442	Weaver & DeSelmo 1973
Oak	323	-	cited in Lousier & Parkinson 1979

TABLE 4-2

Percentage of Silt and Clay Occurring in Dune Sands of Various Ages

Years	Total Fine Earth	
	Silt	Clay
	%	
0	1	1
1,000	1.5	1.0
8,000	1.7	2.0
10,000	4.0	4.0
12,000	8.0	6.0

SOURCE: Olson 1958

TABLE 4-3

Increase in Silt and Clay in the Top 20 Centimetres of Soil over 1,000 Years

Years	Silt Clay
	%
15	12.4
90	14.4
250	11.6
1000	26.3

SOURCE: Chandler 1942

The development of soil porosity is due to activity of soil fauna and plant roots (Russell 1973). The maintenance of pore structure is a function of the mineral matter (Black 1968). The reconstructed soils will have a relatively low bulk density (0.8 - 1.4 g/cm^3) in the surficial 15 cm because of the addition of peat (Rowell 1977). However, even when peat is not added, the bulk density of pure tailings sand could be expected to decrease as vegetation is established and biological activity is increased.

Crocker and Major (1955) found that the bulk density of glacial debris dropped from 1.45 g/cm^3 to 0.6 g/cm^3 in the top six inches of the soil profile over 180 years (Figure 4-4). Although it appears that a long time is needed for change, this example is based on a naturally developing soil, dependent on native plant establishment.

Figure 4-4 also shows the relationship of changes in bulk density to soil depth. There has been virtually no effect on bulk density after 12 inches or 30 cm. The changes in bulk density are closely related to the development of the organic profile, that is, the combined effects of root growth and decomposition, microbial activity and the creation of ephemeral structural units resulting from the decomposition and migration of organic residues and microbial by-products (Crocker and Dickson 1957).

In areas where vegetation is difficult to establish, the changes in bulk density of sands are small and occur over an extremely long time. Olson (1958) measured a decrease in bulk density from 1.6 g/cm^3 to 0.8 g/cm^3 over 1000 years in the surface of sand dunes. The organic debris did not affect the deeper profile over that time period.

In addition to organic matter deposition and decomposition, root penetration and soil fauna activity, the climatic regime can play a direct role in bulk density changes and modifications of soil structure. For example, Crocker and Major (1955) noticed the development of a marked vesicular structure in the upper 6-12 mm of soil immediately after deglaciation. The pattern increased until the vegetative cover was complete (50 years). After alder dominated the newly formed soil and organic debris began to collect, the vesicular pattern disappeared. A later study (Crocker and Dickson 1957) attributed the pattern to the effects of freezing and thawing on the surficial soil. Texture was important because the pattern did not form on very sandy parent materials. When the vesicular structure formed under finer textured materials, the bulk density decreased significantly. The pattern might be described as the micromorphological manifestation of cryoperturbation (Mollard 1979, Pettapiece and Zoltai 1974).

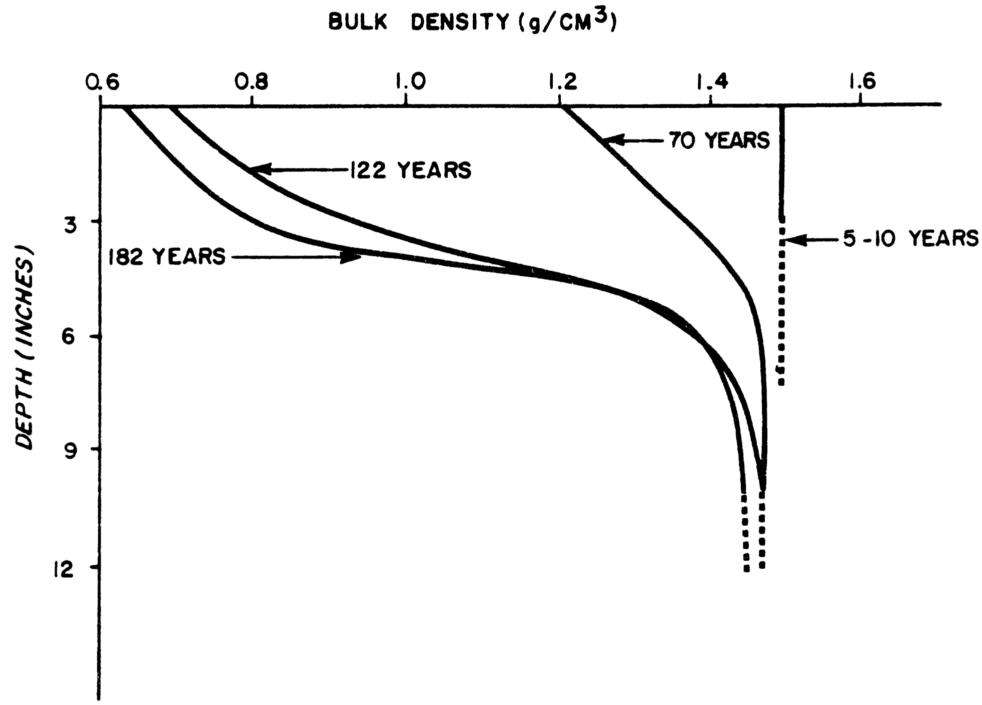


FIGURE 4 - 4

BULK DENSITY DEPTH FUNCTIONS FOR PROFILES OF DIFFERENT AGES (CROCKER AND MAJOR 1955)

434 CATION EXCHANGE CAPACITY

The two components of total cation exchange capacity in soils - the mineral and organic colloids - are not equally represented in a developing soil profile. The contribution of the mineral fraction is less in that only intense mineral weathering can affect it (Birkeland 1974). The organic component, on the other hand, is a function of the biological activity in the soil and, as such, can increase rapidly after initial vegetative colonization.

The relationship of changes in total cation exchange capacity to changes in organic matter contents is seen in Table 4-4. The cation exchange complex went from 2.6 to 19.1 me/100 g in the top 15 cm of the mineral soil after glaciation in Alaska (Chandler 1942). The effect of organic colloids on the increase in exchange capacity is seen in the changes attributable to the litter layer: from no litter and no CEC at 15 years to 38 me/100 g (litter) at 90 years. It is the production of root material and the solubilization and movement of the organic fraction down the profile that accounts for the increase in CEC in the first 15 cm.

Olson (1958) found that the CEC of sands increased from 0.5 me/100 g to 8.0 me/100 g over 1000 years. The organic matter content had gone from $<0.1\%$ to $>1\%$ in the same time period.

The relationship of exchangeable Ca and Mg to an increase in total CEC is also shown in Table 4-4. Seventy-five years was enough to stabilize exchangeable calcium at 1.25 me/100 g in the mineral soil. Magnesium continues to increase up to 250 years reaching a maximum of 1.6 me/100 g.

In the oilsands, the changes in exchange capacity will be related to the fluctuations in organic matter. The mineral materials have a relatively low CEC and the short-term weathering processes (<100 years) will not significantly alter it. The organic matter content, as a function of added peat or developing root mass, can be expected to increase rapidly, creating a larger cation exchange capacity throughout the soil profile.

435 SOIL pH

The development of vegetation on previously uncolonized land surfaces is nearly always associated with a decrease in soil pH. Figure 4-5 is a composite diagram of pH measurements made after recent glacial retreats in Alaska (Crocker and Major 1955). Nitrogen fixing species, such as alder, can cause pH reduction. A drop in pH from 8.5 to 4.5 in 150 years under the influence of alder is not uncommon (Crocker and Dickson 1957). On the other hand, the effect of *Salix*, *Populus* or *Dryas* plant cover on decrease in soil pH is almost undetectable. Similarly, there is almost no change in soil pH in the absence of plants.

TABLE 4-4

The Development of the Exchange Complex in Soil Since Deglaciation Under a Forest Vegetation

Age	Horizon and Depth	CEC	Exchange Ca	Mg
years	cm	me/100g		
15	A:0-15	2.6	0.75	0.20
90	LFH:	38.0	11.60	5.30
	A:0-15	4.5	1.25	0.45
250	LFH:	90.0	35.40	6.30
	A:0-15	7.5	0.90	1.60
+1000	LFH:	96.2	18.20	3.50
	A:0-15	19.1	1.05	0.50

SOURCE: Chandler 1942

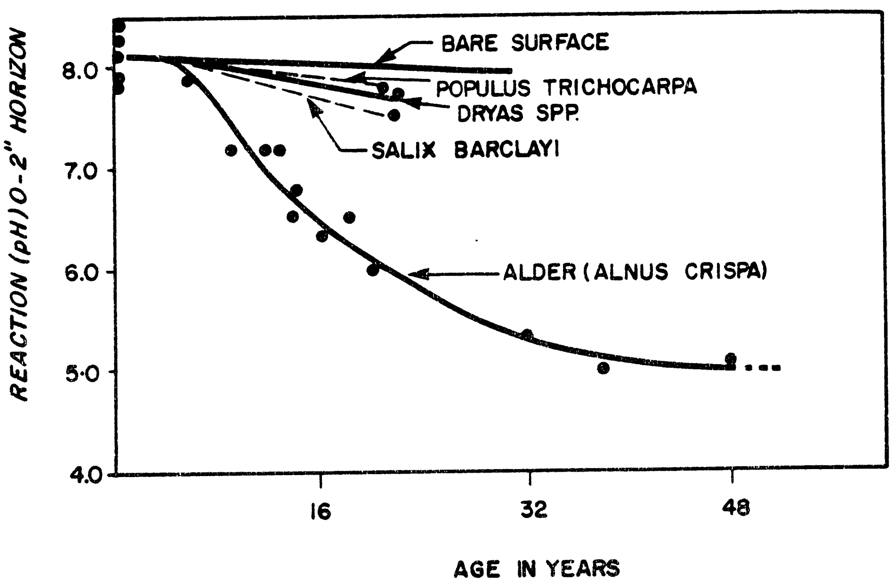


FIGURE 4-5

RATE OF CHANGE OF REACTION 0-2 IN HORIZON RELATIVE TO TYPE OF VEGETATIVE COVER, RATE OF CHANGE IN CALCIUM CARBONATE CONTENT UNDER ALNUS (CROCKER AND MAJOR 1955)

Tailings sand and peat mixtures typically begin with high pH values (8.5) and low cation exchange capacities (1-10 me/100 g). The exchange complex is normally saturated with calcium and sodium (Takyi et al. 1977). After the addition of peat, mechanical mixing, the application of fertilizers and four years of rainfall and vegetation growth, the pH of the surficial 30 cm drops to 6.4 and that of the underlying 30 cm to 6.9 (Table 4-5).

Dune sands have been shown to decrease in pH in relation to the decline in calcium carbonate (Salisbury 1925). Figure 4-6 shows how the rate of leaching of calcium carbonate from dunes is combined with a decrease in pH over several hundred years. Even under conditions of high rainfall (>1000 mm/yr) and intensive leaching on sandy materials, the drop in pH is slow. Salisbury (1925) shows that at later stages the rate of loss of $CaCO_3$ is dependent on the amount present, not on the total precipitation. In the case shown in Figure 4-6, there is a $CaCO_3$ decrease of 0.62%/yr in both dunes. Another study has shown that when carbonates were present in high amounts ($\simeq$1%) in sands, it was more than 1000 years before a bleached A_e horizon (pH - 4.5) developed under forest vegetation (Olson 1958) and even in this case, the lower horizons remained basic.

4.4 CHANGES IN SOIL MOISTURE SUPPLY

The soil moisture status as defined in Chapter 3 consists of the available water content and the rate at which water is transmitted through soils. The soil properties that will change over short periods of time and also affect one or both of these soil moisture components are: organic matter content, bulk density and soil horizon depth.

441 INCREASED AVAILABLE WATER WITH INCREASED ORGANIC MATTER

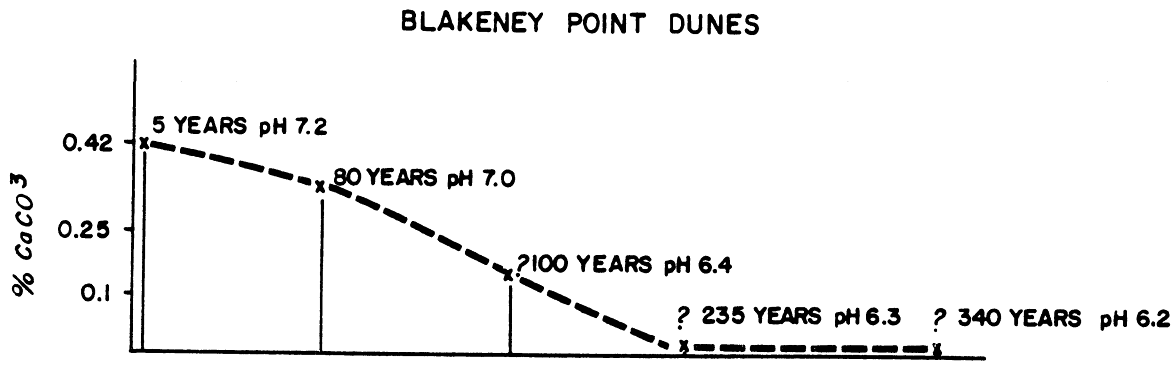
For each percent increase in well-humified organic matter, there will be approximately a 1% increase in available water. Because it is unlikely that organic matter will decrease (although the situation is dependent on the rate of peat decomposition), we can expect a gradual and continual improvement in amounts of available water in all reclaimed soils. At the same time, the development of full vegetation canopies over the first 10-20 years will also mean that the potential for evapotranspiration will also increase. Consequently, more water will be required for plant growth in the tenth year than in the first year.

TABLE 4-5

Soil Properties of Dike Slopes Constructed from Tailings Sand Before and After the Addition of a Peat Amendment (Takyi *et al*. 1977)

Year	Depth	pH	Mineral N	Total N	P	K	Org. C
	cm		ppm	%	ppm	ppm	%
1969	0-30	8.5	0	-	3.5	12	-
(before peat	30-60	8.4	0	-	2.5	6	-
addition)	60-90	8.5	0	-	3.0	8	-
1975	0-15	6.4	0.75	0.24	13.2	47.2	5.7
(peat added	15-30	6.4	0.61	0.09	2.6	17.8	1.4
in 1970)	30-60	6.9	0.45	0.01	1.1	14.8	0.5

SOURCE: Takyi *et al*. 1977



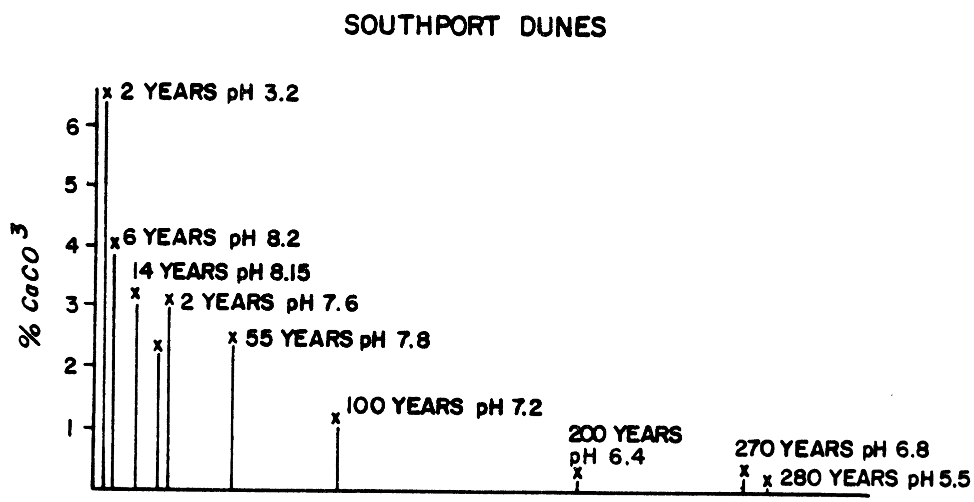


FIGURE 4-6
RATE OF LEACHING OF CALCIUM CARBONATE FROM DUNES (SALISBURY 1932).

442 CHANGES IN BULK DENSITY AND WATER TRANSMISSIVITY IN SOILS

The rate water is moved through the soil is dependent primarily on the nature and distribution of the soil pores and the extent to which they are filled with water. It has been pointed out that soil bulk density is expected to decrease with additions of organic matter, extension of root systems and increased activity of soil organisms. A decrease in bulk density of this kind is normally associated with an increase in smaller diameter pores per unit volume of soil. These smaller diameter pores tend to hold water against drainage more tenaciously than their larger diameter counterparts; at the same time, soils with low bulk density and a high content of small diameter pores usually have a substantially higher capacity for water transmission to plant roots. Overall, a decrease in bulk density will result in an improvement in the ability of a soil to supply water to the vegetation cover.

443 CHANGES IN SOIL HORIZON DEPTH

This study recommends that peat and overburden materials be mixed into tailings sand in varying proportions to varying depths depending on the expected vegetation type. This will result in a certain degree of "horizonization", even though the reconstructed soil horizons are not comparable to naturally formed soil horizons.

Horizonization as described here will influence rooting patterns and water relations. Rowell (1977, 1979) has found that grass root systems are initially confined to horizons which are mixtures of peat and sand or peat, overburden and sand. Grass roots do not penetrate from mixed materials into pure tailings sand strata easily.

Sharp changes in horizons (from an abundance of peat to no peat or from heavy textured overburden to sand) also create special boundary conditions influencing soil water storage and movement (Gardner 1979). In fact, in the first few years, the stratification proposed for each of these soil types increases the amount of water available for plant use by comparison to non-stratified soils. The different layers slow the movement of water causing more water to remain in the upper part of the root zone.

Over time, the original stratification of soil boundaries will disappear, peat will be decomposed, organic acids will be produced that release iron and other primary minerals, and organic ligands will chelate iron and move it downward in the profile.

In addition, root production and decay, soil faunal activity and the freezing-thawing and wetting-drying cycles will cause the upper parts of the profile (0-50 cm) to be partially mixed. The most predictable result, however, is that a new horizonization or stratification will occur. Although time periods are too short (80 years) to expect a large amount of clay mineral redistribution, the decomposing peat may create conditions for the deposition of iron "hard pans" or other products of mineral solubilization following soil acidification (Collins and Coyle 1980, Coyle and Collins 1981). The effect of these possible changes on water movement and root systems is similar to the original effects of stratification - more water will be held in the soil layers above a "hard pan" and roots will have difficulty penetrating them.

4.5 CHANGES IN NUTRIENT STATUS

It was possible in Chapter 3 to design soils with nutrient supplies sufficient for the establishment and initial growth (approximately two years) of three distinct vegetative communities. This task was accomplished by knowing: (1) the physiological requirements of each plant community at the beginning of its rotation, and (2) the soil mechanisms associated with the storage and release of the essential nutrients.

The larger objective of this report, however, is to design reconstructed soils capable of supporting maintenance-free vegetation communities over the long term, that is, to create soils capable of supplying each plant community with sufficient nutrients to satisfy annual uptake* requirements over the full rotational age of the forest stand. These communities are more complex than those initially established by virtue of the diversity in species, the ranges in plant size and spatial influence and, in the case of the boreal forest, the longevity of the tree component. The most important factors that add to this complexity are the immobilization (or "tie-up") of large quantities of elements in the biomass for long periods, partial cycling of some elements, changes in demand during various life stages of the plant species and changes in soil conditions.

The purpose of this section is to estimate the nutrient demand of each vegetation community throughout the rotational period and compare these results with the soil-vegetation supply capability based on considerations of nutrient additions, nutrient losses and internal nutrient cycling.

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* Following Morrison (1974), uptake is taken to include all absorption processes whether active, passive, mycorrhizal or symbiotic nitrogen fixation.

451 NUTRIENT DEMAND

The annual nutrient requirements of forested areas can be estimated in at least two ways (Morrison 1974): (1) the total nutrient content of the plant community divided by the stand age - the result is known as "annual accumulation" - and (2) "nutrient transfer" calculations involving an indirect estimation of uptake or nutrient absorption over a year. The first method - annual accumulation - is not appropriate for a perennial grass community because nutrients are cycled mostly in plant detritus, outside the thriving plant itself (Ziemkiewicz 1982). For this reason, calculation of annual accumulation will be performed on jack pine and mixedwood communities, and calculation of nutrient transfer will be done on these forest stands in addition to the grass community on dike slopes.

.1 Annual Accumulation

The total nutrient content of comparable pole-size stands of jack pine, white spruce and trembling aspen are presented in Table 4-6. In addition, the nutrient reserves are given for the organic and mineral portions of the soil beneath these stands. The pine forest and mixedwood stands are located on very similar soils and are subject to similar climatic influences due to their geographic proximity.

Annual accumulation is calculated by dividing the total accumulation in the vegetative component (as reported in Table 4-6) by the stand age. This results in the following values:

Element	Jack Pine	Mixedwood
	kg/ha	
Nitrogen	7	12
Phosphorus	<1	2
Potassium	3	8
Calcium	5	24
Magnesium	<1	2

For purposes of estimating the mixedwood annual nutrient accumulation, the values of white spruce and trembling aspen stands in Table 4-6 were averaged and divided by a 40 year period of accumulation.

The patterns of nutrient accumulation can vary with age as well as type of forest stand. The changes in total nutrient content of 20 to 60 year old jack pine stands reflect the fluctuations occurring during the maturation of a forest ecosystem (Table 4-7). In corroboration of these trends, Switzer *et al.* (1968), cited by Morrison (1974), found that annual accumulation in slash pine (*Pinus taeda*) per unit area peaked during the first decade for nitrogen, during the second for phosphorus and potassium and during the third for calcium and magnesium.

TABLE 4-6

Comparison of Nutrient Content (kg/ha) of Jack Pine and Mixedwood Forest Stands on Similar Soils in Canada and the Northern U.S.A.

Stand	Component	N	P[1]	K[2]	Ca[2]	Mg[2]	Source
Jack Pine (*Pinus banksiana*) 30 year old natural stand on glacial till, western Ontario, Canada	Tops	190	16	92	122	19	Morrison 1974
	Roots	40	2	8	15	3	
	Understory	4	< 1	3	1	< 1	
	Humus	347	2	39	92	11	
	Soil (0-100 cm)	2987	34	192	156	30	
White Spruce (*Picea glauca*) 40 year old planted stand, nearly pure, on glacial till in northern Minnesota U.S.A.	Tops	382	57	229	719	40	Alban *et al.* 1978
	Roots	67	7	25	90	6	
	Understory	1	< 1	1	1	< 1	
	Humus	752	61	76	1398	77	
	Soil (0-36 cm)	2542	68	299	2808	338	
Trembling Aspen (*Populus tremuloides*) 40 year old natural stand, 85% pure, on glacial till in northern Minnesota U.S.A.	Tops	368	47	287	858	58	Alban *et al.* 1978
	Roots	89	20	80	216	18	
	Understory	15	2	10	23	4	
	Humus	667	60	78	1081	89	
	Soil (0-36 cm)	2058	86	294	2643	266	

1 All phosphorus values in vegetation components are "total" P; soil phosphorus (humus and soil) is "available" P.

2 All potassium, calcium and magnesium values in vegetation components are "total"; humus and soil values for these elements are reported as "exchangeable" contents.

TABLE 4-7

N, P, K, Ca, and Mg Contents (Adjusted to Normal Stocking; Root Included) in *Pinus banksiana* of Differing Ages

Age	Nutrient Element				
	N	P	K	Ca	Mg
years	kg/ha				
20	133	12	63	81	14
30	171	15	85	117	19
60	205	17	105	154	25

SOURCE: Foster and Morrison 1976

.2 Nutrient Transfer

The flow into, the flow out of and the accumulation of elements within the plants themselves are important in determining the nutrient demand of vegetative communities. This overall flow is called "nutrient transfer".

Nutrient Transfer in Forest Stands

The various fluxes involved in nutrient transfer for forest stands are represented diagramatically in Figure 4-7. In this case annual accumulation is the result of gain minus losses. Gain is a sum of nutrient absorption in the roots (total uptake in Figure 4-7) and absorption from interception of precipitation; losses include foliar leaching (canopy wash), stemflow, litterfall (from both trees and understory), and root slough and exudation. Nutrient absorption from precipitation is measured in practice by subtracting amounts in throughfall and stemflow from total incident precipitation (Morrison 1974). From this the overall process is represented by:

$$A = U + P - T - S - L - R$$

where:
- A is annual accumuation
- U is total uptake
- P is incident precipitation
- T is throughfall
- S is stemflow
- L is litterfall
- R is root slough

By rearranging the expression we can show that total uptake can be estimated from measurements of quantities on the right-hand side of the equation:

$$U = A - P + T + S + L + R \qquad \text{(Equation 4-1)}$$

The estimates of all nutrient components necessary for calculation of total uptake in jack pine and mixedwood forests are included in Table 4-8. All information regarding nutrient transfer in jack pine was measured directly by Foster and Morrison (1976). However, comparable data for processes in mixedwood forests are not available; therefore, we have assumed that transfer rates will follow closely the total nutrient content, and have increased the nutrient value for each process in mixedwood stands by the ratio of total nutrient in mixedwood to total nutrient in jack pine. As an example, nitrogen throughfall in jack pine is measured as 4.0 kg/ha/yr; nitrogen throughfall in mixedwood is estimated as 8.0 kg/ha/hr (average nitrogen in tops of white spruce and trembling aspen in Table 4-6 is 315 kg divided by 190, the N in jack pine, and multiplied by 4.0 kg/ha/yr).

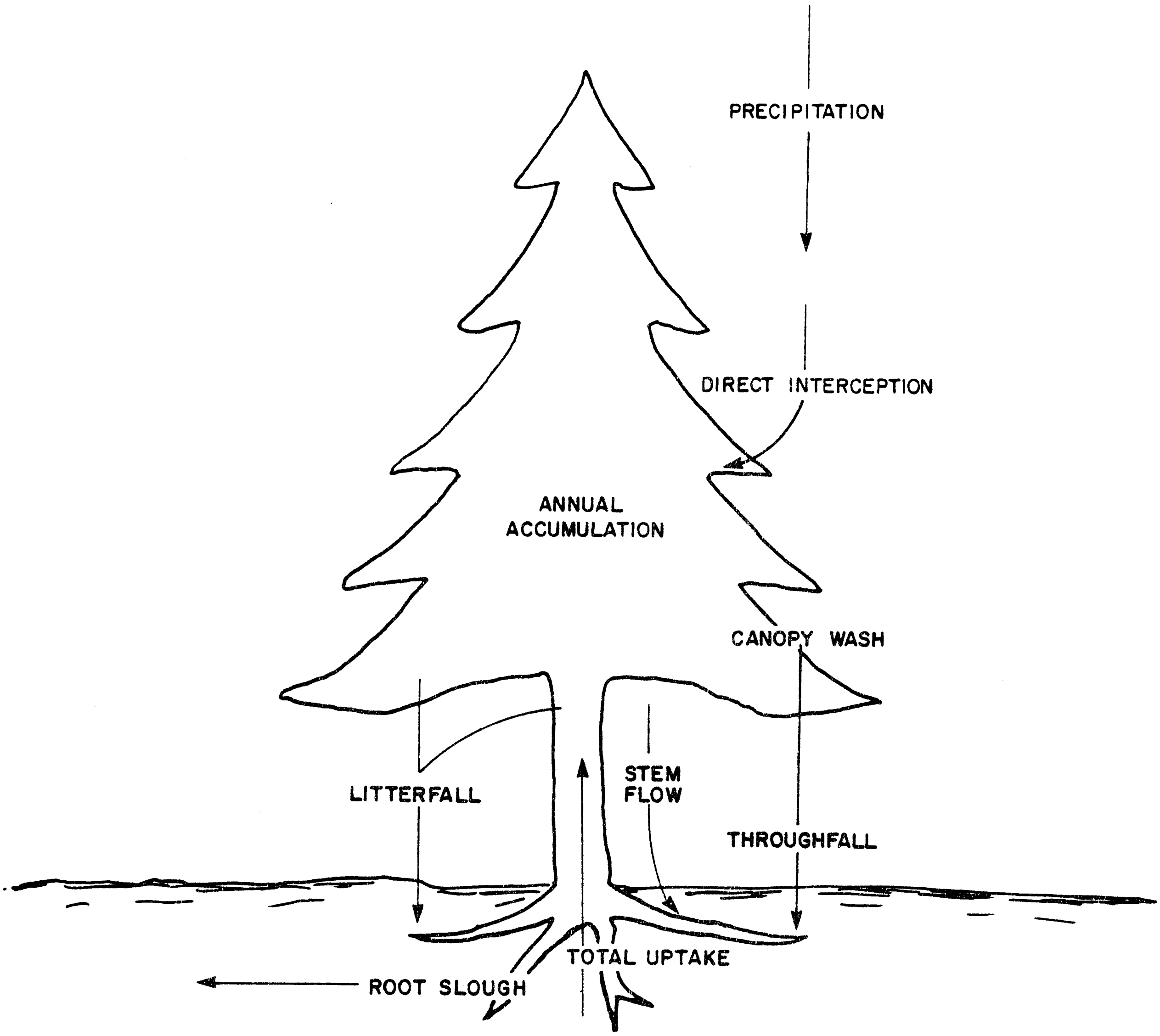

FIGURE 4-7

ELEMENTS OF NUTRIENT CYCLE NECESSARY IN ESTIMATING "DEMAND."

TABLE 4-8

Annual Nutrient Transfer in Jack Pine and Mixedwood Forest Stands

Process	Forest Type	Nutrient Elements				
		N	P	K	Ca	Mg
				kg/ha		
Precipitation[1]	-	7	0.1	4.0	5.6	0.8
Annual Accumulation[2]	Jack pine	7	< 1	3	5	< 1
	Mixedwood	12	2	8	24	2
Throughfall	Jack pine[3]	4.0	0.1	10.0	6.6	1.1
	Mixedwood[4]	8.0	0.6	80.0	46.7	2.3
Stemflow	Jack pine[3]	0.1	< 0.1	1.6	0.6	0.1
	Mixedwood[4]	0.2	< 0.2	12.8	4.3	.2
Tree Litterfall	Jack pine[3]	20.5	1.2	4.9	13.3	1.7
	Mixedwood[4]	41.0	4.5	39.2	94.4	4.3
Understory Litterfall[5]	Jack pine	4.7	0.4	2.2	1.7	0.4
	Mixedwood	9.4	1.2	4.4	20.4	1.0
Root Slough[6]	Jack pine	2.8	0.4	1.6	3.0	0.6
	Mixedwood	15.6	2.6	10.4	30.6	2.4

1 Precipitation data as reported in Section 433.
2 Calculations as per Table 4-6.
3 From Foster and Morrison (1976).
4 Estimated by multiplying amount reported in jack pine by following ratio: total nutrient in mixedwood ÷ total nutrient in jack pine. This calculation was carried out for each nutrient element; total nutrient information taken from Table 4-6.
5 Same calculation for mixedwood as described above, but ratios were calculated for understory rather than nutrient content in trees.
6 No information available; calculations reported here assume 20% of root nutrient content lost per year for both forest stand types.

Total uptake, as expressed in Equation 4-1, is considered to be a better estimate of demand than annual accumulation because it represents the nutrient flux over much shorter time periods (Morrison 1970). Using the values of each process for each forest type, the following balance sheet results:

Stand	N	P	K	Ca	Mg
Jack pine	32.1	2.2	19.3	24.6	4.1
Mixedwood	79.3	11.0	150.8	214.8	11.4

A balance sheet calculated from considerations of nutrient transfer as displayed above indicates a total nutrient demand five to ten times higher than that indicated by annual accumulation. The nutrient transfer calculations are thought to be more reliable because more component estimates are included and the time period is specific - usually one or two years of measurements made when the stand is mature but not at rotation age - as compared to the 30 or 40 year averages used in annual accumulation figures.

Annual Nutrient Demand on Grass-Legume Covered Dike Slopes

The amount of nitrogen, phosphorus, potassium and calcium absorbed by a grass-legume mixture on oilsands tailings dikes during the establishment year is shown in the first two columns of Table 4-9. In the year following establishment there was a 20% increase in absorption of all nutrient elements for both tops and roots (Rowell 1978). Some of the increase is attributable to the spurt of growth made by the grass component after the cover crop of oats was removed. In both years nitrogen and potassium were present in highest amounts (approximately 100 kg/ha), followed by calcium (33 kg/ha), and phosphorus (26 kg/ha). The annual turnover of perennial grass systems has been estimated at 2% to 1000% (Coleman 1976). In this study the annual nutrient demand of a grass-legume cover on tailings sand is estimated by adding 20% to the amount of nutrients in the top growth (to cover the increased uptake in years after establishment) and 20% of the root content (to cover the portion of nutrients lost from the roots and the increase from one year to the next). Annual requirements can be calculated from the following equation:

Nutrients in top growth + 20% nutrients in top growth
+ 20% nutrients in roots = annual demand (Equation 4-2)

The apparent annual nutrient demand for a grass-legume cover on dike slopes as reported in Table 4-9 is similar to a mixedwood forest when comparing nitrogen, phosphorus and potassium. However, the requirement for calcium is nearer to jack pine than mixedwood.

TABLE 4-9

Annual Nutrient Uptake and Annual Nutrient Requirement of Grass-Legume Mixtures on Tailings Sand Dikes

Element	Nutrient Uptake[1]		Annual Nutrient Requirement[2]
	Tops	Roots	
	kg/ha		kg/ha
N	62.8	23.7	80.1
P	8.4	17.5	13.6
K	74.2	21.5	93.3
Ca	11.6	21.2	18.2

1 Figures are actual measurements from Rowell (1977) for grass-legume mixture during the establishment year; average of three fertilizer treatments and seven surface amendments.

2 Calculated from Equation 4-1.

452 NUTRIENT SUPPLY

The net amount of nutrients supplied to the plants from the soil depends on the balance between additions and losses and the rate of nutrient turnover from organic or inorganic reservoirs within the soil. This section describes and quantifies as far as possible the net nutrient balance expected to occur in each of the plant communities planned for the oilsands area.

.1 Additions

The addition of nutrient elements to an ecosystem originates from precipitation, dust, eroded soil materials, biological fixation or the weathering of minerals within the soil.

Erosion and dust accumulation are important only in special situations, particularly in sites at the foot of slopes or under conditions of high dust fall-out, and are therefore not considered further in this section.

Precipitation

The earth's atmosphere is an enormous reservoir of nitrogen and the majority of nitrogen added to terrestrial ecosystems falls either in precipitation or is fixed biologically by a plant-microbial symbiosis. Nitrogen increments originating from precipitation range from 0.74 - 30 kg N/ha/yr in northern Europe (Wollum and Davey 1975) to 1 - 19 kg N/ha/yr in North America (Youngberg and Wollum 1970); the most commonly cited range for Canada is between 4 and 8 kg N/ha/yr (Weetman 1961, 1962, Foster 1974, Foster and Morrison 1976).

Precipitation also contains significant quantities of calcium, potassium and magnesium; phosphorus contents are normally very low (Rowell 1977). Foster and Morrison (1976) measured the following elements and their concentrations in precipitation occurring in a jack pine forest in Ontario.

Elements (kg/ha/yr)				
N	P	K	Ca	Mg
6.0	0.1	4.0	5.6	0.8

Biological Fixation

The biological fixation of atmospheric nitrogen is extremely important to the nitrogen economy of natural communities. There are heterotrophic, autotrophic and photosynthetic microorganisms capable of reducing dinitrogen (N_2) to ammonia (NH_3) and nitrogen containing organic compounds. Free-living nitrogen fixers can glean their reducing power

(H ions) from inorganic sources (autotrophs), from light and water (phototrophs) or from previously formed organic compounds (heterotrophs). However, as their vernacular name (free-living) implies, they are not directly dependent on other living organisms. Asymbiotic fixation (another name for free-living) occurs ubiquitously in grassland and forested communities but rarely results in more than 5 kg N/ha/yr (Youngberg and Wollum 1970). No direct measurements of asymbiotic N fixation have been made in the oilsands area (Rowell 1979).

Symbiotic nitrogen fixation is the fixation of atmospheric N by an association of microbe and plant. Neither symbiont is capable of fixing N in the absence of the other. Symbiotic fixation of nitrogen is carried out by both gymnosperms and angiosperms (Youngberg and Wollum 1970). Of the two groups, the angiosperms are most important and are represented by legumes and non-legume species. Legumes are characterized by taxonomic criteria (family: Leguminosae) and by the endophyte found in the root nodules - Rhizobium. The non-legumes have an actinomycete as the nodule endophyte. It is now common to refer to the latter group as "actinorhizal plants" (Fessenden 1979).

Measurements of nitrogen fixed symbiotically by leguminous and actinorhizal plants vary from 5 to 320 kg N/ha/yr (Weetman 1961, Fessenden 1976, Wollum and Davey 1975, Tarrant and Trappe 1971). When high rates of nitrogen fixation are discussed in the literature (>100 kg/ha/yr), the usual reference is to prolific pasture legumes including species such as alfalfa, white clover and subterranean clover (Templeton 1976). Recent evidence of extremely high nitrogen fixing capacity has been reported for actinorhizal plants (Tarrant and Trappe 1971).

Actual measurements of N fixation in the oilsands area have not been made. The work to date in dike slope revegetation has shown that the establishment of cultivated forage legumes is difficult (Rowell 1977, 1978, 1979). However, when a proper mix of legumes and grasses is achieved on tailings sand, up to 100 kg N/ha/yr could be biologically fixed. The low levels of organic nitrogen present in the sand and overburden will not inhibit the physiological functioning of the legume development. Prior evidence also suggests that actinorhizal genera such as Myrica and Alnus spp. could be used effectively in the initial stages of forest plantation (Crocker and Major 1955, Crocker and Dickson 1957, Tarrant and Trappe 1971). For purposes of this study we will assume that the legumes and actinorhizal plants will fix an average of 30 kg N/ha/yr in each of the plant communities designated for the oilsands area.

There are no other nutrient elements which are biologically added to a plant community from the atmosphere. Extensive work has shown that mycorrhizal fungi are capable of mobilizing phosphorus from non-labile soil pools (Mara and Bryan 1975), and Voigt (1970) has demonstrated the capacity of tree roots to differentially extract potassium from a variety of K-bearing minerals. However, the dominant material in the oilsands area is quartz and therefore total phosphorus pools and potassium laden clays are both in limited supply. For all major nutrient elements except nitrogen, the additions through rainfall, weathering and specific nutrient amendments will play a larger role than biological fixation.

Mineral Weathering

Under natural conditions, most of the major nutrients essential to plant growth, particularly calcium, magnesium, sodium, potassium, phosphorus and the micronutrients, are supplied through rock weathering. Because the rocks vary in both their mineralogy and chemistry, they have different capacities to supply nutrients. Sedimentary rocks, for example, are often deficient in one or more nutrients because the processes responsible for their formation tend to disperse some nutrient elements and concentrate others. Sandstones, as siliceous materials, are low in bases, while limestone is low in alumino-silicates (Brownlow 1979).

The weathering of the primary minerals within the solum is termed pedochemical weathering (Jackson and Sherman 1953). The processes and products of pedochemical weathering are well documented; the weathering rates are not well defined.

Quartz has a high proportion of silicate tetrahedron linkages and an extremely low content of base elements per unit of cell structure, and is thus one of the least weatherable minerals. However, the grain size as well as the mineralogical structure affect the weathering rate, and therefore, the comminution of quartz grains by physical weathering or treatment may permit faster dissolution rates (Clayton 1979).

A comparison of nutrient release from several kinds of rocks shows that the wide fluctuations in release rate correspond generally to differing nutrient concentrations and degree of consolidation of the parent rock material (Table 4-10). For instance, in a rock type formed from precipitated calcium (dolomite), the annual calcium release is high - 86 kg/ha/yr. In serpentine or metashales, total calcium contents are much lower and release rates are estimated to be less than 10 kg Ca/ha/yr (Table 4-10). All other elements show similar patterns of variation, albeit the absolute rates are different.

The outwash sand (last row, Table 4-10) is the most similar geological material type to oilsands in terms of particle size distribution (sandy), degree of consolidation (unconsolidated) and elemental content (high silica, low nutrients). Using this assumption of similarity, we can expect the unamended oilsand tailings to release approximately 10 kg potassium, 25 kg calcium and 8 kg magnesium per hectare per year.

TABLE 4-10

Comparisons of Elemental Release from Rock Weathering Using Mass Balance Techniques

Location	Rock Type	Na	K	Ca	Mg	SiO_2	Fe
				kg/ha/yr			
White Mountains California	dolomite	2	4	86	52	32	0.06
White Mountains California	adamellite	1	8	17	2	21.1	0.03
Cascades, Oregon	tuffs/breccias	28	1.6	47	17.6	213	-*
Luxembourg	metashale	9	0.2	8.7	15.7	-	-
Priedmont, Maryland	schist	2.6	2.3	1.3	1.7	119	-
Priedmont, Maryland	serpentine	t	t	t	34.1	55.8	-
Hubbard Brook, New Hampshire	moraine/gneiss	5.8	7.1	21.1	3.5	39	-
Brookhaven, New York	outwash sands	6.7	11.1	24.2	8.4	-	-

* indicates no data.

t = trace

SOURCE: Clayton 1979

.2 Losses

The largest nutrient loss from reclaimed oilsands tailings is due to erosion (Rowell 1979). An estimate of nutrient removal from erosion is calculated by multiplying the element concentrations by the average loss of soil per year:

Total N Concentration:	0.4%
Annual Soil Loss:	3×10^3 kg
Annual Loss N by Erosion:	$0.4\% \times 3 \times 10^3$ kg = 12 kg N/ha/yr

The figure of 3×10^3 kg soil loss/ha/yr represents a possible annual average for dike slopes, mixedwood and jack pine forest soils. The dike slopes will tend to lose more soil per year than the relatively flat, forested soils. Nitrogen concentration at 0.4% in the surficial 15-30 cm is also an estimated average for the three vegetative communities.

Using the same assumptions regarding the relationship of nutrient loss to erosion rate for other elements, we can predict that annual losses will approximate the following amounts:

Concentration/Loss	Nutrient Element				
	N %	P %	K me/100g*	Ca me/100g*	Mg me/100g*
Nutrient Concentration (total in surficial 15 cm)	0.4%	0.05%	45	15	40
Estimated Annual Loss	kg/ha/yr				
	12	0.5	53	9	14

* K, Ca, Mg concentrations are reported as total, not exchangeable cations.

The loss of soluble ions through leaching depends upon the amount of water moving through the soil (see Section 212.4 - Drainage) and the concentration of ions in solution. The tailings sand produces conditions characteristic of large losses because of a high infiltration rate. Rowell (1977) found that 13-34% of the intercepted rainfall on dike slopes reached a depth of more than 30 cm. This figure corresponds well to the estimate of MacLean (1980): 25% of total water loss in oilsands materials is attributable to drainage, as calculated from volumetric water contents and field measurements of suction pressures.

The two nutrients most susceptible to loss by leaching are nitrogen and potassium (Black 1968). The anionic nature of nitrate makes it, rather than ammonium, the nitrogen form most highly mobile in the soil matrix (Wollum and Davey 1975). Table 4-11 examines the relationship between water leached to 30 cm and the measured nutrient losses. Both nitrogen and potassium losses can be considered high in this instance. In 1977 less than 2.3 kg N/ha were leached to 30 cm (Rowell 1978). The difference is due to the lesser quantity of water percolating through the profile (15 mm). Phosphorus losses due to leaching on dike slopes have been consistently low.

Mature forests generally have extremely low leaching losses because of deep and extensive rooting systems and a capacity for nutrient "tie-up" in the leaf litter layer (Likens et al. 1969). Mature forests on coarse textured oilsands materials, however, can be expected to loose a substantial amount of nutrients annually through deep drainage. The figures in Table 4-11, although measured as part of an experiment on grass-legume effects, will also be used to represent estimated nutrient losses of mature forest stands on reconstructed soils in the oilsands area.

The precipitation which does not enter the soil can solubilize and remove surficial nutrients as "runoff". Rowell (1978) measured only 1-2% of the total rainfall over the growing season as runoff. The amounts of nitrogen and potassium collected in runoff were extremely low (< 1 kg/ha). The application of nitrogen and potassium fertilizers immediately before the measurement of nutrients in runoff did not significantly increase losses (Takyi et al. 1977).

The gaseous loss of nutrients to the atmosphere - volatilization - affects only nitrogen. Volatilization includes the loss of ammonia (NH_3), dinitrogen (N_2) and various nitrogen oxides (NO_x). Ammonia collects as a result of the chemical conversion of ammonium to ammonia; with acidification of the soil the chemical equilibrium of NH_3 and NH_4 is shifted toward the latter (Ballard personal communication):

$$NH_3(aq.) + H^+ \rightleftharpoons NH_4^+$$

$$(K_b = 1.73 \times 10^{-5})$$

When the pH is increased the equilibrium can radically shift to favour the formation of NH_3 (Table 4-12). A low cation exchange capacity, high temperature and high rate of evaporation can also shift the equilibrium toward the formation of ammonia and the volatilization of nitrogen.

Denitrification - the conversion of nitrate (NO_3^-) to dinitrogen or nitrogen oxides - is both an abiotic and biotic process in soils; however, the purely chemical reaction has not been found to be important. Biological denitrification is a respiratory mechanism of many dif-

TABLE 4-11

Lysimeter Experiment to Determine Water and Nutrient Losses Due to Leaching Under Grass-Legume Mixture

Total Water Leached	Total Nutrient Losses		
	N	P	K
mm		kg/ha	
32.8	7.5	<0.1	3.2

* Total precipitation during measurement was 178.5 mm. Results are averages of 21 totals including seven amendments and three levels of fertilizer application.

SOURCE: Rowell 1977

TABLE 4-12

Relationship of pH to the Concentration of NH_3 in Comparison to NH_4

pH	% NH_3	% NH_4
6.0	0.1	99.9
7.0	1.0	99.0
8.0	10.0	90.0
9.0	50.0+	50.0-

SOURCE: Wollum and Davey 1975

ferent microorganisms which use nitrate as an electron acceptor. The requirements are few: nitrate, low partial pressures of oxygen, and an energy source (Wollum and Davey 1975). The products of the biological reduction of nitrate are NO_2^-, N_2O and N_2.

Denitrification can occur in every type of soil. The various autotrophic and heterotrophic bacteria are ubiquitous; some fungi possess the necessary enzyme complexes for denitrification (Russell 1973). When conditions are right, 84% of applied nitrate nitrogen can be lost from the soil by denitrification within hours (Wollum and Davey 1975). There is one suggestion that up to 30% of the applied nitrogen lost on dike slopes could be attributed to denitrification (Rowell 1979). The nature of the soil materials, low in nitrates, a low CEC and low water holding capacity, make this seem unlikely. Unincorporated peat, however, could provide an excellent habitat for rapid rates of denitrification.

.3 Balance of Nutrient Additions and Losses

The summing up of total nutrient gains and losses over a year shows that nitrogen and calcium are expected to increase, albeit slowly, and potassium and magnesium will be gradually lost (Table 4-13). Total phosphorus is expected to remain static.

The net additions and losses are not expected to drastically affect the nutrient status of any of the three proposed plant communities, even over the full rotation age of the longest lived community. Nitrogen and calcium gains, 650 and 1600 kg/ha respectively, represent an increase in total elemental content of only 10-15%. The possible loss of 3000 kg potassium per hectare over 80 years is not destructive in itself because only 0.4% of the total potassium is in an exchangeable or available form (Doll and Lucas 1977).

It follows from the information presented on Table 4-13 that the nutrient status over the first 80 years of each plant community will not be seriously affected, either negatively or positively, by natural losses or additions of nutrients. It also follows that sufficient nutrient uptake in each community will result from satisfactory rates of internal nutrient cycling.

453 INTERNAL NUTRIENT CYCLING

In order to reduce the complexity of nutrient flow in a large ecosystem to characteristics of vegetation and soil which can be easily measured, estimated and interpreted, we introduce the term "internal cycling", to be distinguished from previously discussed nutrient balances resulting from "external" inputs (such as precipitation) or losses (such as leaching through drainage). Internal nutrient cycling in this docu-

TABLE 4-13

Summary of Estimated Annual Nutrient Additions and Losses for Vegetative-Soil Complexes in the Oilsands Area of Northeastern Alberta

Process affecting nutrient gain or loss	Nutrient Element				
	N	P	K	Ca	Mg
	kg/ha/yr				
Additions					
Precipitation	6	0.1	4	6	1
Biological Fixation	30	NA+	NA	NA	NA
Mineral Weathering	2*	0.5*	10	25	8
Additions: Sub-Total	38	0.6	14	31	9
Losses					
Erosion	12	0.5	53	9	14
Leaching	8	0.1	3	2*	2*
Volatilization	10	NA	NA	NA	NA
Losses: Sub-Total	30	0.6	56	11	16
Balance	+8	0	-42	+20	-7

* Actual numbers not found in published literature; estimates are those of the author.

+ NA - not applicable

ment refers to the two-way transfer of nutrients between soil and plant and to the transfer of nutrients between "pools" within either the soil or plant (Figure 4-8). The reason for considering internal cycling is that soils do not contain an inexhaustible supply of nutrients, and successful, self-maintaining plant communities will necessarily be characterized by an internal nutrient cycle, whereby sufficient nutrients are returned from the vegetative component to the soil and made available for succeeding rounds of plant uptake.

The major components of internal nutrient cycling are shown diagramatically in Figure 4-8. Overall, the internal cycle consists of the movement of nutrients between the soil and plant. The soil has several "pools" of nutrients which function as short- or long-term storage sites for cycling nutrients. The plant can also be divided into components, such as foliage, shoot, roots, etc., all of which have slightly different responses in terms of nutrient storage time and the release of nutrients to the soil. The distribution of nutrients in each of the major components of plant and soil was discussed in Section 431 and will not be reviewed here. However, the rate that nutrients are transferred from one component to another is the major determinant of nutrient cycling and will form the basis for predicting possible nutrient bottlenecks for each community type in the reclaimed soils of the oilsands area.

.1 Internal Cycles of the Major Nutrient Elements

Each of the five macronutrients under study in this report - nitrogen, phosphorus, potassium, calcium and magnesium - have internal cycles regulated by slightly different mechanisms in the soil and the plant itself (Table 4-14). Generally, it can be seen that all of the nutrient cycles are influenced by: (1) the amount of nutrient in circulation, (2) the form in which the nutrient is returned to the soil, (3) the state in which the nutrient is "stored" in the soil, (4) the means by which the nutrient is made available for plant uptake, (5) the size of the "available" pool of nutrients (i.e. available for plant uptake) in comparison to total amounts and (6) the average turnover or cycling time for each nutrient.

Nitrogen

Since nitrogen is returned to the soil and stored in the litter and mineral soil almost entirely as an organic compound, the most influential factors affecting the rate and amount of nitrogen mineralization are microbial activity and the total amount of nitrogen in storage in the soil. The latter factor is predetermined for each vegetative community in the reclaimed oilsands in the sense that initial conditions are defined in Chapter 3 in regard to the necessity for certain amounts of nitrogen. Furthermore, we have seen that total nitrogen is expected to slowly increase (8 kg/ha/yr).

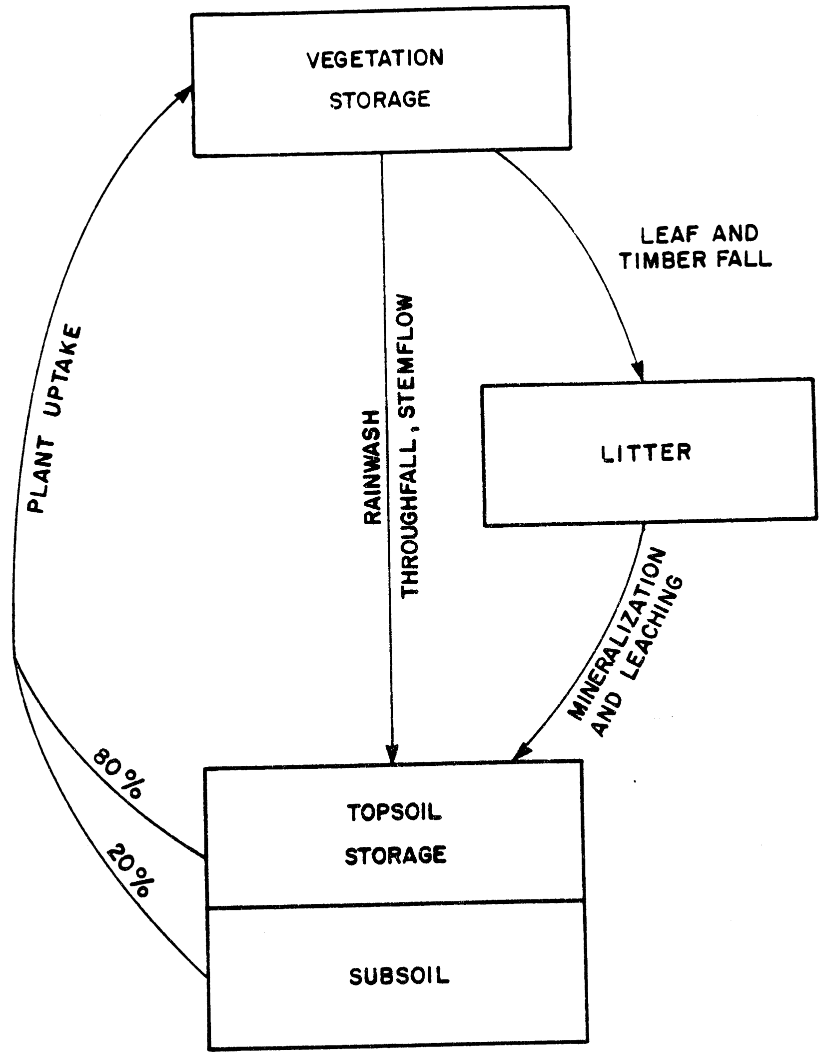

FIGURE 4-8

SIMPLIFIED FOREST NUTRIENT CYCLE
(MODIFIED FROM SANCHEZ 1976).

TABLE 4-14

An Outline of Factors that Affect the Internal Cycling of Major Nutrient Elements in Grasslands and Forests in a Boreal Region

Nutrient Element	Factors Affecting Internal Nutrient Cycling					
	Relative amount in annual cycle (kg/ha/yr)*	State upon return to the soil	Kind of storage (pool) in soil	Mechanism(s) of release in soil	Size of "available" pools in soil (kg/ha/yr)*	Turnover time of cycling nutrient (years)*
Nitrogen	High (30-100)	Almost all organic, most in plant litter	Almost all organically bound	Microbial	Variable low to high, depends on age of canopy, C/N ratio (2-60)	Long (10-50)
Phosphorus	Low (2-15)	Almost all organic, mostly in plant litter	Organic (like N) and inorganic (ligands and precipitates)	Microbial Physio-chemical	Generally small (1-30)	Short (5-15)
Potassium	High (20-175)	High proportion as leachate (water soluble)	Mostly inorganic (exchange complex)	Physio-chemical from exchange, easily soluble from organic	Generally large (100-700)	Very short (3-15)
Calcium	High (20-220)	Almost all organic: plant litter, woody tissue, roots	Mostly inorganic; exchange complex, precipitates	Physio-chemical	Large (at pH > 5.5 = 100-1000)	Medium (8-35)
Magnesium	Low (4-15)	Almost all organic: plant litter, etc.	Mostly inorganic; exchange complex and precipitates	Physio-chemical	Medium (at pH >5.5 = 20-200)	Medium (8-20)

* Figures in parentheses are kg/ha/yr or years as designated under each column.

The level of microbial activity and consequently the rate at which mineral nitrogen is released from the organic pool is dependent primarily on the soil conditions: temperature, water content, pH, levels of other nutrients and the ratio of carbon to nitrogen in the organic matter being mineralized. The long turnover times measured for nitrogen in the boreal forest (Table 4-14, last column) suggest that soil conditions in this climate are not optimum for a high rate of microbial activity. We might expect as a result that nitrogen will accumulate in the litter and organic portion of the mineral soil for several decades until the vegetation community reaches a limit in respect to the establishment of an equilibrium between plant and environment. The amount of mineral nitrogen available for plant uptake will decrease gradually, until approximately the third or fourth decade, at which time a small proportion (we have assumed 1%) of the entire nitrogen pool in litter and soil will be mineralized annually.

Phosphorus

There is a relatively small amount of phosphorus in the internal nutrient cycle (2-15 kg/ha/yr). Phosphorus, like nitrogen, is returned from the plant to the soil almost entirely as an organic compound and therefore is subject to the same process of microbial release. However, the physical-chemistry of phosphorus storage in soil after mineralization (inorganic ligands and precipitates) signifies that this nutrient will cycle much more rapidly than nitrogen. If there is a large pool of available phosphorus in the soil prior to the initiation of nutrient cycling, phosphorus will probably not be in short supply for 10 to 15 years, at which time the organic debris - mineral cycle of phosphorus should be capable of supplying the annual needs of the vegetation community.

Potassium

The internal cycling of this element is distinguished from all others by virtue of its high solubility in water and the very short periods of turnover time (3-15 years). Potassium is not usually found in high concentrations in organic compounds even within the plant system. For this reason potassium is moved relatively easily from living or dead tissue to the soil by water. In the soil the major storage pool is the exchange complex, and potassium is readily available for plant uptake from this pool.

Calcium

Large amounts of calcium are cycled annually (20-220 kg/ha/yr). Calcium is found in both inorganic and organic forms in the plant, but the latter predominates. Storage in the soil is mostly in an organic form, and calcium availability depends primarily on the physio-chemical equilibria reactions in the soil. If the soil pH is above 5.5, large amounts of calcium will be available for plant uptake throughout the rotation age of the plant community.

Magnesium

The same principles governing the cycling of calcium apply to magnesium except that magnesium is used in much smaller amounts by the developing vegetation. The amount of magnesium in soil is also generally much smaller than calcium.

.2 Variance of Internal Nutrient Cycling by Vegetation Type

This document assumes that a separate soil mixture will be used for each vegetation community in the reclamation of the oilsands. Both soil type and plant community will be operative in creating variances in the kind and amounts of internal nutrient cycling, and these differences will be accentuated over time. Some of the more easily predicted characteristics of nutrient cycling in each vegetation community are identified a priori by examining the results of ongoing reclamation studies in the oilsands area and related studies in natural boreal forest communities.

Nutrient Turnover on Dike Slopes

The soil environment on the dike slopes in the oilsands area is similar to the dune sand environment described by Olson (1958). As is shown diagramatically in Figure 4-9, one can expect a rapid rise in nutrient content (we use nitrogen in this example to illustrate a general principle) in the first years after stabilization. The slope of the curve that describes the rate of nitrogen accumulation decreases after 200 years. In the case of soil development in dune sands, the limiting nitrogen value (a point above which nitrogen does not increase) might be reached sometime after 400 years (Figure 4-9).

On dike slope soils in the oilsands, the initial period of reclamation is characterized by very low levels of total nitrogen (Takyi et al. 1977), and even the addition of 15 cm of peat to the mineral soil does not increase nitrogen levels to more than 0.03%. After seven years of grass management and fertilization, Rowell (1979) measured an organic nitrogen pool in dike slopes of 1000 kg/ha, less than one-quarter of the total needed for self-maintenance, if we assume a 1% annual mineralization rate. Continued management and nitrogen additions can be expected to double the amount within the next ten years. The last 2500 kg N/ha needed to "top-up" the pool will be more slowly stabilized than the first 50%. Precipitational inputs of nitrogen (<10 kg/ha/yr) will account for some of the readily utilized nitrogen, but this input is also subject to the same dynamics as fertilizer nitrogen or recently mineralized nitrogen.

The rates of mineralization of phosphorus and potassium are different from that of nitrogen, and because much of the phosphorus and potassium storage is inorganic, different mechanisms influence the

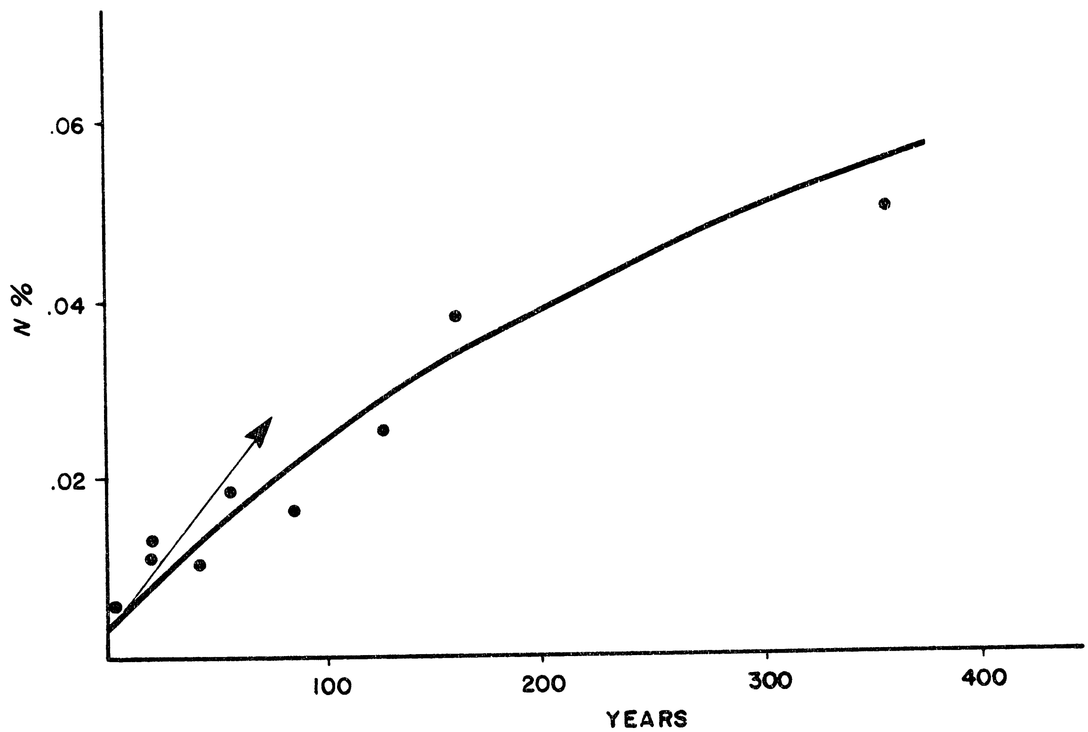

FIGURE 4-9

SOIL NITROGEN INCREASE IN SURFACE DECIMETER OF SOIL AS A FUNCTION OF DUNE AGE. (OLSON 1958)

ARROW REPRESENTS INITIAL RATE OF INCREASE (dN/dt FOR TIME ZERO) WHICH CORRESPONDS ROUGHLY TO ANNUAL INCOME OF NITROGEN. NET GAIN SLOWS AS ANNUAL LOSSES INCREASE IN ROUGH PROPORTION TO TOTAL NITROGEN.

availability of these elements on dike slopes. There is insufficient information to date to predict how these elements will react over time under dike slope conditions. However, empirical data suggest that both nutrients are in adequate supply after several years of fertilization (Table 4-15).

Nutrient Turnover in Jack Pine Soils

Tree litterfall is the most important component of annual return in jack pine soils (Table 4-16). Litterfall from ground vegetation and throughfall are of nearly equal importance. Throughfall measures the amount of nutrients leached by rain directly from the standing vegetation onto the forest floor. Table 4-16 shows that the ground vegetation accounted for only 8% of the total dry weight of annual litterfall under jack pine, but the above average concentration of nutrients within its litter made it disproportionately more important in its contribution to the total nutrient cycle. Ground vegetation should not be overlooked in the total nutrient balance.

Nitrogen is the element returned in largest quantities. The nutrient return assumed the following order in terms of total amounts:

$$N > Ca > K > Mg > P$$

Of the total amount of each element absorbed by the forest biomass, the following percentages were returned in the annual litterfall (Foster 1974):

N	-	95%
P	-	95%
Ca	-	80%
Mg	-	80%
K	-	40%

Nitrogen and phosphorus cycle annually; only 5% of the amounts accumulated in the trees remains after the litter has fallen. As explained in the previous section, the largest portion of potassium is returned to the forest floor by direct leaching from the foliage by intercepted rainfall (Table 4-16).

Nutrient Turnover in Mixedwood Forest Soils

The rates of internal nutrient cycling in mixedwood forests vary with (1) the location of the forest, (2) the structure or composition of the stand, and (3) the kind of nutrient element. Table 4-17 summarizes several investigations carried out by or reported by Lousier and Parkinson (1979). Although a comparison of variance in turnover time due to location and element is possible, the structural differences of these forest stands is unreported.

TABLE 4-15

Analysis of Soil Samples from a Vegetated Tailings Dike in the Oilsands Area
September 1977

	Treatment*			Depth	Mineral N		P	K	pH
	N	P	K		NH_4-N	NO_s-N			
				cm	ppm		ppm	ppm	
Low	279	138	188	0-15	2.1	0.1	17.0	41	6.4
				15-30	1.3	0.1	4.5	23	6.5
				30-60	1.3	0.0	3.0	16	7.0
Medium	549	207	458	0-15	9.4	17.2	29.3	127	6.6
				15-30	2.2	1.8	5.0	29	6.6
				30-60	1.5	0.8	3.0	21	6.9
High	639	230	548	0-15	7.0	18.1	48.2	219	6.9
				15-30	3.5	4.3	9.7	28	6.1
				30-60	1.9	2.3	4.3	20	7.1

SOURCE: Rowell 1977

* Treatments are amounts of applied fertilizer from 1971 to 1977 in kg/ha.

TABLE 4-16

Average Annual Amounts of Nutrient Elements Returned to the Forest Floor by Litterfall and Throughfall in Jack Pine

Process	Litterfall (D.W.) or Rainfall	Nutrient Elements				
		N	P	K	Ca	Mg
	kg/ha-mm	kg/ha				
Tree Litterfall	3728	20.5	1.2	4.9	13.3	1.7
Ground Vegetation Litterfall	331	4.7	0.4	2.2	1.7	0.4
Precipitation	953*	5.0	0.1	4.9	5.6	0.8
Throughfall	759.5*	3.9	0.1	10.0	6.6	1.1

* Measurements followed by an asterisk are in millimetres.

SOURCE: Foster 1974

TABLE 4-17

A Comparison of Turnover Rates of Forest Floor Reserves and Nutrient Elements in Some Temperate Mixedwood Forests in Canada and the United States

Location	Forest Type	Forest Floor Reserve	Residence Time					
			Forest Floor	Nutrient Element				
				N	P	K	Ca	Mg
		x 10^3 kg/ha	years					
Canada								
Alberta	Aspen	91-142	12.5	41	15	15	35	19
U.S.A.								
Alaska	Aspen (50 yr)	28	12	27	11	7	8	9
Alaska	Aspen (120 yr)	76	27	30	11	10	10	11

Adapted from Lousier and Parkinson (1979)

The location and, by association, the soils and climate, are influential factors affecting the residence time of each element. In the foothills of southern Alberta (the Kananaskis area west of Calgary), the turnover time for each nutrient element is approximately 50% longer than that of similar stands in Alaska. There are not enough details listed about the soils and climate to evaluate which variables are associated with the longer turnover time in Alberta.

Table 4-17 shows that nitrogen, in comparison to all the major nutrient elements, has the longest turnover time in a mixedwood forest irrespective of location or structure. Nitrogen resides in the litter or mineral soil from 27 to 41 years, depending on location. We might expect that under conditions of newly reclaimed soils in a somewhat harsher environment, like the oilsands area, nitrogen residence time will be even longer.

All of the other major elements - phosphorus, potassium, calcium and magnesium - cycle internally much faster (Table 4-17). In fact, phosphorus and potassium appear to cycle three times for every cycle that nitrogen completes, regardless of location. The residence times of calcium and magnesium are more variable, but because these elements are normally found in much larger amounts in the mineral soil matrix, their residence times are less significant in contributing to nutrient bottlenecks.

.3 The Prediction of Future Nutrient Bottlenecks in Reclaimed Soils in the Oilsands Area

An analysis of the internal cycling characteristics of each element in three vegetation communities indicates that there will probably be only one nutrient bottleneck that needs careful monitoring over the next 40 years. Potassium, calcium and magnesium are nutrient elements which will probably not cause any nutrition restrictions on tree or grass growth and productivity over 80 years, if the initial soils are constructed to meet the specifications of this document. All three of these elements are represented by relatively large reserves in the soil and their residence time in the litter and mineral soil is relatively short. Each of the reclaimed soil types has low contents of phosphorus, i.e. the soil reserves are low, but only small amounts are required by the plant community. Furthermore, phosphorus is stored and released by both organic and inorganic mechanisms, and as such is made available over the long term under widely differing circumstances. The long-term supply of phosphorus does not appear to be a problem. The short-term aspects of phosphorus availability were explained and accounted for in Chapter 3.

An adequate supply of nitrogen over the first 50 years in all three vegetation communities may be the only real nutrient supply problem to be encountered. A continual supply of nitrogen from reclaimed soils is made difficult by several factors:

- nitrogen is needed in relatively large amounts by all vegetation types;

- nitrogen is stored almost entirely as an organic compound and released (made available) by microbial activity; and

- carbon/nitrogen ratios are normally high in the beginning, resulting in a long period of nitrogen immobilization until the ratio is lowered.

On the other hand, it should be noted that nutritional problems due to nitrogen shortages are among the most easily diagnosed and remedied. Also, the overall predicted balance of nitrogen shows that approximately 8 kg/ha/yr will accumulate. In summary, there may be a nitrogen deficiency over time, but the deficit should decrease with an increasing maturity of soil and plant community, and nitrogen deficiencies can be alleviated simply and inexpensively by periodic fertilization.

4.6 CHANGES IN EROSION SUSCEPTIBILITY

The development of a complete plant cover in all three cases of planned vegetation communities will have a larger, more dramatic impact on erosion susceptibility than on any other soil process. In essence, if the plant canopy is uniform and complete, erosion potential on all soils, including the dike slopes, will be reduced to less than five tons per acre per year.

The model that allows near certainty about the lessening potential of erosion with plant development is outlined in detail in Chapter 3. The effect of developing the plant canopy by one year caused a decrease in erosion of 37% in the case of no amendments and 91% when 15 cm of peat is added to the dike slopes. It is highly probable that the development of the plant canopy over several more years will cause the erosion potential to decrease even more.

Furthermore, the predicted accumulation of organic matter in soil also will contribute to a decrease in soil erodibility by increasing the infiltration rate, permeability and total water holding capacity (Wischmier et al. 1971). A layer of organic matter (litter) on top of the soil reduces runoff velocity and rainfall impact by mitigating the dispersion, abrasion, splashing and transporting forces of rainfall on soil (Beasley 1972).

CHAPTER 5

SUMMARY

CHAPTER 5 - SUMMARY

CONTENTS

TABLES

5.1 INTRODUCTION

The objectives of this report are the following:

1. Define the minimum physical and chemical soil properties necessary for the support of three vegetation communities - jack pine forests, mixedwood forest and grass/legume stands on dike slopes - in the oilsands area of northeastern Alberta;

2. Show how a mixture of tailings sand, mineral overburden and peat can be used to meet the minimal properties;

3. Ensure that the design of the reconstructed soils incorporates the necessary properties such that the three vegetation types are self-maintaining and stable enough to prevent serious erosion; and

4. Identify weaknesses in the assumptions needed for the development of the supporting arguments or in the data base itself and to recommend studies which would strengthen one or both. This last component is not included in this chapter but is discussed in Chapter 6.

The soil reconstruction strategy assumes that the critical relationships between soil and plant, in terms of successful vegetation establishment and the long-term evolution of self-maintenance are: (1) the storage and supply of sufficient moisture in the rooting zone; (2) the provision of adequate amounts of nutrient elements; and (3) the development of a physically stable medium. It is also assumed in this study that soil reconstruction is performed by mixing together, to a predetermined depth, the necessary amounts of peat, overburden and sand.

The revegetation strategy is based almost exclusively on the type, mixture and density of plants introduced in each vegetation area. In the case of a mixedwood area we propose that a mixture of white spruce and aspen seedlings be introduced in the first year at a density of approximately 1100 per hectare (700 white spruce, 400 aspen). We suggest that prickly rose be seeded between tree seedlings to serve eventually as the dominant understory component. Jack pine areas are seeded first to grass and legumes for erosion control purposes, and the tree seedlings are introduced into vegetation free circles in the second year. The native understory species will invade jack pine areas and eventually eliminate the grass-legume component. It is our assumption that dike slopes will be seeded as quickly as possible to grasses and legumes to prevent water erosion. Although we do not recommend the managed introduction of native trees or shrubs, it is likely that jack pine and its associated understory will eventually invade these slopes.

5.2 THE BIOPHYSICAL ENVIRONMENT

Water balance, the properties of soil materials and the empirically identified relationship of soil properties to vegetation type are three components of the existing biophysical environment used in this report to identify the manageable parameters of soil reconstruction.

521 WATER BALANCE

Water balance is defined as the balance between input of water, in the form of rain or snow, and the outflow of water, by way of evapotranspiration and drainage. An accurate calculation of water balance produces an estimate of water surplus, water deficit, runoff, drainage and changes in soil moisture storage. Water balance is ultimately related to the weather (or climate over longer time periods) and the reserves of plant available water in the soil.

Water balance calculations for the Fort McMurray area result in the following yearly averages or ranges:

Mean annual temperature	-0.5°C
Frost free period	69 days
Precipitation (rain equivalent)	488 mm
Evapotranspiration	370-531 mm
Surface runoff	44 mm
Drainage (beyond root zone)	100-125 mm
Water budget deficit (20 year average)	37 mm

Assuming that the sandy soils of the oilsands area have an average available water storage capacity of 7.5%, this study finds that the soil water deficit begins in late June and reaches its maximum in August. This situation occurs in spite of the fact that July is the month having the highest average precipitation.

As a consequence of the soil moisture deficit, vegetation growth is limited in late summer. Most of the precipitation from June through September is lost through evapotranspiration. Deep rooted trees are less susceptible to moisture losses under these conditions.

522 LOCAL MATERIALS

The materials available locally for soil reconstruction are overburden, peat and tailings sand. The physical and chemical characteristics of each are summarized in Table 5-1.

TABLE 5-1

Summary of Physical and Chemical Characteristics of Locally Available Geological Material

Soil Property	Geomaterial		
	Overburden	Peat	Tailings Sand
Physical			
Parent material	Glacial till, glacio-fluvial sands and gravel, glauconitic sands and shales	Decomposed organic materials with small amounts mineral inclusion	Quartzose sands
Depth (m)	1-72 (mean 22 m)	0.3-6 (mean 1)	
Fines content (silt and clay)(%)	5-70		1-7
Water holding capacity (%)	10-40	600-850	4-25
Bulk density (g/cm^3)	1.2-1.5	0.04-0.1	1.6
Chemical			
Cation exchange complex			
Total (me/100 g)	5-40	35-180	2-5
Ca (me/100 g)	5-11	17-112	0.25-0.5
Mg (me/100 g)	0.4-4	8-15	0.3-0.5
K (me/100 g)	0.6-3	0.1-0.3	0.03-0.3
Na (me/100 g)	0.2-8.6		0.04-0.5
Base saturation (%)		24-93	
pH	7-8	3.7-6.6	6.2-9.2
Organic carbon (%)	0.1-6	40-45	< 2
Total nitrogen (%)		0.9-2.4	0.003-0.01
Available phosphorus (ppm)	2-15	6-54	0.3-3.5
Available potassium (ppm)	5-47		

The overburden includes Pleistocene deposits (glacial drift and the soils developed upon it), and the Clearwater or McMurray formation. The latter deposits are sand with lenses of silty clay or shale. When the glacial deposits are predominant the fines (silt and clay) contents are generally over 5%. Normally a high water holding capacity (>10%) and cation exchange capacity (>10 me/100 g) are associated with the increased contents of silt and clay.

Peat materials cover approximately 80% of the entire area and include both sphagnum peat deposits per se and fen (sedge) bogs. These organic materials can hold up to 800% of their dry weight in water and, thus, contribute to higher soil water contents when they are mixed with sand. Peat contains from 0.9 - 2.5% total nitrogen (Table 5-1) and is used in conjunction with overburden materials to establish the nitrogen levels necessary for plant development. The high cation exchange capacity of peat (35-180 me/100 g) represents a large storage capacity for the stablization of nutrient ions, added as amendments or in the form of other materials.

Tailings sand is produced in massive quantities and, therefore, forms the primary matrix to be used in soil reconstruction. Large particle size fractions are predominant (90% of the sand particles are more than 0.05 mm diameter) and bulk densities are high (>1.5 g/cm^3). The high sand content is associated with rapid drainage, a low cation exchange capacity and a deficiency of nutrient elements. Although available water contents are relatively low (7.5%) in comparison to overburden, large amounts of fine sand (0.05 - 0.5 mm diameter) in relation to medium or coarse sand fractions shift the moisture characteristics toward those of a soil with high contents of silt.

523 PLANT COMMUNITIES AND ASSOCIATED SOILS

Three plant communities are established initially on reclaimed soils in the oilsands area: grass-legume mixtures, jack pine and mixed-wood. Under natural conditions in the boreal region of Canada, and more specifically in the Fort McMurray area, each of these vegetation communities is associated with several soil types. The variation in soil properties under the same plant community is due mostly to differences in soil parent material or topographical position.

Grass and legume communities are found in the boreal forest under conditions of low soil water supply or in areas where repeated fire occurrence probibits the establishment of pine, spruce or aspen. As an example, the large sand dune area around Lake Athabasca has a permanent grass cover. Soils in this case have approximately 5% silt and clay, a low cation exchange capacity (<7 me/100 g) and <0.5% organic carbon in any part of the mineral profile.

Jack pine is one of the most xerophytic tree types in the boreal forest and as such is commonly found on well drained sandy plains and hills. Jack pine stands transpire approximately 130 mm of water per growing season in the oilsands area. Soils capable of holding between 7 and 10% available water by volume will support jack pine without subjecting the established trees to irreparable water stress.

The chemical characteristics of jack pine soils are uniform when the same parent materials and climatic zones are compared. Jack pine soils have a low cation exchange capacity (4-6 me/100 g), low levels of exchangeable cations (0.5 - 2.0 me of Ca and Mg per 100 g soil) and only 10 to 15 ppm of available P_2O_5. However, available potassium (measured as exchangeable K) can reach 90 to 150 ppm and organic matter varies from 0.2 to 0.7% in the surficial mineral horizon.

Tree species commonly associated with mixedwood include white spruce, aspen and lesser amounts of jack pine, black spruce, larch, birch, balsam poplar and balsam fir.

Mixedwood soils tend to be heavier textured (loams) with higher silt and clay contents and are less well-drained than soils under jack pine. Due to the higher fines content, a mixedwood soil can have twice the available water of a jack pine soil. Growing season transpiration for mixedwood forests is approximately 325 mm, or more than twice the recorded amount for jack pine stands (130 mm); the exact amounts are influenced by the occurrence of perched water tables or lateral drainage.

Mixedwood soils exhibit greater variability in chemical properties than jack pine soils. The A_e horizon may not be as well developed under mixedwood due to higher silt and clay content, less eluviation, and slightly elevated pH levels, all of which inhibit the rates of mineral and biotic weathering. Mixedwood soils tend to contain a wider range and higher levels of exchangeable cations and nutrients, especially in the A and B horizons where the primary nutritional needs of the root systems are met.

North American mixedwood soils have a deep leaf litter layer with a high percentage of nitrogen. Oilsand soils in the study area seldom exceed 1.3% organic matter, and organic carbon and total percentage of nitrogen are quite similar under both jack pine and mixedwood stands.

5.3 THE DESIGN OF SOILS FOR THE REVEGETATION OF THE OILSANDS

The three primary processes relating soil quality to plant performance in the oilsands area are defined in Chapters 1 and 2 as moisture supply, nutrient supply and physical stability. The objective of Chapter 3 is to identify the minimal level of each soil property necessary for the successful establishment and growth of each of these plant communities. We are able to identify these levels of soil properties by considering four questions:

1. What soil properties are most important in determining each major process, i.e., moisture supply, nutrient supply and physical stability?

2. What is the quantitative relationship between the level of a property and any one of the three processes?

3. What is the minimal level of each process for each vegetation community?

4. What level of each property is needed to meet the minimal level of the process?

531 SOIL MOISTURE SUPPLY

Although there are several physical and thermodynamic characteristics of soils that control moisture supply, we simplify an extremely complex phenomenon by restricting ourselves to plant available water and the soil properties which influence it. The major influence on plant available water is particle size distribution. Optimum moisture conditions occur in soils with less than 60% sand by weight, less than 25% clay and more than 15% silt (loam texture). Secondly, mineral soils with medium bulk densities (between 1.0 and 1.4 g/cm^3) supply water to plant roots faster than soils with higher or lower bulk density values. Thirdly, there is approximately a 1% increase in available water for each 1% increase in stable organic matter. Lastly, plant available water is proportional to the depth of soil exploited by the roots; soils without restricting layers have a higher moisture supply capacity than soils with impermeable horizons.

Reasoning from the information presented in Chapter 2 on water balance calculations in the oilsands area and the water holding characteristics of the locally available materials, this study recommends the following criteria relating soil depth and water content for the establishment of each plant community:

Plant Community	Reconstructed Soil Depth (for purposes of water supply) (cm)	Available Water Content in Reconstructed Horizons (%)
Grasses and legumes on dike slopes	30	15
Jack pine	15	15
Mixedwood (1) Surface horizon	15	15
(2) Subsurface horizon	35	10

The dike slope soils and jack pine soils will have a single reconstructed horizon of 30 cm and 15 cm, respectively. The mixedwood soils will have two reconstructed horizons - the upper layer will be 15 cm thick and the subsurface layer will be 35 cm thick, resulting in a total reconstructed soil horizon of 50 cm.

In order to supply 15% available water, each reconstructed soil horizon must have a minimum of 30% fines content (silt and clay) by weight to the depth recommended for each plant community. This amount of mineral fines can be reduced by 3 to 4% for each increase of 1% in stable organic matter. We estimate that approximately 60,000 kg/ha (dry weight) peat mixed into 15 cm mineral soil will represent a 1% increase in stable organic matter.

The mixedwood soils have two reconstructed horizons. The uppermost will have moisture supply characteristics similar to that of the jack pine soil; the subsurface horizon, extending from 15 to 50 cm in the profile, must be capable of supplying 10% available water and thus should contain about 20% fines. If we assume that the unamended tailings sand from 50 to 100 cm contains 3% silt and clay, a 100 cm mixedwood soil profile will contain approximately 10% fines, a figure that corresponds to a forest site index of 40 and a harvestable biomass yield of 1.4 m^3/ha/yr over an 80 year rotation.

532 SOIL FERTILITY

The soil properties which have the largest influence on nutrient supply in soils are cation exchange capacity, organic matter content and quality, and soil pH.

The cation exchange capacity of a soil is increased approximately by 0.27 and 1.47 me/100 g for each 1% increase in fines content and organic matter, respectively. Organic matter acts as the primary storage pool for nitrogen and as a secondary source (after the clay minerals), of phosphorus, sulphur and potassium. Organic matter fractions in soil with a carbon-nitrogen ratio less than 15:1 tend to indicate that nitrogen will be released from the reservoir and become available for plant uptake; carbon-nitrogen ratios greater than 15:1 usually signify that available nitrogen will be immobilized by the soil microflora and thus made unavailable to plants. Similar principles apply to phosphorus and sulphur, but the critical C:P and C:S ratios are approximately 100:1. The majority of nutrient elements (NO_3^{2-}, P_2O_5, K_2O, Mg, S, Cu, B) are most available at pH values between 5.5 and 7.5. Calcium, molybdenum and sodium increase in availability at slightly higher pH values (7.0 - 8.5) and aluminum, iron, manganese and zinc are more available to plants (but possibly toxic) at low pH (< 5.0). The pH of tailings sand is not well buffered; small additions of acid or alkaline material will effect significant changes in pH. The addition of peat and mineral overburden to tailings sand, however, results in an increase in buffering capacity.

The essential nutrient elements for plant establishment and growth in the oilsands area are nitrogen, phosphorus, potassium, calcium and magnesium. Nitrogen reservoirs in undisturbed surface soils are generally large (>5000 kg/ha in the surface 15 cm), but only 1% of this amount is made available for plant uptake each year. The local materials are low in total nitrogen (<0.01%) except peat (1.5% N) however nitrogen supply from peat can also be restricted because of a 30:1 carbon - nitrogen ratio. Approximately 12 kg N/ha/yr is released by each 1% increase in stable organic matter.

Phosphorus content in the soil solution is generally very low and, therefore, solution phosphorus has to be renewed daily from phosphorus adsorbed on clays or precipitated in the mineral matrix. Clay content is the single most important property influencing the rate of phosphorus supply.

The tailings and the peat in the oilsands area contain litle available potassium (12-120 ppm). The overburden, however, has as much as 390 ppm and represents the major potential source of this element.

Calcium and magnesium cations, like potassium, are supplied to the plant by way of the exchange complex. Overburden and peat are abundantly supplied with calcium (1000 - 26,000 ppm) and magnesium; tailings sand has much lower contents (<150 ppm), but no deficiencies of either nutrient element are likely.

Based on the kind of plant community, the density of seedlings per unit of surface area and the level of expected productivity, the following available nutrient levels are needed for each soil type in the initial stages of plant establishment.

Nutrient	Soil Type / Plant Community		
	Dike Slopes	Jack Pine	Mixedwood
Nitrogen (kg/ha)	210	110	98
Phosphorus (kg/ha)	115	60	348
Potassium (me/100 g)	0.25	0.20	1.0 (0.2)*
Calcium (me/100 g)	0.125	0.50	5.0 (3.0)*
Magnesium (me/100g)	0.216	0.216	1.0 (0.6)*

* Number in parentheses under mixedwood soil type refer to concentration needed in subsurface horizon (15-50 cm)

A supply capacity of 210 kg available nitrogen per hectare per year is based upon a soil with 9% organic matter. Since organic matter contents are unlikely to be greater than 5%, the dike slopes will require an input of 50 kg N/ha/yr from the associated legume and another 50 kg/ha/yr in fertilizer applications. The organic matter pool in the mixedwood soils needs to be approximately 7% in the upper horizon (0-15 cm) and 3.5% in the subsurface horizon. It is wise to include nitrogen fixing shrubs in the mixture of plant species to reduce this nitrogen requirement. The jack pine nitrogen requirements can be met by including organic matter contents of 2.5% and an associated herbaceous legume capable of fixing 50 kg N per hectare per year.

Most combinations of tailings sand, peat and mineral overburden will result in available phosphorus levels of approximately 10 ppm (20 kg P/ha/yr for a 15 cm horizon with a bulk density of 1.3 g/cm^3). Therefore, large amounts of phosphorus fertilizer have to be included in soil mixtures designed for dike slopes and mixedwood forest establishment. In the latter case, in order to ensure an adequate level of phosphorus for five years without annual additions, the soil mixture should include 1000 kg/ha of P_2O_5.

The appropriate levels of potassium, calcium and magnesium in each soil type can be achieved by maintaining a sufficiently high cation exchange capacity (assuming 75% base saturation). Exchangeable potassium normally represents at least 5% of the total cation exchange complex; therefore a CEC of 5.0 me/100 g will result in exchangeable potassium levels of 0.25 me/100 g or 75 ppm. Furthermore, calcium and magnesium levels will easily surpass the minimum requirements, if CEC levels are maintained at the recommended level. In the case of mixedwood soils, the level of cation exchange capacity necessary for sufficient potassium supply is 14 me/100 g in the surface horizon and 9 me/100 g in the subsurface horizon. Again, calcium and magnesium concentrations will be substantially higher than the minimal level, if these CEC criteria are incorporated.

A cation exchange capacity of 5 me/100 g will result from a soil containing either 20% silt and clay or 3.5% stable organic matter or a combination of the two. The mixedwood soil must contain 30% fines and

4% organic matter to have a CEC of 14 me/100 g. The subsurface horizon must have a minimum fines content of 20%, in addition to 2% organic matter content, to reach a CEC of 9 me/100 g.

533 SOIL EROSION CONTROL

The dike slope soils are those most susceptible to erosion, mainly by water, because of their relatively steep gradients and long slopes between terraces. The maximum rate of annual erosion that permits no loss in long-term productivity is termed the "soil loss tolerance". In the oilsands area the acceptable soil loss tolerance is 10 t/acre/yr* (20,000 lbs/acre/yr). Serious environmental damage will ensue if rates greater than 20 t/acre/yr occur. This study, therefore, recommends that the long-term average not exceed 10 t/acre/yr, and that soil erosion loss in any one year not exceed 20 t/acre/yr.

The prediction of soil loss due to water erosion in the oilsands area is based on the Universal Soil Loss Equation (USLE):

$$A = R.K.LS.CP$$

where A = soil loss (t/acre/yr);
R = rainfall factor based on the intensity of a two year return storm;
K = soil erodibility factor based on soil texture, organic matter content, structure and permeability;
LS = combination of slope length and gradient; and
CP = a factor including plant cover and erosion control practices.

In the oilsands area the R factor is constant, K varies from 0.14 to 0.17 depending upon the mixture of tailings sand with peat and overburden, LS ranges from 4.6 (27% gradient and a 50 foot length) to 17.3 (50% gradient and a 100 foot length), and CP is as high as 0.80 for unamended tailings sand in the first year (very little plant cover) and as low as 0.09 for a mixture of tailings sand and peat in any year after initial plant establishment.

Predicted potential soil erosion rates on dike slopes are less than 20 t/acre/yr in the first year and average less than 10 t/acre/yr over several years, when slopes are less than 50% (2:1) and tailings sand is mixed with a minimum of 15 cm peat. Mineral overburden can be added to the peat-tailings sand mixture without increasing the risk of unacceptable erosion rates. These predictions assume that a grass-legume cover is established immediately upon completion of the dike slope; otherwise, erosion risks are increased dramatically.

* All units used in this section are "English Units" in which the applicable formulae have been developed and applied by the U.S. Soil Conservation Service.

The erosion control recommendations for jack pine soils are influenced greatly by the initial establishment of a grass-legume understory. However, if peat is not included in the soil mixture, slopes need to be less than 5%, even with a grass-legume cover. If peat is added to tailings sand, slopes up to 40% and 2000 feet in length can be tolerated.

The mixedwood areas probably will not be seeded to grass and legumes and, therefore, mixedwood stands are recommended for slopes less than 8% when peat is added, or less than 5% when no peat is added.

5.4 THE DEVELOPMENT OF PLANT COMMUNITIES AND RECLAIMED SOILS OVER TIME

The purpose of Chapter 3 is to design three soils capable of supporting the initial establishment of three distinct plant communities. Soils and vegetation change over time, however, and the purpose of Chapter 4 is to predict which soil properties will change fastest, and how the changes will affect the soil processes contributing to the support of self-maintaining plant communities.

541 PREDICTED CHANGES IN SOIL PROPERTIES

The soil properties which will change most rapidly after the revegetation of reclaimed oilsands materials are organic matter content, bulk density, cation exchange capacity and pH. We do not expect a change in soil texture as a result of pedogensis (time periods are too short), but surface textures could change as a result of the selective redistribution of soil particles by wind or water transfer.

Soil organic matter in the mineral horizons will increase very slowly over time as plant debris and roots are stabilized through microbial decomposition and by means of physical protection. Olson (1958) has estimated that organic matter buildup in recently stabilized sand dunes can be as high as 0.01% per year, but calculations based on actual biomass production on dike slopes in the oilsands area (Rowell 1978) indicate that actual rates of organic matter increase in the mineral soil may be as little as 0.001% per year.

The rate of buildup of organic matter in forest litter is substantially different. It is probable that jack pine and mixedwood forests will have a full litter layer (as much as 60,000 kg/ha) in 50 years. Additions of organic matter to the mineral horizons of forest soil will be as slow as similar events on dike slopes.

The change in cation exchange capacity will follow closely the changes in soil organic matter content. The CEC in the litter layer can go from less than 1 me/100 g to 20 me/100 g in less than 50 years. The change in CEC in the mineral soil will be much slower due to the decreased rate of organic matter changes.

In areas where the bulk density of the reconstructed soil is low (<1.2 g/cm^3) due to the incorporation of peat in tailings sand-soil mixtures, the rate of change in bulk density will be slow - possibly a 30% reduction in 80 years. On the other hand, in areas where peat is not added, bulk density values could drop from 1.6 g/cm^3 to 1.2 g/cm^3 in as little as 20 years.

Several measurements have been made on existing dike slopes in the oilsands area which show a decrease in pH (in surficial horizons) from 8.5 to 6.0 in as little as four years. Although there are not sufficient data available to be certain, it is highly probable that pH decreases much less in the deeper parts of the soil profile. In general, a decrease in soil pH of 2 units would not be expected in less than 150 years, when vegetation and leaching are the primary factors controlling these changes.

542 THE EFFECT OF CHANGE IN SOIL PROPERTIES ON SOIL MOISTURE SUPPLY

The modification of soil moisture supply capacity will be related to several phenomena:

- available water content will increase with increases in soil organic matter
- losses of water by runoff will decrease with an increase in leaf litter layer
- the development of a full vegetative canopy will increase the actual rate of water use (transpiration)
- a decrease in bulk density will usually result in an improvement of water transmissivity rates in the soil
- the maintenance of higher water contents in the upper soil layers, due to a stratification of reconstructed soils over tailings sand, will be lost as the profile deepens and the original strata are broken down
- new stratification of soil horizons could result from peat decomposition, organic acid mobilization of cations, chelation, changing pH values and freeze-thaw and wet-dry cycles.

Overall, it can be expected that available water content in soil and unsaturated hydraulic conductivity will increase very slowly over time. Furthermore, the soil profile will deepen allowing more soil volume for root development.

543 PREDICTED CHANGES IN NUTRIENT DEMAND AND NUTRIENT SUPPLY

The objective of this section is to estimate the nutrient demand of each vegetation community throughout the rotational age (or succession stage) and compare the demand with the supply capacity as based on nutrient additions, nutrient losses and internal nutrient cycling.

The best estimate of nutrient demand of a plant community considers the individual components of nutrient transfer, i.e., average demand (or uptake) is equal to the amount of nutrients lost yearly in leaf fall, root slough, stemflow and throughfall plus the average annual increase as accumulation. The nutrients added directly in precipitation are subtracted to calculate "net average demand".

Average nutrient demand in three vegetation communities in the oilsands area is as follows:

Nutrient	Vegetation Community		
	Grass-Legume	Jack Pine (kg/ha/year)	Mixedwood
Nitrogen	80	32	79
Phosphorus	14	2	11
Potassium	93	19	150
Calcium	18	25	215
Magnesium		4	11

The amounts listed above for each community are substantially smaller than the levels of nutrients in soil needed for plant establishment (Chapter 3). There are essentially two reasons for the large differences: first, the levels reported in Chapter 3 are "soil available nutrients" rather than the amounts actually taken up by the plant community; secondly, the calculation of nutrient demand in Chapter 4 is based on semi-mature vegetation communities, 20 to 40 years after establishment, and thus represents a biogeochemical system tending toward equilibrium.

The calculation of nutrient balance in the oilsands area takes into consideration the estimated additions of each nutrient by way of precipitation, biological fixation and mineral weathering, and the estimated losses by erosion, leaching and volatilization. The net balance is as follows:

	N	P	K	Ca	Mg
Balance (kg/ha/yr)	+8	0	-42	+20	-7

We know at this point: (1) the average amount of nutrients required over many years by each plant community, and (2) the net addition or loss of nutrients in the whole ecosystem. Since the soils are designed to supply larger amount of nutrients in the initial period than after 20 years, theoretically only nutrient bottlenecks related to internal nutrient cycling can impede self-maintenance.

The nutrient elements which probably will not be affected by future bottlenecks are phosphorus, potassium, calcium and magnesium, albeit the reasons for the adequate supply of each are different. Phosphorus is required in relatively low amounts (2-14 kg/ha/yr) after the initial establishment of a vegetative cover. Furthermore, in 10 to 15 years the phosphorus cycle from soil to plant and back to soil is complete. Potassium is lost from the system gradually, but maximum losses will represent only 0.01 to 0.1% of the total soil potassium contents. Potassium is highly soluble in water and is transferred easily within the ecosystem. The soil contents of calcium and magnesium, like potassium, are high (1000 - 20,000 kg/ha) and can be provided by mass flow alone in substantial amounts for many years. If the soil pH is not reduced throughout the root zone to less than 5.5, calcium and magnesium availability will remain adequate.

In the first two years the major nutrient bottleneck will be nitrogen. Nitrogen supply and demand in all plant communities has several characteristics which make it the most critical element:

- nitrogen is needed in larger amounts by all plants;
- nitrogen is stored in the soil mostly in an organic form and therefore, depends upon microbial activity for its release; and
- the initially high carbon-nitrogen ratios of non-humified organic additions (peat or plant debris) result in long periods of nitrogen immobilization and, consequently, slow nutrient transfer rates.

It seems apparent that nitrogen supply will be a potential bottleneck in all three plant communities and especially in the mixedwood forest community which needs relatively high amounts of nitrogen (79 kg/ha/yr) over a long period of time.

544 CHANGES IN EROSION SUSCEPTIBILITY

The prevention of erosion on all reclaimed soils in the oilsands area, and the dike slopes in particular, depends on the maintenance of a complete plant cover. The results of this study suggest that plant community structure can change over time - jack pine can invade the grass-legume swards on dike slopes and a wide variety of shrub and tree species can establish themselves in the mixedwood forest areas - and that these changes will not result in denuded areas. If this hypothesis proves correct, soil erosion will remain less than 5 t/acre/yr in all cases.

5.5 MINIMAL LEVELS OF SOIL PROPERTIES FOR SELF-MAINTAINING VEGETATION COMMUNITIES IN THE BOREAL REGION

The minimal levels of soil properties of reconstructed soils necessary for the establishment, development and long-term stability of three vegetation communities are outlined in Table 5-2.

The term "minimal" is used to imply that soils constructed to these specifications will perform according to the criteria outlined in the beginning of this report. Any residual risk of failure could be lessened by systematically increasing the depth or quality of each soil type, but the levels outlined in Table 5-2 represent an acceptable level of performance with a minimum of materials handling.

The thickness of the reconstructed soil horizons is related mostly to available water supply when plants are mature or to early nutritional requirements. The extra subsurface horizon for mixedwood reflects the substantial difference of water and nutrient demand of aspen and spruce when compared to jack pine. In the case of the dike slopes, 30 cm of reconstructed soils over oilsand tailings is judged minimal for permanent erosion control and physical stability.

Available water percentages for each soil are nearly identical, but total contents will change by a factor of two or three depending on the depth of the reconstructed profile. Since the oilsands tailings underneath the reconstructed soil contain a maximum of 7.5% available water, most of the water supply is a function of the depth of the reconstructed soil horizon(s).

The silt and clay content (fines) constitutes, in addition to organic matter, the controlling influence on moisture supply and nutrient storage. The differences in percentage of fines are not great (15-30%) but volumes of materials to be selected and moved will vary by as much as four times because much greater soil depths are required for mixedwood forests.

TABLE 5-2

Summary of the Minimal Physical and Chemical Characteristics of Soils for Three Vegetation Communities

Soil Property	Dike Slope	Jack Pine	Mixedwood Horizon 1	Mixedwood Horizon 2
Physical				
Thickness of reconstructed profile (cm)	30	15	15	35
			(50 total)	
Available water (%)	15	15	15	10
Silt and clay (%)	20	25	30	15
Slope gradient (%)	< 40	< 25	< 8	< 8
Slope length (ft)	50-2000	50-2000	50-2000	50-2000
Bulk density (g/cm^3)	< 1.3	< 1.3	< 1.3	< 1.5
Drainage	moderate	moderate to excessive	moderate	imperv-ious to moderate
Chemical				
Cation exchange complex (me/100 g)	5.00	5.00	14.0	9.0
Exchangeable calcium (me/100 g)	0.20	0.50	5.0	3.0
Exchangeable magnesium (me/100 g)	0.30	0.25	1.0	0.6
Exchangeable potassium (me/100 g)	0.25	0.20	0.7	0.37
pH	5.5-7.5	4.5-6.0	4.5-7.0	5.5-7.5
Organic matter (%)	5	2.5	6	2
Total nitrogen (%)	0.25	0.275	0.25	0.12
Available nitrogen (ppm)	50	55	25	12
Available phosphorus (ppm)	30	30	80	45

The slope gradients and slope length restrictions are purely a result of limitations on erodibility. As the clay and silt contents increase for mixedwood forests, the possibility of soil erosion averaging more than 10 t/acre/yr also rises and, thus, there is a need to reduce the limit of slope gradient.

The drainage and bulk density requirements of all three soil types are the most qualitative and least critical. If the other recommendations for soil properties are met, the drainage and density criteria will follow automatically.

In terms of chemical properties the cation exchange complex and nutrient content are most important. The minimal level of individual cations on the exchange complex is justified by the nutritional role in each soil plant complex. The total cation exchange capacity, however, represents the number of exchange sites needed to ensure that each cation, and especially potassium, is supplied in sufficient amounts. In other words, because potassium normally represents only 5% of the total exchange and 0.25 me/100 g are needed to supply grasses and legumes on dike slopes, the total CEC must be in the order of 5.0 me/100 g. The pH ranges listed in Table 5-2 are wide because plant communities are flexible in their adaptation to changes in hydrogen ion concentration.

Organic matter content is the critical determinant of total and available nitrogen. In all cases the reference to organic matter implies well-decomposed, stable organic fractions, having an average C:N ratio of 15:1 or less. If material like peat or straw is used to represent organic matter, allowances should be made for its eventual breakdown and changing C:N ratio.

Nitrogen requirements of all three plant communities are high, and especially high for dike slope and jack pine soils because of the initial demand by a fast establishing grass cover. Even the amount of available nitrogen outlined in Table 5-2 will not cover the full requirement of these communities; Chapter 3 shows that associated legume species are expected to fix approximately 50 kg/ha/yr and fertilizer nitrogen will be needed to supplement these amounts for at least the first two years after establishment.

The minimal levels of available phosphorus will not result from a mixture of peat and tailings sand. Large amounts of phosphorus fertilizers, sufficient for phosphorus supply over five to ten years, can be incorporated as an amendment during soil reconstruction.

As the foregoing discussion demonstrates, Table 5-2 is a key element in this entire report as it synthesises the minimal requirements for the establishment of the desired plant communities. One cautionary note from Chapter 1 should, however, be repeated here by stating that these values represent what is suggested by the literature and thus represent theoretical conditions. The limitations imposed by machine and operator capabilities and by the variability of the peat, overburden and tailings sand will dictate how closely these target figures can be met in practice and thus what alternative goals might be established.

CHAPTER 6

RECOMMENDATIONS FOR FURTHER RESEARCH

CHAPTER 6 - RECOMMENDATIONS FOR FURTHER RESEARCH

CONTENTS

6.1 INTRODUCTION

In order to formulate a reclamation strategy involving soil reconstruction and revegetation techniques, it is necessary to make assumptions about the major ecological interactions which govern the relationship of climate, soil and plant development. The purpose of Chapter 6 is to identify the assumptions that were made throughout the study and show how they affect the choice of minimum soil properties for each vegetation-soil complex. The identification and discussion of each assumption is followed by a recommendation of project(s) that can be used to either verify the original assumption or improve the evidence such that more realistic assumptions can be substituted.

6.2 SOIL RECONSTRUCTION STRATEGY

The soil reconstruction model outlined in Chapter 1 consists essentially of two points:

1. The reconstructed soils are designed to (1) supply sufficient moisture to plants, (2) supply sufficient nutrients to plants, and (3) be physically stable (non-eroding).

2. Soils will be constructed from tailings sand, peat and mineral overburden. The tailings sand functions as the primary matrix; peat and overburden are used as amendments to improve the quality of the tailings sand.

A wide review of literature in forest science, soil science and reclamation and an in-depth analysis of information pertaining specifically to the boreal forest region of Canada shows that the choice of functions or processes in the first point covers all major areas of concern.

The soil reconstruction procedure - mixing peat and overburden into sand to a specific depth - is the most effective means of building soils <u>in situ</u>. However, the assumption that each class of materials can be characterized in a general way is misleading. In fact all three material types are extremely heterogeneous in physical and chemical properties.

The variability of tailings sand, in particular, affects the choice of minimal properties assigned to each soil type in Table 5-2 (Chapter 5). The properties of tailings sand are used to select standards for the following soil characteristics:

- depth of reconstructed soil horizon
- available water holding capacity
- prediction of pH stability

- nutrient content and supply capacity
- erodibility

In a similar way the wide variability of properties associated with peat and overburden make a general strategy of material "mixing" difficult to implement, unless a more accurate classification of material type is made.

The following recommendations are made to strengthen the usefulness of the soil reconstruction strategy:

1. Define the distribution and variability of particle sizes in tailings sand for each area to be reclaimed. This analysis should ensure that fine sand fractions are measured separately from coarse or medium size fractions.

2. Classify the overburden material type to be used in soil reconstruction on the basis of similarity in texture, mineralogy and chemical properties. Highly sodic or saline materials of the Clearwater Formation should be avoided where they are likely to contribute to the deterioration of the soil profile or limit plant growth.

3. Characterize the available peat resources in terms of the degree of decomposition of each major horizon that may be handled separately. Organize the peat classification in a way that organic soils, with established ranges of properties, can be grouped into classes and used to improve reconstructed horizon soils with known degrees of confidence. The most important characteristics that will affect the reconstruction strategy are: carbon-nitrogen ratio, total nitrogen, cation exchange capacity, percentage base saturation, water holding capacity and available phosphorus.

6.3 REVEGETATION STRATEGY

The requirement for three vegetation communities adapted to different kinds of soil and landscape geography signifies a need for three slightly different revegetation strategies. The assumptions supporting each of these strategies and the effect they have on selected soil properties are outlined below.

Dike Slope Vegetation

The revegetation strategy for dike slope soils is based on the assumption that water erosion will be a primary problem. Therefore, the immediate objective is the stabilization of these slopes, and a grass-legume mixture is formulated to provide a fast establishing, relatively permanent, cover of plants. We assume also that over time jack pine and other plant species adapted to drier soil conditions will invade the dike slopes and gradually replace the grass-legume cover, without negatively influencing the physical stability of the dike slopes.

If dike slopes can be stabilized for one or two years with peat mulches it might be possible to plant trees and shrubs on the dikes and avoid the intensive management inputs associated with grasses and legumes. Although tree communities take longer to establish, their inclusion in the beginning would reduce the risk of physical disruption when transition from managed sward to tree cover is effected.

It is also possible that selected mixtures of topsoil (leaf litter mixed with mineral A horizon) can be used as an addition to peat to create a fast establishing cover on reclaimed soil in the oilsands area. The peat would be used as a mulch to stabilize the surface, while the topsoil is used as a readily activated source of native plants in the form of seeds, root stock, cuttings or other propagules. The topsoil in this case will also provide the optimum conditions (nutrition, aeration, moisture) for plant establishment.

Further research is required on:

1. Erodibility of dike slopes stabilized with peat mulches alone (see Section 6.4).

2. The establishment of trees and shrubs directly on dike slopes, with and without the influence of grass and legume understory.

3. The use of locally prepared (mixtures of locally available soil) topsoil as a source of both fast establishing plants (native plants considered to be weeds under cultivated conditions could be valuable here) and slowly growing trees and shrubs.

<u>Jack Pine Forest</u>

The major assumption underlying the jack pine establishment strategy is that water erosion, even on gently undulating areas, could be serious enough to include a grass-legume cover. In order to avoid the possible problem of competition for water and nutrients, we recommend the establishment, through herbicides, of vegetation-free circles for jack pine introduction. If, however, the areas designated for jack pine stands are not susceptible to erosion, or if the erosion hazard can be controlled easily by the use of practices such as peat mulching, it is probable that trees and shrubs can be planted directly without need of a grass legume understory. It is also possible, as explained under the topic of dike slope vegetation recommendations, that native topsoil could be used as a source of erosion controlling plants and jack pine seeds. Also, low shrubs, e.g. <u>Arctostaphylos uva-ursi</u>, might serve as an adequate ground cover instead of cultivated grasses and legumes.

Further investigation is required for the following topics:

1. Erodibility of jack pine soils under conditions of gentle undulating topography, and the relative merits of mulching versus grass-legume protection.

2. Competition between jack pine seedlings of different ages and grass-legume combinations planted in varying densities.

3. The use of spot applied herbicides to control vegetation in localized areas.

4. The feasibility of using local topsoil as a source of fast establishing plant cover and jack pine seedlings.

5. The possibility of planting native species, such as *Arctostaphylos uva-ursi* on a large scale.

Mixedwood Forest

The basic assumptions behind this vegetation strategy include erosion potential and inter-specific competition. As the erosion potential has been assumed to be less than in the other situations, a grass-legume cover has not been suggested. If the assumption is made that erosion may not be sufficiently controlled with tree and shrub seedlings alone, grasses or mulching would then have to be considered and tree/grass competition investigated.

Although there is a recommendation for white spruce/aspen ratios of 1.75 to 1 to yield an adequate mixture of these species in the oilsands area, there is little evidence of optimum mixtures in the published literature. In fact, the extremely wide variability of soil and landscape conditions in native, undisturbed mixedwood forests make extrapolation of information to reclaimed locations a dubious exercise. Furthermore, it is known that mixedwood forests, as their name implies, are composed of many plant species and change their composition, if not their level of productivity, in response to shifting biophysical conditions.

Further research is required to investigate:

1. Erodibility of the proposed mixedwood soils.

2. Inter-specific competition between aspen and white spruce seedlings and roses.

3. Planting ratios of aspen and white spruce seedlings.

4. The use of other combinations of trees and shrubs to achieve the same productivity under less strict soil conditions.

6.4 SOIL EROSION

The length and degree of slopes built to contain tailings sand and decant water from oil extraction make the potential for soil erosion by water a major consideration of this study. In addition jack pine will be established on areas of gently rolling topography and, also could be subjected to water erosion damage. The purpose of this section is to outline the assumptions used in the application of the Universal Soil Loss Equation (USLE) to predict potential erosion losses and how soil properties can be modified to reduce the risk of serious damage.

Two limits of soil erosion have been established as a means of justifying the design criteria for each soil type: erosion should not average more than 10 tons soil loss per acre per year over the long term, if soil productivity is to be maintained; secondly, no one year loss of soil should exceed 20 tons per acre, if serious environmental damage is to be avoided. These figures are adopted from information from the United States Department of Agriculture and do not reflect site specific information for the Canadian boreal forest. If the limits were increased, the acceptable levels of slope gradient and length could be relaxed; if limits were decreased, a tighter control on slopes and reformulated levels of silt and clay and organic matter contents would be required.

Rainfall, soil erodibility and a cover management factor are the most influential determinants of potential soil erosion amounts in the oilsands area. The rainfall factor is based on a two year return storm calculation and requires a wide data base for correct estimation. Soil erodibility is estimated from organic matter content, structure, permeability and particle size distribution; the latter element differentiates between fine sand and medium sand and is greatly influenced by a shift in either direction. The cover management factor includes the effect of controlling erosion by mulching and establishing a plant cover. The only two experiments carried out in the oilsands area to date have been short term and have shown a wide range of responses in relationship to mulching and cover establishment.

The soil properties outlined in Table 5-2 (Chapter 5) are consistent with the results of experiments and surveys conducted in the oilsands area; however, the data base is incomplete and the results are inconclusive.

Further investigation is needed to:

1. Define limits of erosion tolerance acceptable under conditions of the boreal forest region.

2. Obtain the best estimate of the rainfall factor for the oilsands area.

3. Improve the estimate of soil erodibility by improving the estimate of particle size distribution on dike slopes and tailings sand.

4. Estimate the effect on peat mulches and plant cover on erosion control on dike slopes and jack pine sites. Furthermore, some research on these effects needs to be carried over for several years to collect evidence about the long-term development of plant cover and erosion prevention. All experiments must be replicated sufficiently to allow for an extremely wide range of performances, as exemplified in the previous unsuccessful attempts to quantify the cover management factor.

6.5 SOIL WATER BUDGET

A calculation of a soil water budget is required for purposes of selecting soil properties needed to provide sufficient moisture for each plant community. In fact much of the justification for selecting soil depth, available water percentage, silt and clay content and organic matter content is based on the estimation of a slight annual water deficit (37 mm) in the oilsands area.

The factors used to calculate the soil water budget are the following:

- evapotranspiration (potential and actual using the method of Thornthwaite and Mather (1957)).
- the physical limits of available water in soils, i.e. tensions relating to field capacity and permanent wilting point.
- the amount of available water in soils and soil reconstruction materials.
- rooting depth of each plant community as an index of soil volumes supplying water for plants.
- changes in hydraulic conductivity in lower horizons as a measurement of drainage rates.
- rates of infiltration and runoff.

In order to formulate a precise model of moisture behaviour in soils, all of these characteristics require more exact definition. However, under conditions in the oilsands, where accuracy is more important than precision, the most critical examination should be given to (1) the phsyical limits of available water in soils, (2) the measurement of amounts of available water (using the physical limits) and

(3) the rooting depths of plant communities. Overall, a soil water budget for reconstructed soils can be defined if accurate estimations of plant available water and plant rooting depth are formulated.

This report has assumed that there is no regional influence on soil water status. Specifically, the varied influence of groundwater and runoff on recharge, discharge and surface accumulation has been ignored. The nature and amount of soil amendments and properties could change if these characteristics were included. Future investigation might show that landscape design, including the manipulation of water by changing topographical form, is a more reasonable and cost effective means of matching site index requirements to plant community.

Priority for further research in soil water relationships should be given to the following topics:

1. Define the moisture retention characteristics of tailings sand, taking into account the differential effects of amendments such as peat and mineral overburden, the use of -0.1 bar pressure as a measure of field capacity, and the variable influence of sand size fractions.

2. Measure the rooting depth of each mixture of plant species at various time periods after establishment or, alternatively, survey undisturbed stands of similar composition on similar material.

3. Define the estimates of actual and potential evapotranspiration by collecting more detailed (daily) weather information for Fort McMurray and applying more precise models of the prediction of evapotranspiration.

4. Redevelop a regional (100 hectares or more) reclamation plan that incorporates intersite relationships of water movement and storage. One might be able to plan groundwater and surface water occurrence such that minimum soil quality is reflected more in landscape position than in the level of individual property.

6.6 PEAT AND SOIL ORGANIC MATTER DYNAMICS

Peat is a fundamental material for soil reconstruction in tailings sand. It is presently being used in large amounts for reclamation by commercial oil consortiums in the oilsands area. This study has shown it to be absolutely vital for erosion control on steep slopes.

The tacit assumption throughout the studies and reports on the oilsands area is that peat will function like naturally formed organic matter. Organic matter is the result of physio-chemical and biological reactions within soil. It is the source of available energy for the microbial transformation of the nutrient elements; it is the stable reservoir of nitrogen, phosphorus and potassium; it harbours enzymes and microorganisms needed for high soil fertility; it plays a role in the development of structure and physical stability of soils; it protects against erosion; it promotes water infiltration and hydraulic conductivity; and it may increase the available water content of quartzitic sands.

In order to use peat as a short- or long-term substitute for soil organic matter the following information is needed:

1. A measurement of peat stability in reclaimed soils; the rates of and extent of peat decomposition under conditions of soil mixing and fertilizer application.

2. A measurement of the rates of nutrient release or immobilization when peat is added: how does the carbon-nitrogen ratio (or the degree of decomposition) of the peat offset nutrient availability, especially of nitrogen, phosphorus and sulphur?

3. An analysis of the effect of recent peat additions on tailings sand properties and how these effects change over the time of peat decomposition: quantify the effect on cation exchange capacity, exchangeable Ca, Mg and K, increases in available water and hydraulic conductivity, bulk density and porosity and buffering capacity.

4. Characterization of the effect of peat decomposition on physical and chemical structures in soil: is enough organic acid produced to release iron and aluminum and move them to fixed ("hard pans") positions in the profile? Does the decomposition of peat cause a significant decrease in pH levels of reconstructed soils?

6.7 NUTRIENT DYNAMICS IN RECONSTRUCTED SOILS

Nutrient cycling between plant and soil is described in this document in terms of (1) the plant demand or nutritional requirements of the plant cover, (2) the amount of nutrient in the major storage reservoirs, (3) the amount of nutrient in a plant available form and (4) the rate of transfer from storage reservoir to labile pool.

In Chapters 3 and 4 we have attempted to estimate each of these components for reconstructed soils in the oilsands area. We have also estimated the approximate nutrient balance (gains versus losses) of the oilsands area.

The formulation of minimum properties for each soil in Table 5-2 takes into account the initial conditions of nutrient storage and estimated rates of flow, as well as the demand plants will make upon the labile nutrient pool. However, several fundamental assumptions are made regarding these estimates that could be modified with better information:

1. Approximately 1% of the total nitrogen in soil is made available for plant uptake each year.

2. Carbon/nitrogen ratios of 15:1 or less will result in a net mineralization (release) of nitrogen, available for plant uptake.

3. Approximately 5% of the total cation exchange capacity of soils is occupied by potassium.

4. The efficiency of nutrient absorption by grasses and legumes is 60% for nitrogen, 30% for phosphorus, and 50% for potassium, calcium and magnesium.

5. Annual nutrient demand for grasses is best estimated by adding the nutrients in the foliage for the first year plus 2% extra for succeeding years and 20% of the root content.

6. Nitrogen fixing plants in the oilsands area (herbs or shrubs) can contribute an average of 50 kg N/ha/yr.

7. Internal nutrient cycling time for nitrogen in a mixedwood or jack pine stand is approximately 40 years or two to three times that of potassium or phosphorus.

8. Phosphorus can be supplied to plants in large amounts (up to 40 kg/ha/yr) over long time periods (up to ten years) by mixing in large quantities of fertilizer phosphorus with the reconstructed soil.

6.8 SPECIAL SOIL PROBLEMS IN THE OILSANDS AREA

In order to limit the scope of this study, we excluded the possible influence of residual hydrocarbons, excess salts remaining after oil extraction, excess salinity and sodicity in the overburden materials and the potential impact of sulphur dioxide emissions. It is apparent, however, that the desired properties of each soil would change if one or several of these conditions were identified. Furthermore, preliminary evidence suggests that several of these problems are present now and have been present since the initial stages of reclamation in the area.

The following recommendations are made to make the criteria of reconstructed soil design more relevant to actual conditions in the oilsands region.

1. Measure the hydrocarbon content of overburden materials and tailings sand after oil extraction. Implement a study to quantify the "hydrophobic" effect (if any) of hydrocarbons on soil water characteristics such as infiltration, storage and hydraulic conductivity. Incorporate these results into a modified design for soil water storage and transmissivity and soil stability (the prevention of erosion).

2. Measure the degree of salt and/or sodium contamination of oilsand tailings and mineral overburden. Calculate the effect these constituents, where present, might have on water relations to plants (osmotic stress or structural impedence of water flow).

3. Monitor the rates of sulphur deposition (dry or wet) on reclaimed areas near the plant sites. Recalculate the level of pH, the degree of base saturation and the buffering capacity needed to mitigate severe depositional episodes or withstand long-term acidification influences.

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