

PHOSPHORUS REDISTRIBUTION
IN SASKATCHEWAN SOILS

LORNE PETER LETEMAN

1993

PHOSPHORUS REDISTRIBUTION IN SASKATCHEWAN SOILS

A Thesis

Submitted to the Faculty of Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in the

Department of Soil Science

University of Saskatchewan

by

LORNE PETER LETKEMAN

Saskatoon, Saskatchewan

November, 1993

The author has agreed that the Library, University of Saskatchewan, may make this thesis freely available for inspection. Moreover, the author has agreed that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of the Department of Soil Science. It is understood that due recognition will be given to the author of this thesis and to the University of Saskatchewan in any use of the material in this thesis. Copying or publication or any other use of this thesis for financial gain without approval by the University of Saskatchewan and the authors written permission is prohibited.

Requests for permission to copy or to make other use of material in this thesis in whole or in part should be addressed to:

Head of the Department
University of Saskatchewan
SASKATOON, Canada

ABSTRACT

Phosphorus (P) is one of the least soluble and least mobile nutrients found in the soil environment. Despite its low solubility and mobility there has been considerable redistribution of P in soil profiles over the time of soil formation. The soil-forming processes thought to be largely responsible for soil P redistribution are leaching and biocycling, the translocation of P to surface soil horizons by roots. The intensity of both leaching and biocycling is primarily controlled by soil moisture conditions. It was the purpose of this study to examine the redistribution of P in soil profiles along an environmental gradient and over toposequences, as these factors can strongly influence soil moisture conditions.

Soil profiles were sampled from uncultivated land near Swift Current (Brown soil zone), Aberdeen (Dark Brown soil zone), and Spiritwood (Gray Luvisol), making up an environmental gradient from the semi-arid southwest to the subhumid central region of Saskatchewan. At the Swift Current and Aberdeen locations soil profiles were taken from the top and bottom of catenas on native pasture, while at Spiritwood soil profiles were taken from a native forest and an adjoining alfalfa field which had been cultivated for about 50 years of continuous wheat crops.

All the soils were formed on uniform deposits of glacial till parent material. Using soils of glacial till parent material was essential as only these soils allow for the distribution patterns of P with soil depth to be attributed to soil-forming processes and not systematic variations in the parent material composition.

Redistribution of soil P was found in all the soil profiles sampled. Soils were found to generally accumulate P in the surface horizons, experience P depletion from the rooting zone (upper B horizons) and, in the well-drained soils, P accumulations were found in the lower profile (lower B, and upper C horizons). The profiles taken from the grassland depression landscape positions were found to show greater P

redistribution than the upland positions and they also contained considerable P accumulations in the subsoil (50-150 cm depth). It was determined, by mass balance, that as much as 130 g m^{-2} of P had been moved out of the depletion zone while only 60 g m^{-2} could be accounted for in the surface horizon accumulation. It was concluded that over one-half of the P lost from the depletion zone had translocated down into the subsoil below as the result of leaching. Phosphorus fractionation analysis indicated that the subsoil accumulation was made up of primarily secondary P_i forms. This suggested that deep leaching of P may be occurring as the result of soluble P_i translocation, and not by organic P or clay translocation as others have suggested.

Greater P redistribution was found in the Swift Current depression soil profile, which was part of a large water catchment basin, than the Aberdeen depression soil profile, which was part of a much smaller catchment basin indicating that local topography has a greater control over soil moisture conditions than the influence of a narrow environmental gradient.

Both Gray Luvisol soils at Spiritwood showed a loss of P from the solum. Pedogenic indexing indicated that the native soil had lost about 7% of its estimated original P content. The cultivated soil was found to have lost between 25 and 35% of its original P according to a mass balance approach of quantitatively calculating P redistribution. Of the 150 to 200 g m^{-2} of P determined to have been lost from the solum only 100 g m^{-2} was estimated to have been lost due to crop removal. It was concluded that between 8 and 16% of the original P in the solum was lost from the cultivated soil as the result of processes other than those related to agricultural practices.

ACKNOWLEDGMENTS

The author would like to thank Dr. H. Tiessen for his guidance, supervision, patience, and many constructive comments during the course of this study and the review of this manuscript. Thanks are also extended to Dr. C.A. Campbell, Dr. D.W. Anderson, and Dr. K.C.J. van Rees for their constructive advice as committee members.

The author is also indebted to Les Henry for his time, effort, and help in selection of the sampling sites. Thanks are also extended to Jackie Moir and Barry Goetz for their friendship, willingness to help, and capable technical assistance in teaching me soil analytical chemistry. Mr and Mrs Patzer, Barry Goetz, and Les Henry all allowed access to their property and willingly allowed me to remove soil cores.

The friendship of fellow graduate students, staff, and faculty of the Saskatchewan Institute of Pedology over the past two years was greatly appreciated.

The financial assistance of the Potash and Phosphate Institute of Canada (PPI), Natural Sciences and Engineering Research Council of Canada (NSERC), and Agriculture Canada is gratefully acknowledged.

I thank God for giving me the good health, strength, and perseverance needed to complete this thesis. Finally, I would like to thank my wife Kathy for her support and encouragement during the two years it took to obtain this degree.

TABLE OF CONTENTS

1	INTRODUCTION.....	1
2	LITERATURE REVIEW	
2.1	Introduction.....	5
2.2	Parent Material	
2.2.1	Glaciation and parent material deposition.....	5
2.2.2	Parent material uniformity.....	7
2.2.3	Weathering of parent materials.....	10
2.3	Soil Formation.....	13
2.3.1	Leaching.....	14
2.3.2	Biocycling.....	15
2.3.3	Climate.....	18
2.3.4	Vegetation.....	19
2.3.5	Rooting depth.....	21
2.3.6	Vegetation history of Saskatchewan since glaciation.....	25
2.3.7	Topography.....	28
2.4	Phosphorus Cycle	
2.4.1	Phosphorus transformations in soil.....	29
2.4.2	Inorganic P.....	32
2.4.3	Organic P.....	33
2.4.4	Phosphorus translocation.....	34
2.5	Hypotheses For P Redistribution.....	37
3	MATERIALS AND METHODS	
3.1	Criteria For Site Selection.....	39

3.2	Description Of Soils And Sampling Sites.....	42
3.3	Landscape Comparison.....	49
3.4	Sampling Procedure.....	49
3.5	Particle Size Analysis.....	51
3.6	Carbon Analysis.....	52
3.7	Phosphorus Fractionation.....	52
3.8	Pedogenic Indexing.....	59
3.9	Root Distribution.....	60
3.10	Other Chemical Characterization.....	60
4	RESULTS AND DISCUSSION	
4.1	Profile Uniformity.....	62
4.2	Profile Descriptions.....	70
	4.2.1 Aberdeen sites.....	73
	4.2.2 Swift Current.....	76
	4.2.3 Spiritwood.....	78
	4.2.4 Comparison of sites.....	80
4.3	Total Phosphorus Distribution In Soil Profiles.....	82
4.4	Phosphorus Fractions In Soil Profiles.....	89
	4.4.1 Phosphorus composition of parent material.....	89
	4.4.2 Distribution of phosphorus fractions in soil profiles.....	90
	4.4.3 Phosphorus transformations and translocations.....	93
	4.4.4 Subsoil phosphorus accumulations.....	103
4.5	Phosphorus Gains and Losses In Soil Profiles.....	107
5	CONCLUSIONS	111
6	BIBLIOGRAPHY	114
7	APPENDIX	121
	A1.1 Phosphorus fractionation for Aberdeen soil profiles ($\mu\text{g/g}$ complete)	122

LIST OF TABLES

TABLE		PAGE
4.1	Aberdeen soil profile descriptions and selected characteristics.....	74
4.2	Swift Current soil profile descriptions and selected characteristics...	77
4.3	Spiritwood soil profile descriptions and selected characteristics.....	79
4.4	Maximum and minimum P redistribution in soil profiles by mass balance.....	86

LIST OF FIGURES

FIGURE		PAGE
1	Redistribution of soil P as compared to original distribution with soil depth.....	2
2.1	Particle size distribution within soil profiles of a stratified (Site 1) and uniform (Site 4) parent material deposit.....	9
2.2	Microorganisms in fertile loam soil at various depths.....	17
2.3	Natural vegetation of Saskatchewan.....	22
2.4	Vertical root distribution for different β 's for the function $Y=1-\beta^d$, describing cumulative root fraction (Y) by depth (d).....	22
2.5	Rooting pattern of aspen roots with soil depth.....	23
2.6	Rooting pattern of little blue stem, psoralea, June grass, ground plum and false prairie boneset with soil depth.....	24
2.7	Vegetation change across the Canadian Prairies since the last glaciation..	27
2.8	Topographic relationships and profile characteristics of Black and associated soils on glacial till.....	30
2.9	The soil phosphorus cycle: Its components and measurable fractions....	31
3.1	Soil sampling locations and soil zones.....	40
3.2	Swift Current profile horizon designations and depths.....	43
3.3	Photographs of Swift Current soil sampling sites.....	44
3.4	Aberdeen profile horizon designations and depths.....	46
3.5	Photographs of Aberdeen soil sampling sites.....	47
3.6	Spiritwood profile horizon designations and depths.....	48
3.7	Photographs of Spiritwood soil sampling sites.....	50
3.8	Flow chart of sequential P extraction.....	53
4.1	Particle size distribution of Aberdeen Knoll site.....	63

4.2	Particle size distribution of Aberdeen Depression (2) site.....	64
4.3	Particle size distribution of Aberdeen Depression (3) site.....	65
4.4	Particle size distribution of Swift Current Upland site.....	67
4.5	Particle size distribution of Swift Current Depression site.....	68
4.6	Particle size distribution of Spiritwood Native site.....	69
4.7	Particle size distribution of Spiritwood Cultivated site.....	71
4.8	The ratio of ZrO ₂ :non-carbonate sand plus silt in soil profiles as a determination of parent material uniformity.....	72
4.9	Total phosphorus distribution in soil profiles from Swift Current, Aberdeen, and Spiritwood.....	83
4.10	Distribution of various P fractions with soil depth for the Aberdeen Knoll soil profile.....	94
4.11	Distribution of various P fractions with soil depth for the Aberdeen Depression (2) soil profile.....	95
4.12	Distribution of various P fractions with soil depth for the Aberdeen Depression (3) soil profile.....	96
4.13	Distribution of various P fractions with soil depth for the Swift Current Upland soil profile.....	97
4.14	Distribution of various P fractions with soil depth for the Swift Current Depression soil profile.....	98
4.15	Distribution of various P fractions with soil depth for the Spiritwood Native soil profile.....	99
4.16	Distribution of various P fractions with soil depth for the Spiritwood Cultivated soil profile.....	100
4.17	The % gain or loss of P in the various horizons of soil profiles determined by pedogenic indexing (Zr).....	108

1. INTRODUCTION

Phosphorus (P) is considered to be relatively immobile in the soil environment. However, over time there has been soil P redistribution. Research suggests that soil formation processes have caused the transformation as well as the translocation of P, and created the present distribution of P within the soil profile (Xiao et al., 1991). Two processes may explain the translocation and subsequent redistribution of P in soil profiles: (a) leaching, and (b) biocycling. Leaching is thought to be the primary process of downward P translocation. Soil water drains through the soil profile as the result of gravitational flow providing a means of downward translocation for material which is either soluble or carried in suspension as fine particles. This includes the movement of P with soil constituents which are mobile in soil solution. There is some evidence of downward translocation of soil P with organic material (Schoenau and Bettany, 1989) as well as with clay particles (Day et al., 1987) resulting in subsoil accumulations of P.

Biocycling is the continual conversion of soil nutrients between inorganic and organic forms by immobilization and mineralization reactions. Inorganic soil nutrients are taken up by plant roots and incorporated into plant tissue (or converted into organic form), by means of immobilization reactions. When plant tissue dies it is decomposed by the soil fauna and microorganisms and the nutrients are converted back to their inorganic form, as the result of mineralization reactions. Plant uptake is the primary process of upward P translocation (Smeck, 1973). Plant uptake of soil P results in the depletion of P from the deeper rooting zone, whereas the decomposition of plant tissue results in the accumulation of P in surface soils. The combination of these processes results in typical profiles of P concentration with soil depth as shown in Figure 1. The

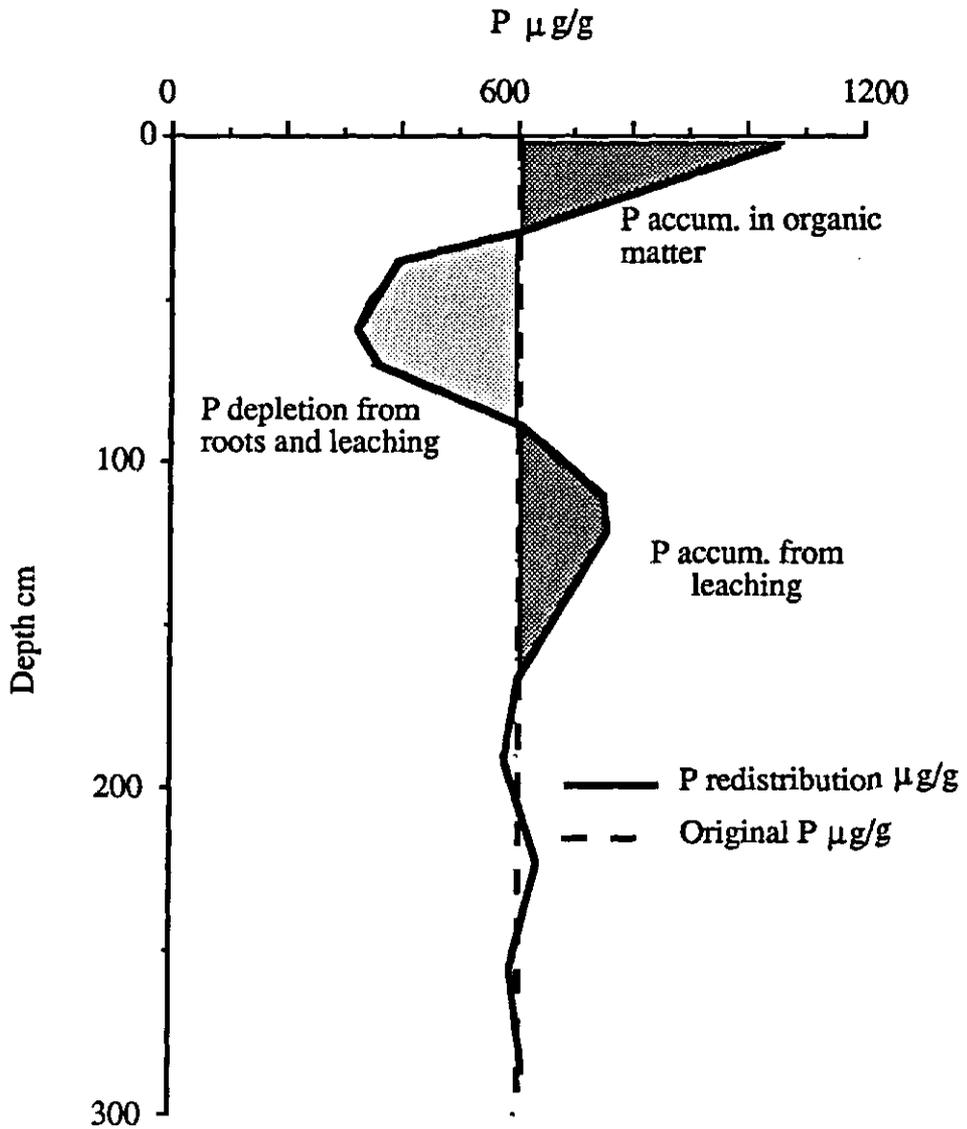


Figure 1. Potential redistribution of soil P as compared to original distribution with soil depth.

extent of these P translocations is unknown for semi-arid, cool regions such as Saskatchewan with its limited plant growth and leaching potential.

Soil moisture is the greatest single factor governing the intensity of both plant growth and leaching in Saskatchewan, where precipitation is limited and evapotranspiration can be high. Thus, the gradient of increasing moisture availability from the southwest to the northeast of the Province, and local soil moisture variations within the landscape both have a great potential to affect the redistribution of soil P.

The environmental gradient of increasing effective precipitation results from both temperature and rainfall differences as one moves from the warmer, drier climate (semi-arid) of southwestern Saskatchewan to the cooler and more moist climate (sub-humid) of northeastern Saskatchewan. Within local areas topography can have a significant influence on soil moisture conditions through runoff, resulting in drier upland soils and wetter depression soils. Thus, differences in P redistribution along the environmental gradient and over a soil catena would be expected. If the redistribution of P was to be related to the soil forming processes of leaching and biocycling, the original P distribution must have been uniform with soil depth before soil formation began. Given a uniform original distribution of P with soil depth, any deviation from a uniform concentration must be the result of soil formation processes. A parent material of glacial till often provides the ideal condition as it is an unsorted mixture of many minerals.

It was the objective of this project to examine the P redistribution with soil depth along an environmental gradient and over toposequences, and to relate the observed patterns to the soil forming processes associated with plant growth (biocycling) and leaching. To meet these objectives soils were sampled on native grasslands, aspen parkland, and a cultivated soil, all developed on glacial till parent material deposits. The soils came from the south (Brown), central (Dark Brown) and northern (Gray Luvisol) regions of the environmental gradient of Saskatchewan.

2. LITERATURE REVIEW

2.1 Introduction

The objective of this thesis was to examine the vertical redistribution patterns of phosphorus (P) in soil profiles from across an environmental gradient and down toposequences, and relate the observed patterns to soil forming processes. Before this could be done three basic concepts required consideration: parent material deposition, soil formation, and P cycling. Parent material deposition is important to the original distribution of P with soil depth, which must be known before a redistribution can be recognized. Soil formation is the result of physical and chemical processes which have influenced P redistribution while converting parent materials into soil, and developing soil profiles into distinct horizons (Walker and Syers, 1976). Phosphorus cycling is continual conversion of P between inorganic and organic forms as the result of the biotic component of the soil formation processes. Thus, if the redistribution of P is to be related to soil forming processes the relationship between the two must be understood. The following discussion provides the background information related to soil P redistribution which helped in the formulation the research design and hypotheses used in this thesis.

2.2 Parent Material

2.2.1 Glaciation and Parent Material Deposition

Parent material refers to geological materials which vary in their mode of deposition. Most of the soils in Saskatchewan were formed on the parent materials deposited by the last deglaciation, the Wisconsin ice age, which is estimated to have

occurred 10,000-16,000 years ago (Christiansen, 1979). As the glacier melted and retreated, the parent material (rock debris) was deposited on which our present soils have formed. This soil formation was only able to proceed after the glacier had all melted. Thus, the time frame of soil formation in Saskatchewan is estimated to be about 10,000 years (Christiansen, 1979). This makes Saskatchewan soils among the youngest in North America.

During the last glaciation the Province of Saskatchewan was under several kilometers of ice in which boulder to clay sized parent material minerals were held. As the glacier moved south, the weight of ice above crushed the parent material below the glacier creating the highly mixed nature of particle sizes, while the movement of the ice created the topography of the province (Edmonds, 1944). Two general classes of parent materials are found in Saskatchewan, lacustrine and glacial till. They differ in their mode of deposition and the degree of sorting found in their particle size composition.

Lacustrine parent material gets its name from the geological formation in which they settled, glacial lakes. Lacustrine deposits resulted from glacial runoff waters carrying the smaller parent material particles to lakes where they settled out on the glacial lake floors. This caused a fairly sorted arrangement of particle sizes; the heavier coarser sands and silts settling out first at the mouth of the lake and the finer silts and clays settling out last in the center of the lake. Due to their size and mass, gravel and stones could not be carried in the slow water flow of glacial lakes and thus are absent from these deposits, except for a few deposited by ice-rafting.

Glacial till refers to a surficial deposit of sediment which is characteristically unsorted in particle size and containing a wide range of minerals in its composition. These deposits are the result of glacial movement causing thorough mixing of all particle sizes and the deposit of these mixed materials remaining relatively undisturbed and unsorted due to minimal melt water flow. They consist of a highly mixed

assortment of materials ranging in size from clay to large stones. For this reason much of the till in Saskatchewan was originally included under a general description of undifferentiated glacial till or boulder clay (St. Arnaud, 1976). The highly mixed nature of glacial till provides a randomly variable distribution of all soil minerals without trends in composition with depth. This absence of trends constitutes a level of "uniformity".

2.2.2 Parent Material Uniformity

Before the distribution patterns of P can be related to soil forming processes the uniformity of the parent material must be established. Lacustrine (aeolian or fluvial) deposits often occur on top of a glacial till deposit. This results in a stratified deposit of parent materials, with highly sorted material lying on top of a deposit of unsorted material. Phosphorus distribution patterns in a stratified soil profile cannot easily be related to soil forming processes. Some of the variability in P distribution may be inherited from the minerals present in the different parent materials. Parent materials of differing deposits will each contain characteristic concentrations of various minerals. This condition will create a P concentration distribution pattern with depth as the result of parent material deposition and not the result of soil forming processes.

Aguilar and Heil (1988) found the distribution patterns of total P along three toposequences in North Dakota to be sensitive to parent material (deposited 75 million yr B.P.) differences and subsequent redistribution of sediments. Day et al., (1987), similarly found that total P distribution patterns appeared to be affected by pedogenic processes and by the presence of a lithologic discontinuity in the parent materials of a Florida hillslope. Thus, if P distribution patterns with depth are to be related to soil forming processes, location of a uniform parent material deposit is necessary.

One cannot assume that if no visual unconformity in soil texture occurs within a deposit that the soil has formed within a uniform material (Sudom and St. Arnaud,

1971). Previous studies in Saskatchewan (Sudom and St. Arnaud, 1971; St. Arnaud and Sudom, 1981) have demonstrated that particle size distribution as well as the ratio of zirconium oxide and quartz content can be used to establish the uniformity of parent material deposits with depth. By plotting particle size distribution with soil depth, deposition variability (stratification) and the effects of weathering can be identified (Figure 2.1). A consistent distribution of particle sizes with soil depth indicates a uniform deposit of parent material which has not experienced a significant amount of physical breakdown of sand to silt and clay size particles.

Sudom and St. Arnaud, (1971), examined a soil profile which had formed on a till but which contained a lacustrine layer on top of the glacial till deposit (Figure 2.1). In the Site 1 profile the IICk horizon can be seen to have considerably more silt and clay content than the above horizons. This represents an eroded surface of the finer textured overlying lacustrine layer. The glacial till deposit (IVCk) is clearly distinguished from the overlying lacustrine layers on the basis of particle size distribution. Such a pattern in particle size distribution is evidence of parent material stratification and indicates that the profile can not be used to relate soil forming processes to P distribution patterns with soil depth.

Sudom and St. Arnaud, (1971), also examined a uniform glacial till deposit on which an Orthic Gray Luvisol had formed. The Site 4 soil profile showed changes in particle size distribution with depth in the A and upper B horizons as the result of weathering and translocation of clay (Figure 2.1). The physical breakdown of coarser fractions to finer sizes and a marked translocation of clay within the A and B horizons was concluded to be characteristic of Luvisols. The relatively uniform composition of the Bmk and Ck horizons represents the critical distinguishing characteristic in this soil profile. The consistent particle size distribution over the lower three horizons shown in Site 4 (Figure 2.1) indicated a uniform deposit of parent material.

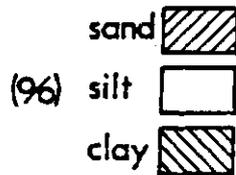
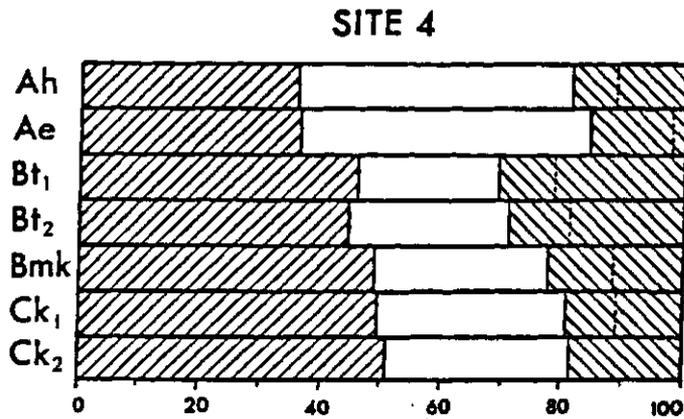
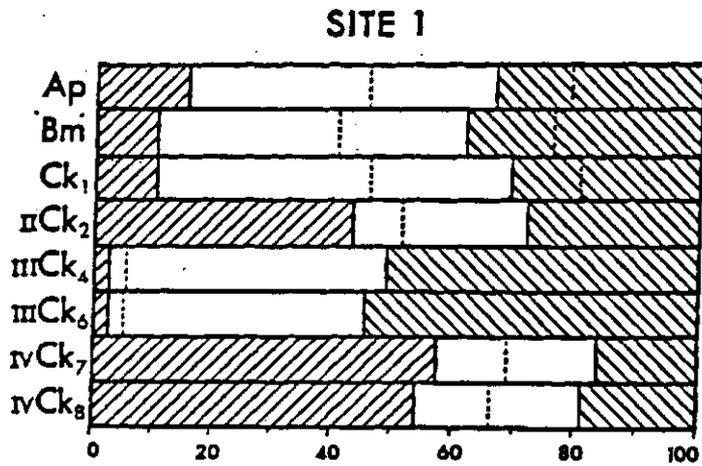


Figure 2.1 Particle size distribution within soil profiles of a stratified (Site 1) and uniform (Site 2) parent material (Source: Sudom and St. Arnaud, 1971).

Santos et al., (1986), devised an appropriate pedogenic index method based on the total quartz content of horizons. It is based on the premise that total quartz content (and similarly total non-carbonate sand plus silt) in a horizon has remained unchanged even though its particle size distribution may have changed (due to clay movement) during soil development. Sudom and St. Arnaud, (1971), found that zircon ($ZrSiO_4$) as estimated by zirconium oxide (ZrO_2) content could be used as a suitable index mineral as it is resistant to weathering and translocation. Thus, the ratio of quartz (or non-carbonate sand plus silt) to ZrO_2 can be used as an indicator of uniformity of parent material deposits, as both have remained unchanged in composition during soil development. The constancy (or restricted range of values) of the ratio of non-carbonate sand plus silt to ZrO_2 with depth is evidence of a deposit with a small random variability. If the ratio shows a significant inconsistency it indicates that there is a discontinuity in the deposit. If the ratio is randomly variable it can indicate that the parent material is also randomly variable (which is considered uniform), as would be expected of a glacial till parent material deposit.

Parent materials which demonstrate a consistent ratio of index minerals are assumed to have contained a fairly uniform variability in phosphorus concentration with soil depth at the time of their deposition (Santos et al., 1988). Present patterns in P distribution, with soil depth, which deviate from the original uniform P distribution pattern are thought to be the result of soil formation processes. The primary process which initiates and is continually contributing to soil formation is the weathering of parent materials (Anderson, 1988).

2.2.3 Weathering of Parent Materials

There are different types of glacial tills which can be separated based on their composition. Glacial tills which contained appreciable amounts of carbonates are associated with the present Chernozemic soils in the grassland area, and with the

Luvisolic soils of high base status in the forested regions of Saskatchewan. Today most of the soils formed on calcareous glacial till parent material have experienced some degree of carbonate weathering. This includes soils of extreme carbonate weathering which have little to no carbonates remaining in their A and B horizons as most of the carbonates have leached and accumulated in the C horizon where they appear as a concentrated layer (Cca horizon).

Weathering is a term used to describe the dissolution, disintegration, and decay resulting from reactions in soil solution which changes rocks into loosened soil (Miller and Donahue, 1990). There are two general types of weathering, physical and chemical, both of which proceed most rapidly at the soil surface and decrease with depth. Physical weathering is a slow process which only causes changes in particle size. The expansion force of water as it freezes and plant roots as they grow are capable of splitting minerals or rocks. The friction of moving rocks or soil particles against each other can be caused by wind, water, ice, and gravity resulting in the disintegration of particles. The greatest effect physical weathering has on soil formation is to increase the surface area of soil particles on which chemical weathering reactions can then take place.

Chemical weathering causes changes in the chemical composition of soil minerals and constitutes one of the most important sources of inorganic nutrients (Anderson, 1988). Minerals are dissolved in solution, changing solid materials into independent soluble ions (Miller and Donahue, 1990). Hydrolysis is one of the most important weathering processes causing soil profile changes. It involves the splitting of a water molecule where the hydrogen atom combines with the anion of a mineral, and the hydroxyl combines with the cation of the mineral.

Hydrolysis allows phosphate anions (PO_4^{3-}) to combine with H^+ ions, to form various orthophosphate species (HPO_4^{2-} , H_2PO_4^- , H_3PO_4) depending on pH conditions of the soil solution (Lindsay and Vlek, 1977). These species are in solution

for only a short time as they are very reactive due to a high charge density. They may become adsorbed to mineral surfaces, precipitate with various cations (Ca, Fe, Al), or be incorporated into microbial biomass and soil organic matter (Tiessen et al., 1984). Thus, the effect of weathering on P is to transform mineral P such as apatite into secondary P forms.

The presence of secondary P minerals in parent material of soils is evidence of mineral weathering that occurred before the last glaciation. Mermut and St. Arnaud (1986) found that feldspars in the glacial till parent materials of some Saskatchewan soils had already experienced considerable weathering prior to their deposition during the Wisconsin ice age. This helps explain the findings of Schoenau et al. (1989) who showed the total P pool in the Ck horizon (undisturbed by present soil formation) of a Saskatchewan Luvisolic soil contained only 75-80% Ca-P and that the remaining P was in secondary forms. Thus, the original P composition was not completely primary minerals but in fact some weathering had occurred in a previous soil causing secondary P formation before the last glaciation. On this basis the Ck horizons of Saskatchewan soil profiles are considered unweathered since the time of the last glaciation if the total P pool consists of about 70-80% in the primary P form.

Parent material weathering which has occurred since the end of the last glaciation can be seen in the development of the soil profile. Distinct horizons are formed which contain physical (particle size distribution, color, bulk density) and chemical (pH, nutrient concentration, organic matter content) characteristics that are the result of parent material weathering and subsequent soil formation. Without the weathering of parent materials the formation of soil profiles could not occur and soil P would not experience redistribution.

2.3 Soil Formation

Soil formation is the result of climate (temperature and precipitation), biota (plants and microorganisms), and topography interacting to influence the physical and chemical processes (weathering) that change the parent material into soil over time. This includes reducing the size of the mineral particles, leaching of soluble components, adding organic matter, changing the kinds of minerals, creating horizons, and producing clays.

The weathering and translocation of CaCO_3 is an initial and relatively rapid process during soil formation. Weathering of other soil minerals and the translocation of clay appear to be limited until carbonates are removed from the solum (McKeague and St. Arnaud, 1969). The depth to a CaCO_3 layer in Borolls (Chernozems) reflects the long-term average depth of water penetration (St. Arnaud, 1976). This makes finding a CaCO_3 accumulation zone in the subsoil important in identifying that portion of the soil profile which has been subjected to physical and chemical weathering. The soil above a CaCO_3 accumulation layer can be differentiated from the parent material below it by changes in physical and chemical properties resulting from soil formation processes.

Simonson (1959) developed a simple visualization of soil formation by considering four types of changes which may occur during pedogenesis: losses, gains, translocations, and transformations of soil constituents. These changes can all be seen in the redistribution of P. Losses of about 40% of the original P during pedogenesis were found in boreal forest soils compared to losses of 23% for less weathered soils developed under grasslands in Western Canada (St. Arnaud et al., 1988). Gains of total P were found in soils occupying water collection basins as the result of runoff erosion transporting P from an upland to the low lying area (Smeck and Runge, 1971). Translocation of P is evident from research which has shown soil horizons of minimum P concentration to be the result of constant removal of P by vegetation and leaching

(Smeck, 1973). Transformations of P from primary minerals to secondary inorganic and organic forms is so closely related to soil development that the proportion of various P forms can be used to estimate the age of a soil, provided other factors are known (Walker and Syers, 1976).

The processes which cause many of these changes are mineral weathering, leaching, and biocycling (by plants and microorganisms), all of which are closely associated with soil water. In Saskatchewan there is an environmental gradient of increasing precipitation and decreasing temperature moving from the southwest to the northeast of the Province. This gradient is not large as the amount of annual precipitation received by any given area of the Province varies by about 100 mm. However, the amount of water which enters and remains in the soil (not lost to evapotranspiration) is greater for the northeast than the southwest as the result of differences in seasonal temperatures and more importantly wind velocity. The higher temperatures and greater wind velocity experienced by the southwest portion of the Province create a great potential for evapotranspiration. The ratio of precipitation to evapotranspiration (P/E ratio) along the environmental gradient is critical, as greater potential evapotranspiration will cause a widening of the environmental gradient with respect to soil moisture conditions. The resulting soil moisture content will govern the leaching environment as well as the amount of plant growth and biocycling experienced by the soils along the environmental gradient. Pedogenic transformations and translocations of P will depend to a considerable extent on the intensity of the leaching environment, as it will determine the intensity of mineral weathering, solute movement, and availability of water and nutrients for biomass production (Anderson, 1988).

2.3.1 Leaching

The removal and translocation (leaching) of weathering products is largely due to the movement of water in the upper regolith (St. Arnaud, 1976). The removal of soil

material (eluviation), both in solution and as particles from upper layers of soil, and movement of such materials into underlying layers (illuviation) produce changes to the soil profile. The leaching of soil constituents causes the formation of distinct soil horizons described as A, B, and C, from the top to the bottom of a soil profile.

One indication of leaching changing the soil profile is the formation of an Ae horizon. Moderate to pronounced leaching and mineral weathering are characteristic of Ae horizons. Ae horizons are readily recognized by their pale grayish color, platy structure, acidic reaction, and lower content of soil colloids than underlying horizons. These horizons are the result of dissolution and translocation of organic matter, iron, aluminum, and soluble salts out of the A horizon. A process known as *lessivage* involves the physical translocation of fine clay particles from the Ae horizon to an underlying Bt horizon. Phosphorus can also be leached when associated with organic matter, cations, and soil colloidal material, including clay (Schoenau and Bettany, 1987; Day et al., 1987). Thus, the greatest movement of P is expected to be found in soil profiles containing Ae horizons. Such processes are common in Luvisols and eluviated Chernozemic soils (St. Arnaud, 1976) found in Saskatchewan.

2.3.2 Biocycling

An important component of soil formation is the addition of organic matter and the subsequent mineralization/immobilization reactions which cycle inorganic material between living plant tissue and inorganic soil nutrients. Inorganic cycling is of considerable importance to elements derived from the weathering of parent materials, such as P (Anderson, 1988). Plants and soil microorganisms require nutrients from the soil as well as the atmosphere for their growth and survival. As physical and chemical weathering processes transform primary inorganic P (Pi) to secondary forms of P, organisms in the soil or on the parent rock take up P from solution, or actively dissolve P for their own consumption (Tiessen and Stewart, 1983). Plants and microbes take

up inorganic nutrients, such as P (immobilization), and transform them into organic compounds by incorporating P into their tissue. When plants and microbes die their cells decay and become apart of soil organic matter which decomposes to release P, as the first steps of P mineralization. The released P is then converted from organic P to inorganic P by soil microorganisms. The inorganic P is then available for plant uptake.

Microorganisms are responsible for a large portion of the mineralization of organic P compounds (Walker and Syers, 1976). The population of microorganisms in the soil is a function of soil depth. The population of microorganisms is much greater at the soil surface than at soil depths greater than 1 m (Figure 2.2). This has an important implication for soil P redistribution. Since the population of soil microorganisms is very low at soil depths of 1 m or greater, the likelihood of significant mineralization of P from decaying plant roots occurring at this depth is small. Cole et al. (1977) while developing a P-cycling simulation model which used field data from Matador, Saskatchewan found that the rates of organic P mineralization decreased dramatically with soil depth (by a factor of 8 from 0 to 30 cm soil depth). There is also the consideration that the distribution of roots is concentrated in the top 30 cm of soil. Thus, secondary inorganic P found at depths of 1 m or greater is more likely the result of downward P translocation than organic P mineralization of root tissue.

With time more P becomes bioavailable and larger amounts become incorporated in soil organic matter. In many soils the maximum amounts of organic matter accumulated depend directly on the amounts of P_i available for biological consumption (Walker and Syers, 1976). The accumulation of organic matter and organic P (P_o) in the surface horizon of soils is a readily observable characteristic of developing soils. The accumulation of P_o in surface soils is the result of roots transporting P to the above ground portion of plants and the subsequent return of dead vegetation including roots themselves in and to the surface of the soil. In this way

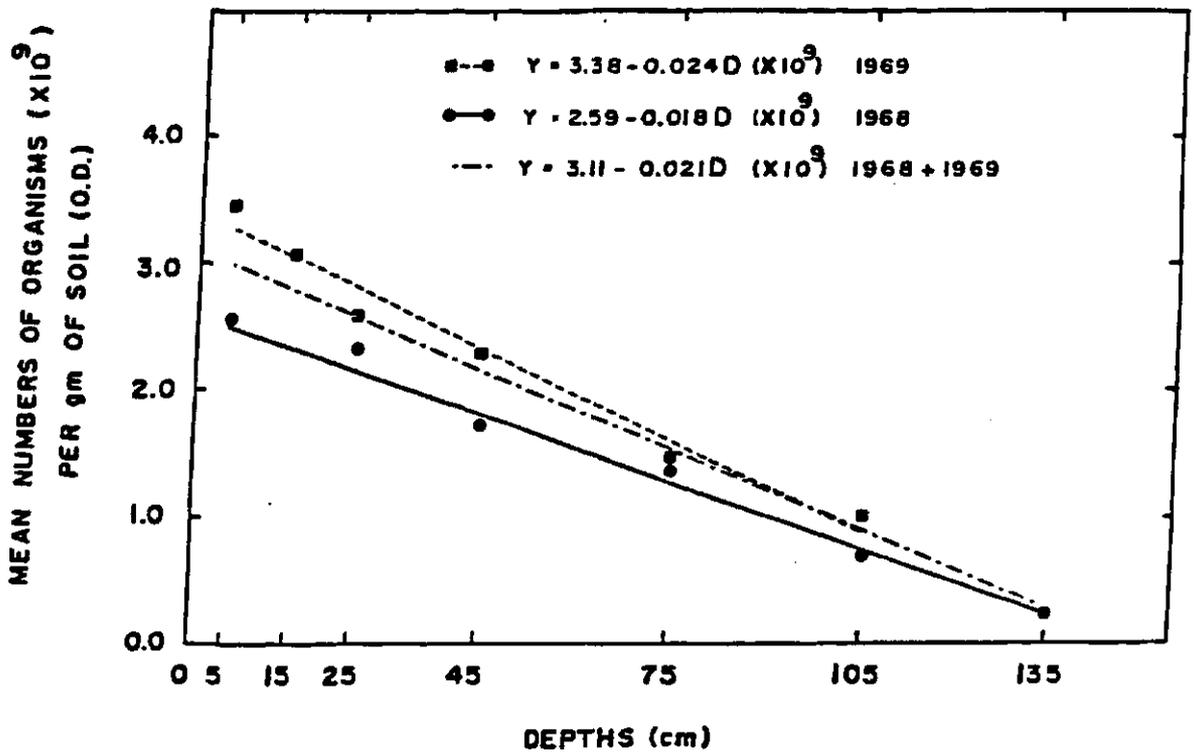


Figure 2.2 Number of bacteria and actinomycetes (determined by the direct count technique in relation to depth from 0 to 150 cm on natural grass, Matador, Saskatchewan (Source: Paul et al., 1973).

biocycling causes a net increase in the concentration of soil P in surface horizons while decreasing the concentration of P from lower horizons from which the P has been derived.

Biocycling will also have an impact on soil formation by increasing the rate of chemical weathering. The formation of organic acids by plant roots and soil microbes will increase the rate of mineral weathering by promoting hydrolysis reactions. Primary P minerals are weathered faster in an acid environment with a pH less than 7. Carbonic acid formed through biological respiration dissolves minerals faster than water alone and forms soluble bicarbonates. Bicarbonate can be exchanged for weakly sorbed phosphate anions on soil colloid exchange sites thereby adding P to soil solution. Thus, biocycling of P can be a significant factor in the transformation and translocation of soil P and in soil profile development.

2.3.3 Climate

Leaching and biocycling as soil formation processes are influenced by the environmental conditions which form a gradient of precipitation and temperature between the southern and northern portions of the province. The intensity of soil forming processes are influenced by this environmental gradient as they relate to soil moisture conditions (Roberts et al., 1985). Where there is high soil moisture there will be greater intensity of soil forming processes as compared to where there is low soil moisture. Saskatchewan has an environmental gradient of increasing moisture effectiveness from the semi-arid grasslands in the southwest (Brown soil zone) to Aspen Parkland in the south-central regions (Dark Brown and Black soil zones) to the sub-humid Mixed Wood forest (Gray Luvisols) in the north-central areas (Coupland and Rowe, 1969). In Saskatchewan mean annual temperatures range from 5 to 0 °C moving from the warm south to the cooler northern part of the province. The narrow

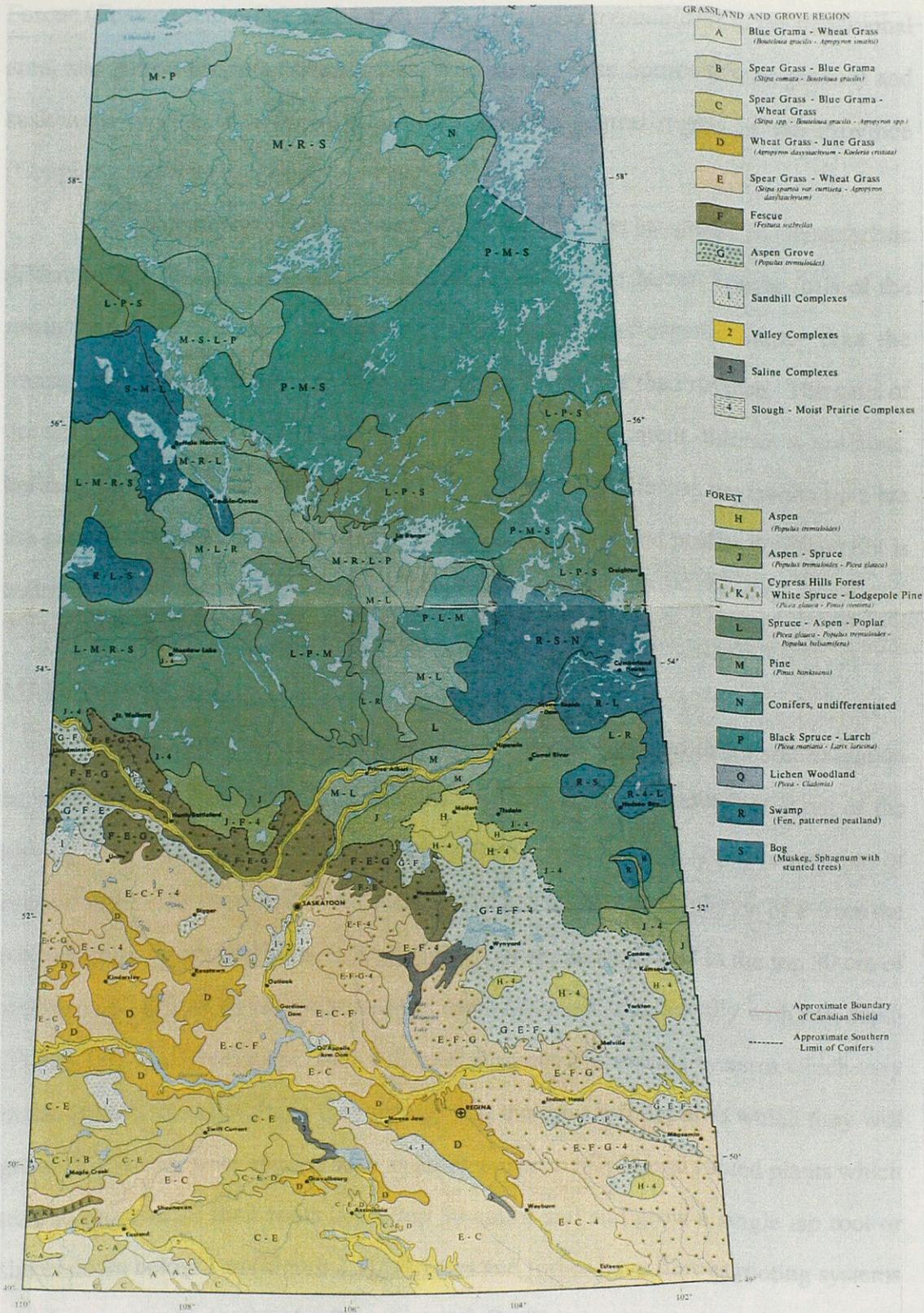


Figure 2.3 The natural vegetation found in Saskatchewan (copied with permission from Richards and Fung, 1969).

Fescue (*Festuca scabrella*), and Aspen Grove (*Populus tremuloides*) in the transitional area, and Aspen (*Populus tremuloides*) with some White Spruce (*Picea glauca*) and saskatoon bushes (*Amelanchier alnifolia*) in the central region of the Province (Coupland and Rowe, 1969).

The combination of climatic and vegetation gradients has produced characteristic differences in the soil properties along this gradient. The Mixed Prairie soils of the southwest corner of the Province have consistently less organic matter than the transitional soils of the Aspen Parkland in the central part of the Province. The soils of the northern forests typically have lower organic matter content, thinner A horizons, build up of a litter layer, and are more acidic due to the coniferous vegetation than are the grassland soils (Anderson, 1987). Thus, soil formation and profile development is a direct result of climatic conditions and vegetation cover.

2.3.5 Rooting Depth

The change in vegetation from south to north has implications for soil formation as well as P redistribution. Plant roots remove considerable amounts of P out of the rooting zone into the above-ground plant tissue. This results in the accumulation of organic matter and organic P in the surface soils and implies the depletion of P from the rooting zone. In general 70 to 80% of plant roots are concentrated in the top 30 cm of surface soil. Below 30 cm the amount of roots decreases dramatically with soil depth (Figure 2.4). Different plant types will have characteristic rooting systems which vary in the amount of soil volume they occupy and the total soil depth to which they will grow. In general, trees species such as aspen are primarily lateral rooted plants which tend to concentrate their roots in the top 50 cm of soil and grow a single tap root or sinker down below 1 m (Figure 2.5). Grasses and forbes have fibrous rooting systems which can grow to depths of 1-2 m (Figure 2.6). This implies a transition from deep

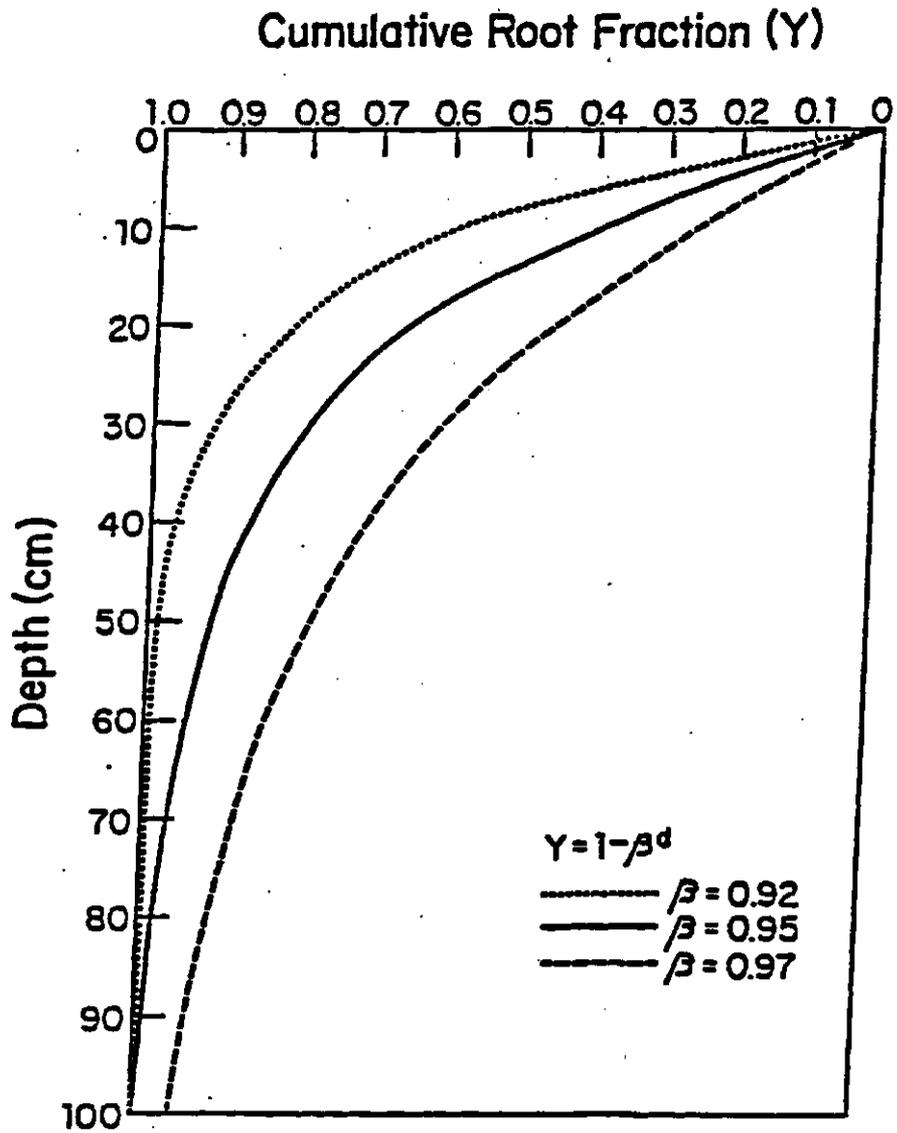


Figure 2.4 Vertical root distribution for different β 's (root distribution) for the function $Y=1-\beta^d$, describing cumulative root fraction (Y) by depth (d) (Source: Gale and Grigal, 1987).

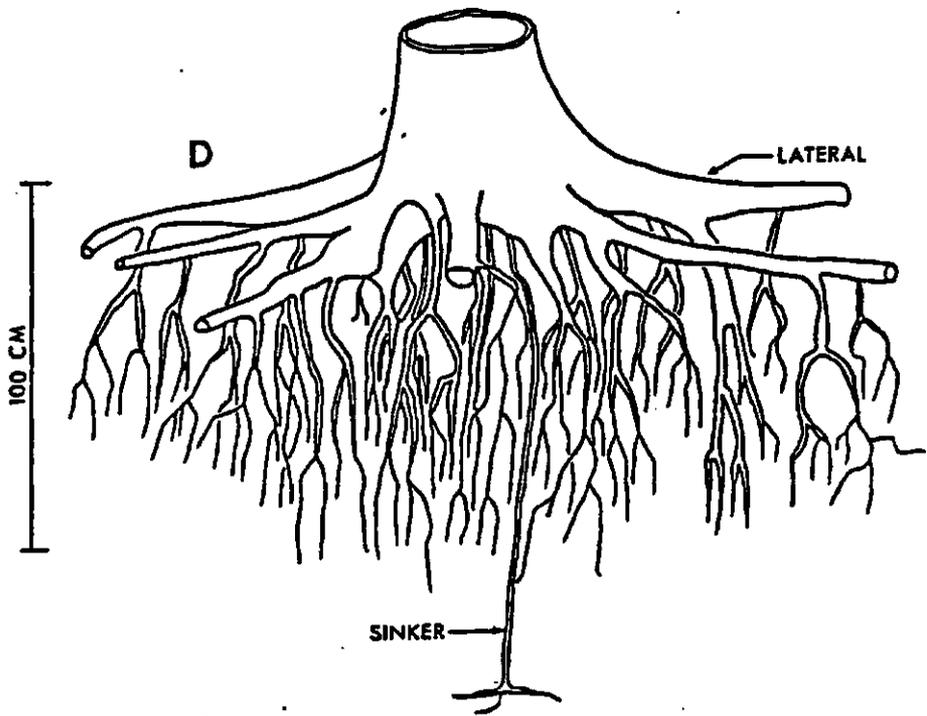


Figure 2.5 Rooting pattern of aspen roots with soil depth (Source: Modified from Strong, 1984).

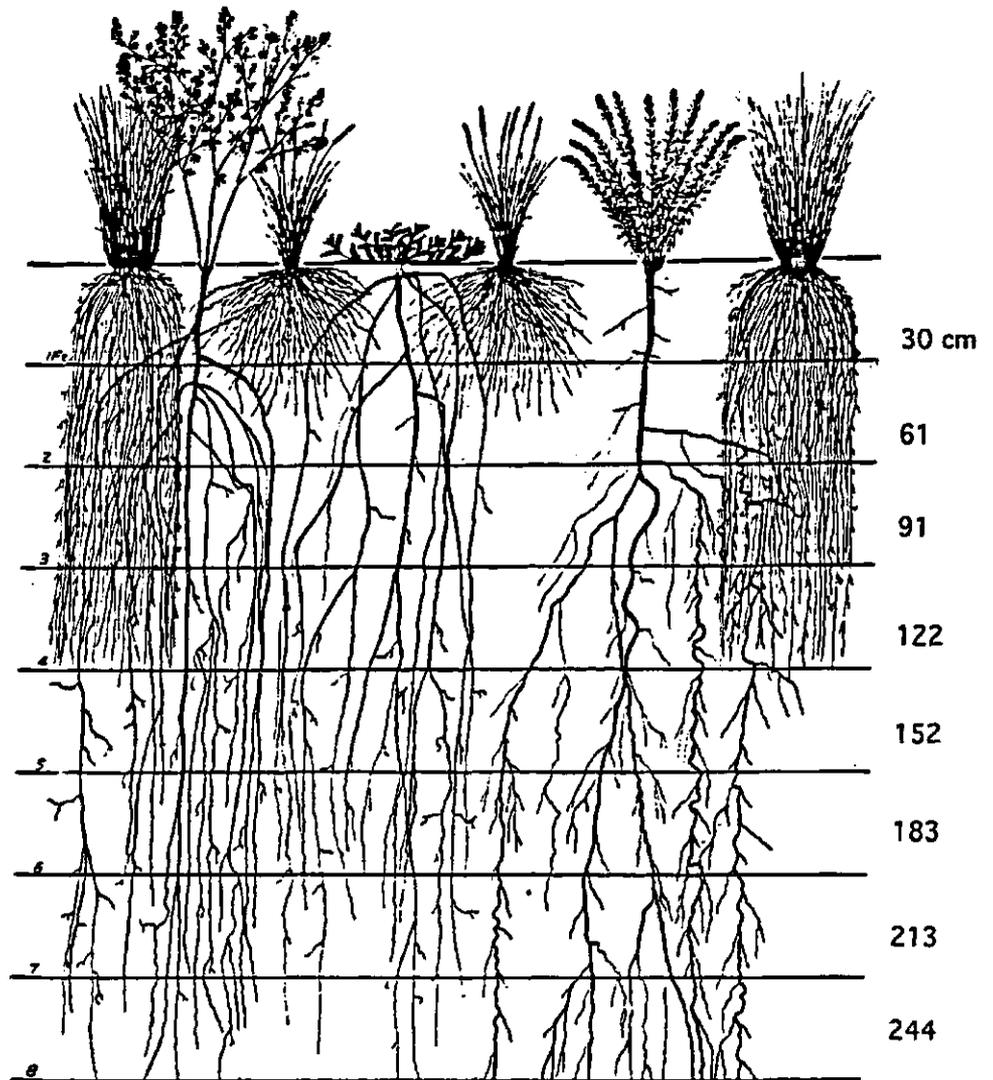


Figure 2.6 Rooting pattern of (left to right), little blue stem, psoralea, June grass, ground plum, and false prairie boneset with soil depth (Source: Shively and Weaver, 1939).

rooted plants (grasses in the south) to shallower rooted plants (trees and shrubs) for the vegetation gradient found from south to north in Saskatchewan.

Plants which have a deep rooting system (grasses) could potentially remove P from greater soil depths than plants containing shallow rooting systems (trees). As well roots will decay *in situ* and become a source of organic matter which could contribute to the level of secondary P and organic P found at soil depths which contain sufficient microbial populations to carry out mineralization reactions. This may affect the pattern of P redistribution found in soils occupied by plants of different species and different rooting depths. Thus, the vegetation gradient found across Saskatchewan may contribute to the redistribution of P as the result of varying rooting depths.

2.3.6 Vegetation History of Saskatchewan Since Glaciation

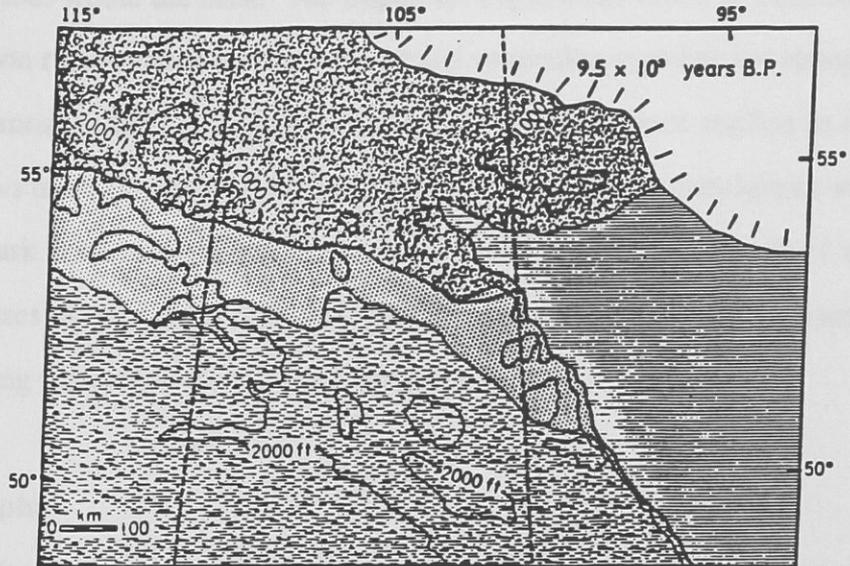
Another consideration is the change in vegetation which has occurred over the period of pedogenesis. The type of vegetation occupying the landscape of Western Canada has changed over the past 10,000 to 16,000 years (Ritchie, 1975). The type of vegetation growing on a developing soil could affect the P distribution in the soil as the result of P uptake by roots and organic P accumulation at the soil surface. Since different plants have different rooting systems and nutrient requirements, different species may cause characteristic patterns in P redistribution by the way they cycle P. If there has been a change in the vegetation type (grass vs forest) occupying a soil zone over the period of pedogenesis, it may result in a change in P distribution which would be difficult to differentiate from other soil forming factors.

Ritchie (1975) attempted to reconstruct the history of past vegetation since the last glaciation. Using pollen spectra (from cores of lake beds) it was estimated that, as the ice disintegrated, ice-free surfaces as well as extensive areas of till-rich stagnant ice were covered by a spruce forest. This early version of the boreal forest expanded northward as the ice sheets melted, and was replaced along its southern margin by

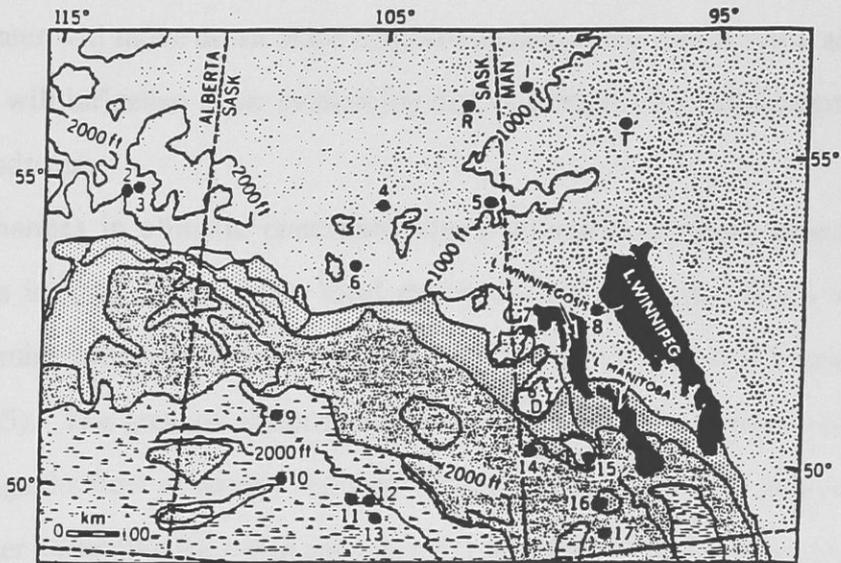
grasslands. In the southern areas of Saskatchewan the forest was completely replaced by grasslands and in the northern areas it was altered in composition and structure by the arrival of pine and the great increase in aspen. Ritchie (1975) further estimates that the period from 13,000 to 9,500 B.P. (years before present) was one of the major changes in both the physical and biogeography of the area. By 10,500 B.P. grasslands had replaced the forests of the Missouri Coteau, the Assiniboine Delta, the Tiger Hills, and the Riding Mountains (these make up most of the prairie provinces). Two important trees arrived in the area about 6,500 B.P., aspen and pine. Since the introduction of aspen and pine there has been the formation of our present day aspen parkland and mixed forest.

Figure 2.7 shows the estimated vegetative cover at 9,500 B.P. as compared to the modern or present vegetative cover of Saskatchewan. This suggests that the vegetation gradient found across Saskatchewan today (grassland to aspen parkland) has formed over the past 9,500 years. The grasslands of the south have remained unchanged since early post-glacial times, while the aspen parkland has developed as the boreal forest has moved southward into areas that had been treeless. The change in vegetation (grassland to forest) which makes up the gradient can not be accounted for adequately in the absence of environmental change. It is Ritchie's assessment that the late-glacial spruce forest in the western Interior was eliminated because the regional climate became unfavorable for tree growth. Judging from the present vegetation of the southern prairies this regional climate has not seen significant change since the late-glacial period as grassland still dominates this region.

Within the Province there will have been local expansions and die back of tree species within landscape features of the grasslands and aspen parkland. This will have been the result of small climatic changes (20-30 year cycles of drought or wet periods) and the influence of fire. During moist conditions trees would be allowed to flourish out beyond their normal range within low lying areas, and during dry periods or as the



A sketch map of part of the Western Interior of Canada at roughly 9.5×10^3 B.P., showing the positions of the ice margin, ; and the extent of Glacial L. Agassiz, ; and the suggested limits of the spruce forest, ; the grasslands, ; and a belt of deciduous forest, . The 305- and 610-m contours and the provincial and international boundaries are shown.



A sketch map of the modern vegetation of the Western Interior of Canada, mapped after Zoltai (1975). Boreal forest, ; transitional forest, ; aspen parkland, ; and grassland, , are shown. The 305- and 610-m contours, political boundaries, and locations of the sites referred to in the text and Table I are indicated.

Figure 2.7 Vegetation change across the Canadian Prairies since the last glaciation (Source: Ritchie, 1976)

result of fire the trees would die back. The important implication which is made from Ritchie's vegetation reconstruction is that the general vegetation type has not changed dramatically for most of the period of pedogenesis for the soil zones studied in this thesis. This allows us to assume that the distribution of P found in Saskatchewan soils of the Brown, Dark Brown, and Gray Luvisol soil zones is mostly the result of soil formation processes under a given vegetation cover and not the result of vegetative succession affecting the overall rooting depth of native plants.

2.3.7 Topography

Topography can produce localized gradients of soil moisture conditions. In environments where water is limited in supply the transition along a catena, from an upland down to a lowland, is characterized by a continuum of change in the soil moisture content along the slope. The upland will have less soil moisture than the lowland as the water will move down slope and accumulate in the lowest lying area. Thus topography will influence water availability and as a result vary soil formation throughout the landscape.

Just as changes in climatic conditions create a provincial environmental gradient, changes in topography create local environmental gradients which will influence soil forming processes, profile development, and P redistribution (Roberts and Bettany, 1985). The greatest effect topography has on soil development is to dramatically change the flow of water. The length and grade of a slope will influence the amount of water infiltrating the soil at any one point, and thereby, the amount which moves to catchment basins. This has many implications to soil formation as the intensity of weathering, leaching, and organic matter additions are largely dependent on the amount of available water in the soil. This is especially true in Saskatchewan where relatively low precipitation is a limiting factor for many soil processes.

On level landscapes water is allowed to infiltrate into the soil on which it was intercepted from rain or snow melt. On landscapes made up of upland and lowland catenas, water flow is directed by gravitational forces either on the soil surface as runoff or in ground water as lateral flow. Soils occupying shoulder landscape positions will experience more runoff and less infiltration. The end result is less soil formation and organic matter accumulation due to low soil moisture conditions in soil profiles of upland landscape positions.

Soil moisture availability is greater in depressional landscape positions (lowlands) as the result of collecting runoff waters. As the amount of water entering a soil profile increases there is more intense weathering, leaching, and organic matter production. In this way topography can enhance the conditions for soil formation and profile development. Figure 2.8 shows how the change in topography will govern the formation of soils and produce profile characteristics related to different positions in the landscape.

Roberts et al. (1985) found that the distribution of organic P (P_o) along catenas was strongly related to differences in weathering intensity between upper and lower slope positions. In lower slope positions there was more P_i weathering and as a result greater P uptake by plants, and consequently there was more P_o found in these soils. The difference in the degree of weathering intensity observed between uplands and lowlands is thus a good indicator of the transformations and translocation of P in the soil environment.

2.4 Phosphorus Cycle

2.4.1 Phosphorus Transformations In Soil

Soil P is found in two general forms: inorganic and organic. The two are closely interrelated making the total P pool a dynamic cycle. Figure 2.9 is a

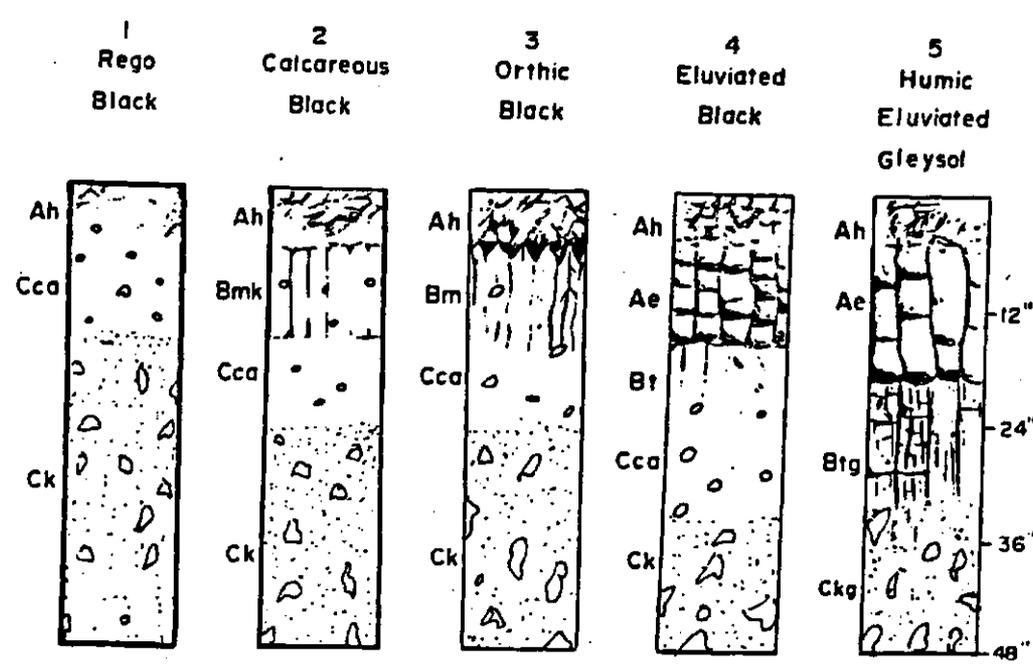
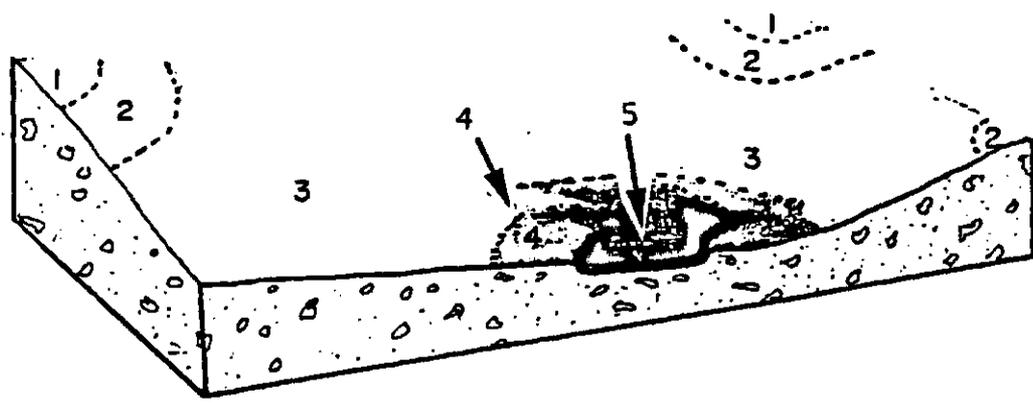


Figure 2.8 Topographic relationships and profile characteristics of Black and associated soils on glacial till (Source: St. Arnaud, 1976).

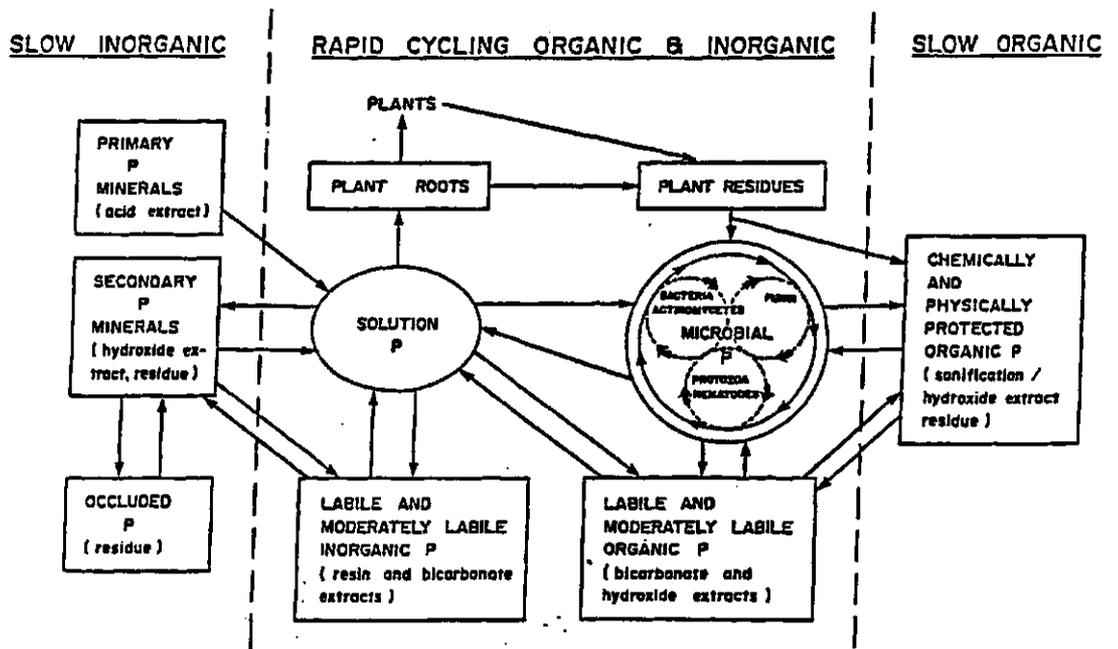


Figure 2.9 The soil phosphorus cycle: Its components and measurable fractions (Source: Tiessen and Stewart, 1983).

diagrammatic description of the many transformations which occur in the soil system. The diagram shows the interactions of various portions of the soil P cycle. The following sections describe the transformations of organic and inorganic forms of soil P which make up the P cycle, as well as the translocation of P which occurs in soil profiles.

2.4.2 Inorganic P

Apatites are the major source of soil P which consist of calcium phosphates (Ca-P) containing variable amounts of carbonate, fluoride, sulfate, hydroxide, and a number of different cations (Tiessen, 1991). Transformations from apatite P (primary) to other P forms (secondary) are part of the process of soil formation (pedogenesis). As chemical weathering and leaching remove carbonate from soil and produce an acid environment (below pH 7.0) there is an increase in the solubility of apatite minerals. This results in the hydrolysis of calcium phosphates and provides inorganic P (Pi) to soil solution (Smeck, 1973), thus allowing the formation of secondary Pi minerals by interacting with mineral (and colloidal) surfaces and free cations such as Ca, Mg, Al and Fe (Tiessen et al., 1984).

Phosphate ions are very reactive in the soil environment and sorption/precipitation reactions readily occur in the presence of cations and positively charged mineral surfaces leaving the majority of soil P relatively insoluble. The solubility of P is largely dependent on soil solution pH. Above pH 7.0, P solubility is governed by Ca phosphates, and decreases as pH increases. Below pH 7.0, the solubility of P is governed by Fe and Al phosphates, and decreases as pH decrease (Smeck, 1973). It is the soluble forms of Pi, which make up the bioavailable or labile pool of soil P, and which are constantly being replenished by the mineralization of organic P fractions.

As basic cations are leached out of upper soil horizons, pH declines and there is an increase in the amount of free Fe and Al oxides, which act as a sink for P, forming iron (Fe-P) and aluminum (Al-P) phosphates of very low solubility (Agbenin et al., 1993). This induced shift from primary Ca-P minerals to secondary Al-P and Fe-P forms creates an increasing amount of P which may become occluded (more resistant to extraction) with time (Stewart and Tiessen, 1987). Phosphate becomes incorporated within developing coatings and concretions of oxides and hydrous oxides of iron and aluminum during pedogenesis. Once P becomes a part of the developing coating on clays and minerals they are removed from active cycling and can not easily participate in equilibrium reactions with the soil solution (Donald, 1991).

2.4.3 Organic P

Organic P (Po) enters the soil through the decay of plants or microbe tissues and through root exudates (Donald, 1991). The soil Po pool is comprised of many P compounds, over half of which remain unidentified as specific chemical compounds. Some of the more common Po compounds that have been identified include the phospho-esters: inositols, phospholipids, nucleic acids. Condron et al. (1985) was able to extract about 80% of soil Po from a New Zealand pasture soil and used NMR (nuclear magnetic resonance) to show that more than 90% of this Po to be orthophosphate monoesters.

As organic P is released into the soil environment by secretion or cell lysis, it may be stabilized in the soil matrix or recycled into the biomass immediately (Magid et al., 1993). The organic P pool is stabilized through adsorption onto mineral colloids, or biochemically through the formation of large humic molecules (Tiessen and Stewart, 1983). Some organic phosphate compounds, including inositol, can compete with Pi for adsorption sites on clay mineral particles thus stabilizing Po (Anderson et al.,

1974). Inositol adsorption is possible due to its ability to form coordination bonds between P-ester groups and surface hydroxyl groups of mineral colloids.

There is also an active turnover of organic P fractions. Soil microorganisms make up a highly dynamic system which has a profound effect on P cycling by promoting hydrolysis reactions (Anderson, 1988). Microbes take up nutrients and convert them into new biomass tissue, then as they die and decompose P is released back into the soil. Many plant materials are extensively modified by microbial action before entering the soil organic matter pool, and the microbial population is an important source for soil Po as well as a significant component of the total soil Po pool (Tiessen and Stewart, 1983). Thus, the chemical nature of soil Po is largely determined by microbial products (Hedley and Stewart, 1982).

Cole et al. (1977) developed and tested a P simulation model which had the stability to operate under a wide range of abiotic and biotic inputs. The model integrated the effects of moisture, soil properties, plant phenology, and microbial decomposition of organic matter which could then estimate the flows, or transformations, of P for balancing P-cycling through the ecosystem. The model predicted plant and decomposer uptake and turnover rates of the principal P compartments. The values predicted by the model (which agreed with data from the Matador, Saskatchewan site) showed that the labile Pi pool is primarily replenished by mineralization of labile Po as well as leaching of water-soluble P from dead biomass.

2.4.4 Phosphorus Translocation

The movement of P within the soil profile and throughout the landscape is the result of soil forming processes such as biocycling, leaching, and erosion. Translocation refers to the vertical and lateral movement of P in soil environments. Vertical movement is the redistribution of P within the soil profile consisting primarily of upward movement by roots and downward movement by leaching (Smeck, 1973).

Lateral movement is the redistribution of P throughout the landscape consisting of surface flow, or erosion due to runoff (Smeck and Runge, 1971), and subsurface flow in ground water. Both of these are strongly influenced by soil texture and topography (Xiao et al., 1991). In the present study only vertical P translocation was quantified. Thus, given a homogeneous parent material (non stratified glacial till), the distribution pattern of P in the soil profile was assumed to reflect the influence of pedogenic processes related to leaching and biocycling.

Saskatchewan native grassland soil profiles usually have maximum P concentration in the surface horizon reflecting the trend of organic matter accumulation. Below the surface soil horizon, P concentration declines sharply due to uptake by plant roots (Roscoe, 1960) and leaching losses (Frossard et al., 1989). Below this depletion zone phosphorus content typically increases with depth to a maximum concentration in the lower B and upper C horizon (Runge and Rieken, 1966; Schimel, 1985), and then decreases to a lower and constant level in the Ck horizon. This eluviation and illuviation of P requires some degree of vertical mobility.

Honeycutt et al. (1990) examined three study sites selected along an environmental gradient from eastern Colorado to northwestern Kansas. They found that total P depletion zones were located deeper on footslopes compared to the respective summit positions in all three catenas. The total amount of P was very similar in the summit and footslope of A horizons within the climatic zones. This suggests vertical translocation by leaching of P had played a more active role in total P distribution in these soil profiles than upward P movement to the soil surface by plant roots. It also suggests the importance of topography to water drainage and leaching intensity throughout the landscape.

The mobility of P_i depends on the soil pH and activity of Ca, Fe, Al, and other cations in soil (Lindsay and Vlek, 1977). P_o mobility is not limited by the same constraints and it has long been known that P_o is much more mobile than P_i in

calcareous soils (Spencer and Stewart, 1934; Schoenau and Bettany, 1987; Frossard et al., 1989). Hannapel et al. (1964), used soil column experiments to demonstrate the predominance of Po (as colloidal microbial cells and cellular debris) over Pi in soil solution leaching. Schoenau and Bettany (1987) found evidence that low molecular weight fulvic acids, produced in biologically active surface horizons, may have been translocated to B and C horizons by percolating water. Of the four elements (C, N, P, S) studied, P appeared to be the most susceptible to deep leaching in the organic form, which is believed to reflect the predominance of P in mobile organic matter. Frossard et al. (1989) demonstrated that soil will adsorb orthophosphate (Pi) anions to a much greater extent than P-containing organic compounds, leaving the organic compounds available for leaching. Xiao et al. (1991) postulated the P lost from the A horizon of Luvisolic soils was mostly in organic form. This leached P accounted for an accumulation of about $100 \text{ kg Po ha}^{-1}$ in the Bt horizons. Xiao et al. concluded that $0.2 \text{ kg ha}^{-1} \text{ yr}^{-1}$ of P was completely leached out of the profile and into the ground water thus moving to other parts of the landscape.

Day et al. (1987) found that total P in soil seemed to be directly related to the clay content in lower landscape positions. Total P in the clay, and P fractionation values, indicated that some P had been redistributed between horizons and possibly between soils on the landscape. Their research showed a strong correlation between zones of illuviated clay and high P content. The capacity of clay minerals to adsorb and retain P as Fe and Al oxides, coupled with the ability of clay minerals to be illuviated suggests that P can be moved in fine particle form in soil.

Frossard et al. (1989) estimated the mobility of phosphate anions and some selected Po compounds by isotopic dilution kinetic experiments. Their results indicated that while Po compounds were more mobile, Pi in the form of phosphate anions showed limited mobility. The phosphate ion mobility in A horizons was found to increase from a Calcareous Brown to a Orthic Black soil and was found to decrease in a

Gray Luvisol. This trend was similar to the resin-P and the NaOH Pi fractions in A horizons. Their conclusion was that Pi has limited mobility in A and upper B horizons but little to no mobility in lower soil horizons due to the high sorptive capacity of lower soil horizons.

2.5 Hypotheses For P Redistribution

Based on the literature reviewed and methods available for quantifying the various fractions of P in the soil, hypotheses were formulated regarding the redistribution of P which has occurred as the result of soil forming processes:

- 1) In Luvisolic soil profiles demonstrating strong Ae horizons subsoil P accumulation zones were expected.
- 2) P accumulation above the original concentration of P in surface soil result from biocycling causing a build up of predominantly organic P; accumulation above the original concentration of P in the subsoil results from leaching, causing the downward translocation of P and subsequent precipitation with Ca in the Cca horizon.
- 3) Depletion below the original concentration of P results from root uptake removing plant available P and translocating it to soil horizons above and/or leaching removing mobile P to lower soil horizons.
- 4) Based on previous research the greatest biocycling and leaching is expected in soils of the wetter Dark Brown and Gray Luvisolic soil zones, and in depression landscape positions as the result of greater moisture availability. For this reason the accumulation of subsoil P is expected to be more pronounced and occur deeper in profiles of northern soils compared to southern soils.
- 5) Subsoil accumulations of P in well-drained profiles are the result of P leaching. These accumulations would be made up mostly of organic P forms as these fractions have been shown to be the most mobile in soils.

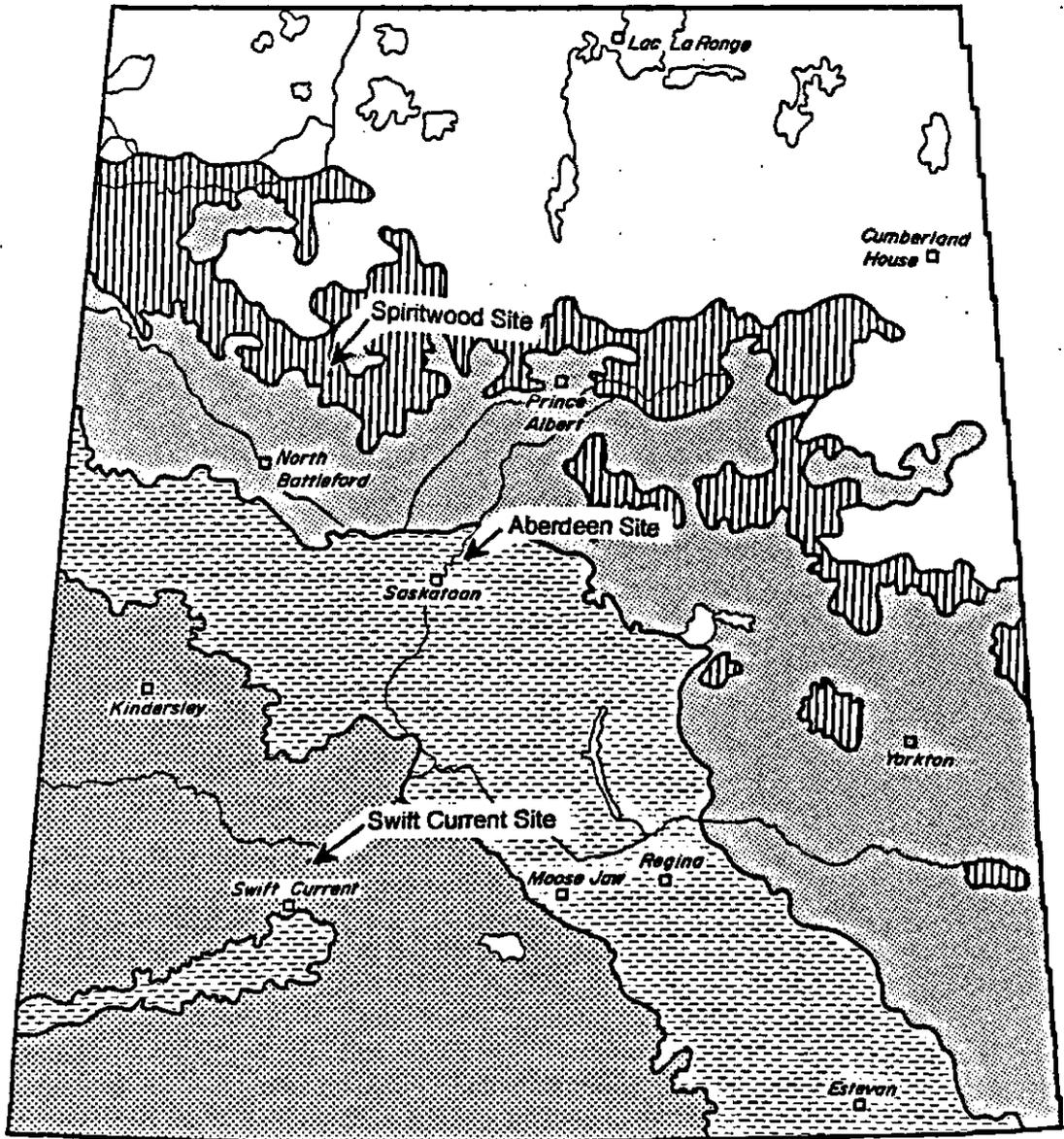
To test these hypotheses, Chernozemic and Luvisolic soils were sampled from along the environmental gradient which runs from the southwest to northeast regions of Saskatchewan in order to determine whether the greater soil moisture conditions of the northern soils experienced greater P leaching than the drier south. Soils were analyzed for P using a sequential extraction method for detailed P fractionation. P fractionation would allow for the interpretation of P translocation as well as P transformations by examining the concentration of various P fractions at different soil depths. Mass balance calculations on the total P budget within soil profiles would allow for the interpretation of the processes which result in the gains and losses of P from different horizons of the soil profile.

3. MATERIALS AND METHODS

3.1 Criteria For Site Selection

The soil zones of Saskatchewan are differentiated primarily on the basis of soil color which is the result of the level of organic matter present in the soil (the darker the color of the soil the higher the organic matter content). The Brown soil zone in the southwest corner of the province is characterized by high water deficit due to low precipitation and high evapotranspiration, resulting in relatively low organic matter content and thus a light soil color. Moving in a northeast direction across the Dark Brown soil zone to the Black soil zone the moisture deficit is much lower due to cooler temperatures, lower wind intensity, and higher precipitation which results in increased soil organic matter production and darker soils (Dark Brown, Black, Gray). Thus, the soil zones are the result of the environmental gradient. It was this environmental gradient which was desirable for determining the influence of climatic conditions on P redistribution patterns with soil depth. On this basis three sites were selected: one from the south of the province in the Brown soil zone near Swift Current, one from the central part of the province in the Dark Brown soil zone near Aberdeen, and one site from the northern part of the province in the Gray Luvisolic soil zone (forested) near Spiritwood (Figure 3.1).

Soil profiles made up of a uniform glacial till parent material deposit were thought to provide the most favorable conditions for determining the effects of pedogenesis on P redistribution, while avoiding any complications associated with a stratified deposit of parent material. An glacial till is a highly mixed (unsorted) material of many different particles sizes (clay, silt, sand, and gravel) providing a random variance in P concentration without trends in the distribution of soil P with depth,



LEGEND

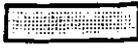
-  Brown
-  Dark Brown
-  Black
-  Gray

Figure 3.1 Soil sampling locations within the soil zones of Saskatchewan.

although there will be some inherent variance (non-uniform P distribution) within a glacial till parent material.

It was also important to locate sites which had a topography which included a knoll (upland) and strongly leached depression in a catena sequence, in order to determine the influence of local topography on P redistribution. We therefore included soil profiles which exhibited strong Ae horizons in the depression which would be expected to exhibit the maximum movement of P through the soil profile due to leaching.

Sites developed on native grassland and forest were most desirable since these profiles would be undisturbed and any irregularities due to cultivation, P inputs by fertilizer additions, and P losses due to crop removal could be avoided for the sake of mass balance calculations (determining net gains and losses of P from individual soil horizons as well as from the entire profile). At the Spiritwood site (northern Saskatchewan) a cultivated field was sampled to provide a comparison profile to determine the influence of soil disturbance on P redistribution.

When sampling the sites it was important to reach a soil depth which contained an accumulation of CaCO_3 (Cca horizon), and, where it was possible, to core below the accumulation into the Ck horizon. Calcium carbonate is used as a reference marker in soil science to determine the effective depth of pedogenic processes and serves as a distinguishing marker in soil classification. The depth to CaCO_3 in soils of semi-arid to subhumid climates reflects the long-term average depth of water penetration (St. Arnaud, 1976). Since Ca-P is less soluble than CaCO_3 it is assumed that it will not have moved as deep as CaCO_3 with water movement. Thus if the soil depth of CaCO_3 accumulation is found, the maximum depth of P movement was assumed to have been reached.

3.2 Description Of Soils And Sampling Sites

Three field sites each of a different soil association (Acton and Ellis, 1978; Ayres, Acton, and Ellis, 1985; Michell, Moss, and Clayton, 1950) and climatic zone were sampled for this study:

i. Ardill Association (Swift Current) Brown Soil Zone

The legal location of the Swift Current sampling sites was Section NW 13, Township 18, Range 12. The Ardill association consists chiefly of Brown Chernozemic soils developed from moderately calcareous glacial till with admixtures of shale giving the soil a clay-loam or heavier texture. Two sites were sampled at locations approximately 50 m apart in a native pasture, one on an upland position (referred to as Swift Current Upland) and the other in the footslope position (referred to as Swift Current Depression) of a catena. The change in elevation between the two sampling sites was about 2 m. Both soils were Orthic Brown series (Gleyed Eluviated Brown) of moderately fine texture. The site in the depression had 7 cm of Ah horizon below which was an Aeg horizon of 15 cm underlain by a 78 cm Bt, a 55 cm Cca, and a Ck horizon below (Figure 3.2). On the upland the soil had a 7 cm deep Ah horizon, a Btj which was 16 cm deep a 9 cm BC, underlain by a calcareous C horizon . The topography of the area was strongly rolling knob and kettle, and the site was moderately stony (Figure 3.3).

ii. Weyburn Association (Aberdeen) Dark Brown Soil Zone

The legal location of the Aberdeen soil sampling site was Section NW 9, Township 38, Range 3. The Weyburn Association includes Dark Brown Chernozemic soils developed on medium to moderately fine textured unsorted glacial till, which is moderately to strongly calcareous. Three soils were sampled in a native pasture, one from a knoll (referred to as Aberdeen Knoll), one from the adjoining depression

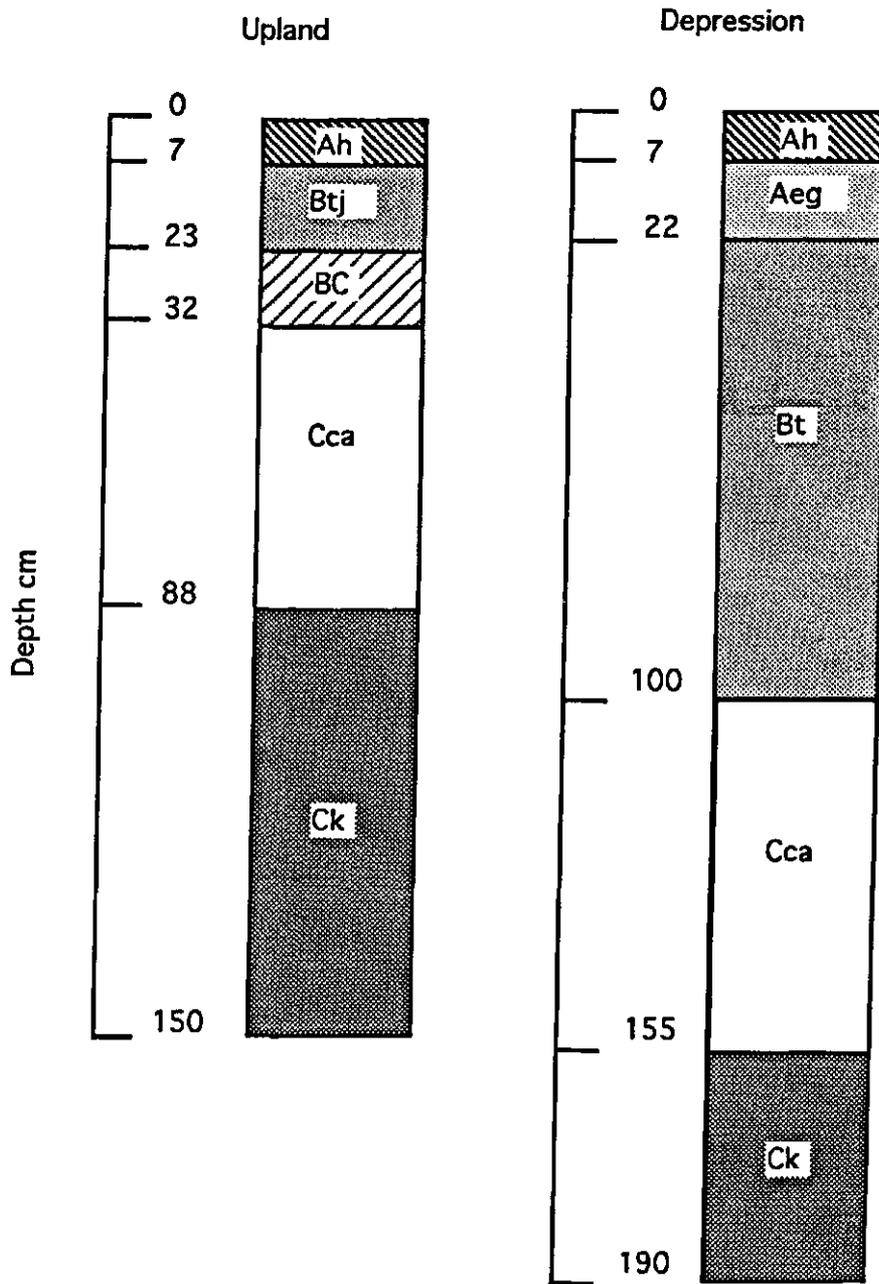


Figure 3.2 Swift Current profile horizon designations and depths.



Figure 3.3 Photographs of the soil sampling sites at the Swift Current location.

(referred to as Aberdeen Depression (2)) and one from a depressional positions (referred to as Aberdeen Depression (3)) which was approximately 100 m to the east (Figure 3.4). The change in elevation between the Knoll and Depression (2) profile was approximately 1.5 m. The second depression was sampled to compare profiles of similar landscape position in the same local area, in hopes of finding comparable soil characteristics and trends in the P distribution pattern. The soil taken from the knoll was a Rego Dark Brown on a uniform glacial till deposit, characterized by a 20 cm Ah, and a 10 cm Ahk horizon underlain by a calcareous C. The soils in the depressions were Eluviated Dark Brown series with a surface clay deposit formed from local hill wash underlain by glacial till. The Ahe/Ae horizons ranged from 14 to 42 cm in thickness underlain by Bt horizons of 25 and 39 cm thickness. In the Depression (2) which was most strongly eluviated, no Ck horizon could be found in the 270 cm sampling depth. The topography of the area was moderately rolling knob and kettle, and the site was moderately stony (Figure 3.5).

iii. Waitville Association (Spiritwood) Gray Soil Zone

The legal location of the Spiritwood soil sampling site was Section NE 34, Township 49, Range 12. The Waitville association is an Orthic Gray Luvisol clay loam developed on unsorted glacial till, and formed under a cover of aspen forest. These soils have been formed under a cover of aspen forest. Two sites were sampled from this location, both from the same upland position (no elevation change), but with different degrees of soil disturbance. Soil was taken from an undisturbed wooded area (referred to as Spiritwood Native) as well as from an adjoining alfalfa field (referred to as Spiritwood Cultivated) about 10 m away. The soil from the wooded area had a 5 cm Ah, 7 cm Ao/Ae, 9 cm Ae, and 53 cm Bt horizon underlain by a calcareous C horizon (Figure 3.6). The alfalfa field had been broken for about 50 years and seeded to continuous wheat up until 8 years ago when alfalfa was included in the rotation. Phosphate

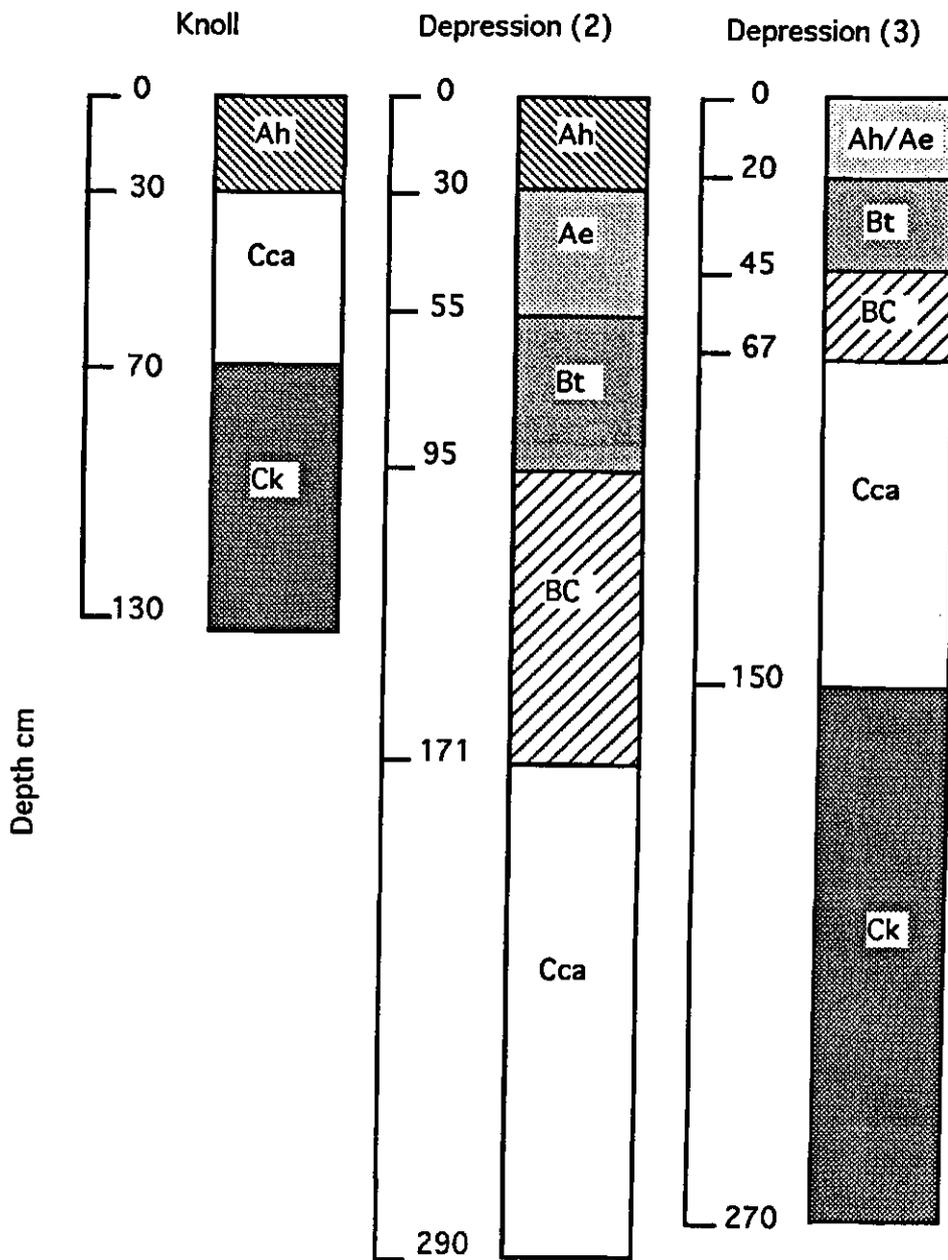


Figure 3.4 Aberdeen profile horizon designations and depths.



Figure 3.5 Photographs of the soil sampling sites at the Aberdeen location.

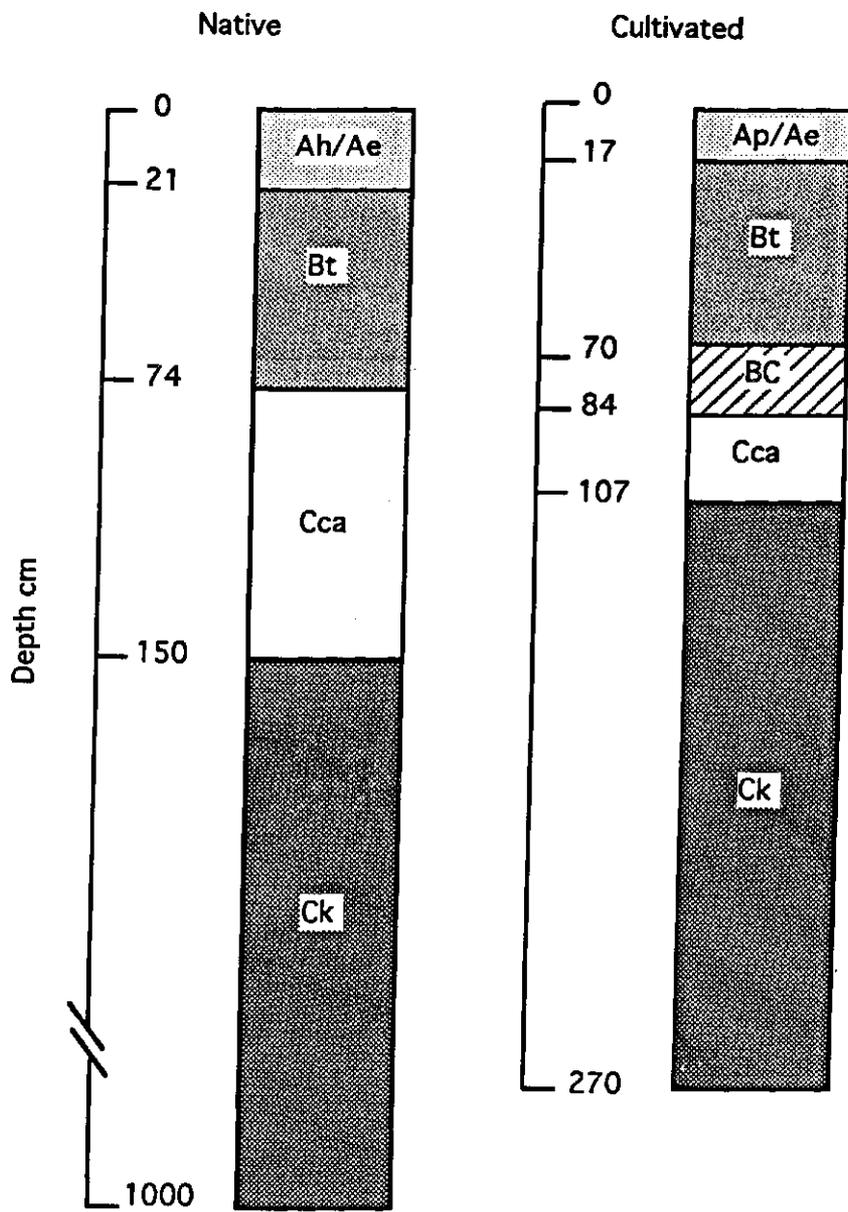


Figure 3.6 Spiritwood profile horizon designations and depths.

fertilizer has only been added to the field in the past 10 years. The soil from the alfalfa field had a 10 cm Ap, 7 cm Ae, and 53 cm Bt horizon also underlain by a calcareous C horizon. The topography was characterized as gently undulating unpatterned, with moderate stoniness and some boulders (Figure 3.7).

3.3 Landscape Comparison

At the Swift Current site the topography between the knoll and the depression consisted of a concave midslope about 50 m in length from knoll to depression and about 30 m across the top of the hill crest. Thus only one hillslope contributed to runoff into the catchment basin making up approximately 1500 m².

The Aberdeen site had two separate catchment basins which were sampled. The first catchment basin consisted of a large bowl-like landform, working much like a funnel. All the topography sloped steeply into this depression allowing runoff to be contributed from all sides. The catchment area was approximately 2500 m². The second catchment basin was much smaller (about 1000 m²), with only one hillslope of shallow grade contributing to runoff.

The topography at the Spiritwood location was made up of a fairly flat upland position with the two soil sampling sites being only a few meters apart.

3.4 Sampling Procedure

Three 10-cm diameter soil cores (one each for observation, root sieving, physical and chemical analysis) were taken from each sampling site to a depth of between 2 and 10 m with a hydraulic punch. Examining three different cores at each site provided the replication needed to observe visual consistency of profile development and texture to insure the cores were representative of the local area. Two sites were sampled at Swift Current and Spiritwood and three sites were used at Aberdeen (total of 7 sampling sites at three locations). Where the 10-cm coring bit



Figure 3.7 Photographs of the soil sampling sites at the Spiritwood location.

could not go deep enough, a smaller 4-cm diameter core was used. Three meters was the desired sampling depth for each soil core, but this could not always be achieved due to rocks or other obstructions, despite efforts to move around them. At the Spiritwood native wooded site a drilling auger was used to remove soil incrementally from 3 m down to a depth of 10 m.

Soil cores were kept intact from the field to the lab by storing them in PVC (poly vinyl chloride) pipe which was equal in diameter to the soil core taken. The pipe had been cut to make two half cylinders which were then wrapped around the soil core, sealed with tape, and transported with minimal soil disturbance.

Each soil core was sectioned according to genetic horizon, and some horizons were further subdivided to provide greater resolution when interpreting chemical analysis and pedogenic processes. Sectioning and measuring the cores was done in the lab with one half of the PVC pipe removed, exposing half of the core for observation and description. This allowed for accurate volume measurements and horizon separations to be made on the intact soil core. Soils from each horizon section were air dried and the entire sample (including stones) weighed to calculate bulk density. Soils were then crushed by wooden roller pin to pass a 2 mm sieve, then subsampled and finely ground with a mortar and pestle to pass a 100 mesh sieve for detailed chemical analysis.

3.5 Particle Size Analysis

Subsamples of all soils were analyzed to determine the distribution of sizes of the primary particles by the pipette method (McKeague, 1976) to describe soil horizons by texture and establish parent material uniformity. Pretreatment with acid and hydrogen peroxide removed carbonates and organic matter respectively. Sand and coarse silt fractions were determined using a series of fine sieves and divided into 5 fractions: very coarse sand (2-1 mm), coarse sand (>0.5 mm), medium sand (>0.25

mm), fine sand (>0.105 mm), very fine sand (>0.047 mm). After sand was removed, silt and clay were determined by rates of settling in water (25°C) by measuring the dry weight of material removed in 20 mL of water at 2 minutes (min.) and then at 7 hours (hr) after the silt and clay slurry was stirred. Particle size fractions were calculated as percent by weight.

3.6 Carbon Analysis

Total carbon in soils was determined by dry combustion (Tiessen et al., 1981). Soil samples were heated to 900 °C in a standard tube furnace and the CO₂ evolved was dissolved in a NaOH trap. The solution was then titrated with 0.1 M HCl from pH 8.3 down to pH 3.7. The amount of 0.1 M HCl used is a direct measure of carbonic acid present, since one mole of H⁺ is used by the system for each mole of CO₂.

Inorganic carbon was determined by acid digestion and two-endpoint titration (Tiessen et al., 1983). In this method soil samples are digested with 5 M HCl under a stream of nitrogen gas, the evolved CO₂ is captured in a NaOH trap, and titrated directly as carbonic acid as was done for total carbon described above.

3.7 Phosphorus Fractionation

To follow the interactions of various portions of the soil P cycle, Hedley et al. (1982) developed a sequential extraction procedure that characterizes inorganic and organic P forms in terms of their extractability in specific reagents, and related these fractions to their bioavailability, or lability (Tiessen and Stewart, 1983). A modified version of this procedure, used in this study to fractionate P, is described in detail in section 3.7.1 and illustrated in Figure 3.8. This procedure allows soil P to be separated and characterized as P released to an anion exchange resin, and P soluble in alkali and acid of varying strengths (Hedley et al., 1982).

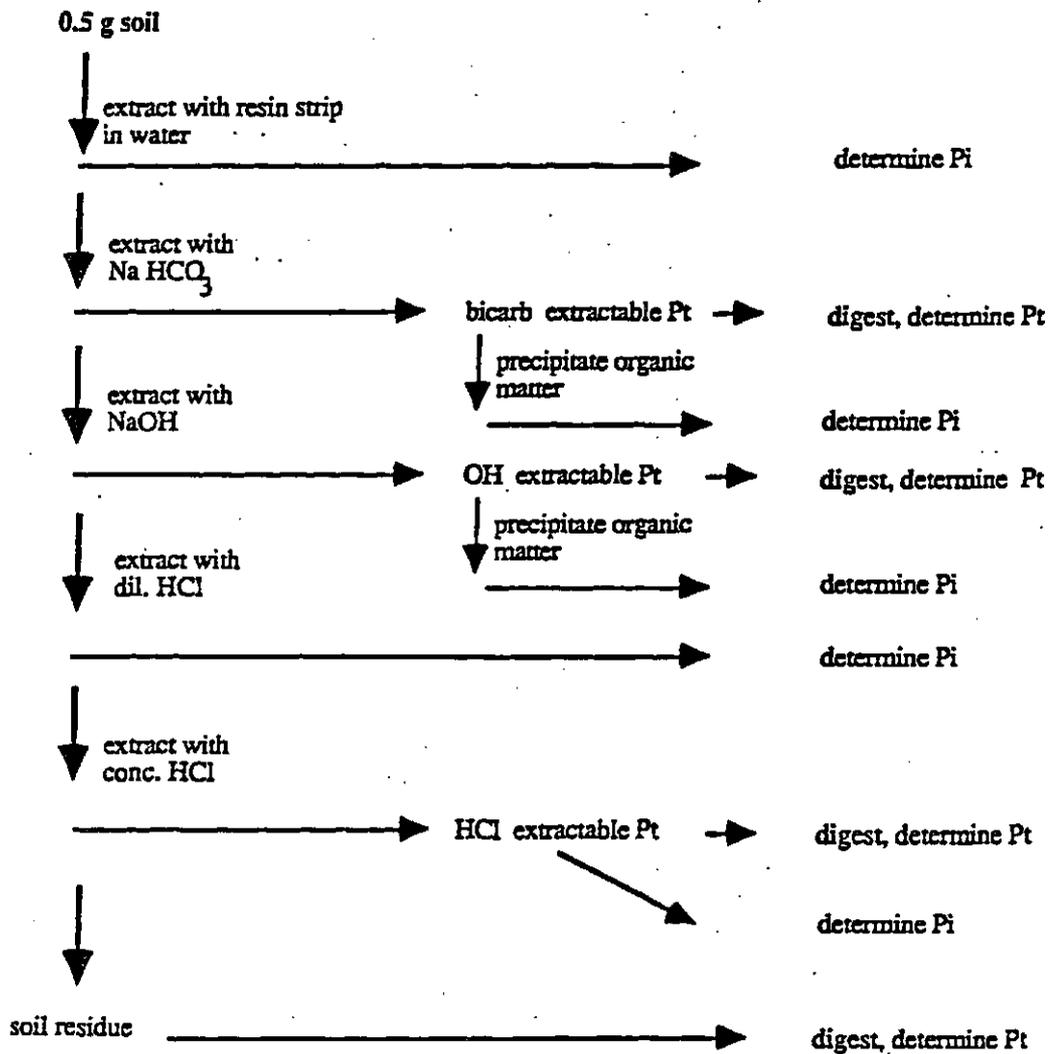


Figure 3.8 Flow chart of the sequential P extraction (Source: Tiessen and Moir, 1993).

An anion exchange resin is used first to extract inorganic P which is directly exchangeable with soil solution and thus is regarded to be of high biological availability (Bowman et al., 1978). The residue after resin extraction is then followed by an extraction with NaHCO_3 which removes labile Po and Pi weakly sorbed to soil colloids (Bowman and Cole, 1978a). Then NaOH is added to the soil material remaining after bicarbonate extraction to extract the more resistant Po associated with humic compounds and Pi held more strongly by chemisorption to Fe and Al components of soil surfaces (Bowman and Cole, 1978b). The NaOH extract is followed by a 1M HCl extraction to remove the more stable P (primary minerals) associated with Ca, which is mostly apatite (Williams et al., 1980). The residue of this extract, believed to be composed primarily of highly resistant (occluded) Po and Pi of very low bioavailability, makes up between 20 and 60% of the total P (Tiessen and Moir, 1993). Then a modification to the original Hedley method was included wherein a hot concentrated HCl extraction of the residue was made (Metha et al., 1954). This extract is useful for distinguishing Pi and Po in very stable residual pools (Tiessen and Moir, 1993) as well as for extracting P held in unstable particulate organic debris which may contribute to rapid mineralization of P by soil flora and fauna (Magid et al., 1993). Finally the remaining soil residue is subjected to a complete digestion using H_2O_2 and concentrated H_2SO_4 , to extract any remaining residual P.

At the end of the procedure nine separate fractions of P are quantified by determining total P (Pt) and Pi , and subtracting Pi from Pt to obtain Po (Figure 8, from Tiessen and Moir, 1993). These fractions, referred to by their extractant, form, and in order of bioavailability from most available to unavailable are: resin Pi , bicarb Pi and Po , OH Pi and Po , 1M HCl Pi , hot conc. HCl Pi and Po , and residual Pi .

3.7.1 Phosphorus Fractionation Procedure

Phosphates with differing degrees of lability were sequentially extracted by a Modified Hedley Phosphorus Fractionation method (Tiessen et al., 1993). All samples were analyzed in duplicate and the sum of all fractions (total P) was compared to total P as determined by an autoanalyzer. The total P as determined by fractionation was within 10% of the values determined by the autoanalyzer. Comparing the fractionation sum to the autoanalyzer provided confidence in the values obtained in the fractionation procedure. The procedure is outlined below in chronological order (Notes are described at end of Day 6):

Day 1

Weigh 0.5 g soil into a 50 mL centrifuge tube, add 2 resin strips (Note A), 30 mL distilled/deionized water, and shake (on end over end shaker) overnight (16 hr).

Day 2

Remove resin strips and wash soil back into tube. Place resin strip in a clean 50 mL tube, add 20 ml 0.5 M HCl (Note D), and cap loosely. Set aside for 1 hr to allow gas to escape (if strips in sodium bicarbonate form), cap tightly and shake overnight. Determine P using the method described by Murphy and Riley (1962) (Note B).

Centrifuge soil suspension at 10,000 rpm for 10 min. at 0°C. Decant water through millipore filter (pore size 0.45 µm). Discard water and wash any soil off filter back into the tube with a little 0.5 M NaHCO₃ (pH 8.5) solution (Note D). Make volume of NaHCO₃ (bicarb) solution to 30 mL (done by weight) and shake overnight. Making sure all soil is free from bottom of tube before putting on the shaker.

Day 3

Centrifuge soil suspension at 10,000 rpm for 10 minutes at 0°C. Decant bicarb extract through a millipore filter into a clean vial. Determine inorganic and total P in bicarb extract (Note C). Wash any soil off filter back into the tube with a little 0.1 M NaOH (Note D). Make volume of NaOH solution to 30 ml and shake suspension overnight.

Day 4

Centrifuge soil suspension at 10,000 rpm for 10 min. at 0°C. Decant NaOH extract through a millipore filter into a clean vial. Determine inorganic and total P in NaOH extract (Note C). Wash any soil off filter back into the tube with a little 1 M HCl (Note D). Make volume of HCl solution to 30 mL and shake suspension overnight.

Day 5

i) Centrifuge soil suspension at 10,000 rpm for 10 min at 0°C. Decant HCl extract through a millipore filter into a clean vial. Determine P in HCl extract (Note B). In this step any residue on the filter paper is not washed back into the tube, and decant gently not to lose soil.

ii) Soil residue is heated with 10 mL conc. HCl in a waterbath at ~82°C for 10 min (Vortex to mix soil and HCl well, and loosen caps before putting into the hot bath. The mixture will take about 10 min to come to temperature- check with a thermometer in a tube containing HCl only- i.e. the tube will be in the hot water bath for a total of 20 min). Remove and add a further 5 mL conc. HCl, vortex and allow to stand at room temperature for 1 hr (vortex every 15 min). Tighten caps, centrifuge at 10,000 rpm for 10 min at 0°C and decant supernatant into a 50 mL volumetric flask. Wash soil with 15 mL and 10 mL deionized water, mixing, centrifuging and adding the supernatants to the 50 mL volumetric flasks after each addition. Make to volume, filter if necessary through a No. 40 paper (i.e. soil in solution) and determine inorganic and total P in HCl solution (Note B and C, respectively).

Day 6

Add 10 mL deionized water to soil residue and disperse soil. Suction suspension into 75 mL digestion tube (use the minimum amount of water possible to transfer all the soil residue), add 5 mL conc. H₂SO₄ + 1 boiling chip, vortex and put on a cold digestion block. Raise the temperature very slowly to evaporate water and when 360°C is reached start treating with H₂O₂ (Note D). Continue digestion until liquid is clear

(needs 10 additions of 0.5 M H₂O₂). Cool, make to volume, shake and transfer to vials (either filter or allow residue to settle overnight). Determine P in solution (Note B).

(Digestion procedure, see Thomas et al., 1967)

Notes

A. The type of resin strip used and recycling procedure. Use BDH anion exchange membrane (Prod. 55164) cut into strips (9 x 62.5 mm), in the chloride form for acid soils or bicarbonate form for alkaline soils. (To regenerate, wash resin strips for 3 days with 6 batches of 0.5 N HCl, and finally rinse well (10 times) with deionized water, or continue by washing a further 3 days with 6 batches of 0.5 M NaHCO₃ (pH 8.5), and then rinse well with deionized water).

B. The Murphy and Riley color development solution, its use, and preparation. Pipette suitable aliquot into a 50 mL volumetric flask, adjust pH with 4 M NaOH and ~0.5 N H₂SO₄ using paranitrophenol as an indicator. Add 8 mL of color developing solution, make to volume, shake and read on spectrophotometer at 712 nm after 10 min (color stable for 24 hr).

Solutions for developing reagent:

- 40 g ammonium molybdate/L
- 26.4 g l-ascorbic acid/500 mL
- 1.454 antimony potassium tartrate/500 mL
- 278 mL conc. H₂SO₄/2 L = 5 N H₂SO₄

Developing reagent: To 250 mL 5 N H₂SO₄, add 75 mL ammonium molybdate solution, then 50 mL ascorbate solution and finally 25 mL of antimony potassium

tartrate solution (add chemicals in above order, swirling contents after each addition).

Dilute to a volume of 500 mL and mix.

C. Determination of inorganic P on 0.5 M NaHCO₃, 0.1 N NaOH (hot HCl already below pH 1.5, go to step 6 immediately, pipette into 50 mL volumetric flask)

1. Pipette 10 mL solution into a 50 mL centrifuge tube.
2. Acidify to pH 1.5 and set in fridge for 30 min:
0.5 M NaHCO₃- use 6 mL of 1.8 N H₂SO₄
0.1 N NaOH- use 1.6 mL of 1.8 N H₂SO₄
3. Centrifuge at 10,000 rpm for 10 min at 0°C.
4. Decant supernatant into 50 mL volumetric flask.
5. Rinse tube carefully, so as not to disturb the organic matter, with a little acidified water and add to the solution in the flask (2 or 3 times).
6. Adjust pH and develop as M & R (Note B).

Determination of total P on 0.5 M NaHCO₃, 0.1 N NaOH and hot conc. HCl extracts.

1. Pipette 5 mL solution into a 50 mL volumetric flask.
2. Remove organic matter from solution:
0.5 M NaHCO₃- add 0.6 g ammonium persulfate + 1 mL 11 N H₂SO₄
0.1 N NaOH- add 1.2 g ammonium persulfate + 1 mL 11 N H₂SO₄
hot conc.HCl- add 0.6 g ammonium persulfate + 1 mL 11 N H₂SO₄ +
5 mL deionized water
3. Gently boil solution on hot plate, to evaporate water, until "white wisps" of smoke can be seen in the bowl of the flasks (~ 0.3 mL of solution should be left), being careful not to char sample.
4. Allow to cool, add about 20 mL of deionized water and adjust pH and develop M & R (Note B).

D. Solutions.

0.5 N HCl	:	88.5 mL conc. HCl/2 L deionized water
0.5 M NaHCO ₃	:	84 g NaHCO ₃ + 1 g NaOH/2 L deionized water
0.1 N NaOH	:	4 g NaOH/L deionized water
4 N NaOH	:	160 g NaOH/L deionized water
1 M HCl	:	177 ml conc. HCl/2 L deionized water
conc. HCl	:	11.3 N
H ₂ O ₂	:	30% hydrogen peroxide
5 N H ₂ SO ₄	:	278 mL conc. H ₂ SO ₄ /2 L deionized water
1.8 N H ₂ SO ₄	:	100 mL conc. H ₂ SO ₄ /2 L deionized water
0.5 N H ₂ SO ₄	:	100 mL 5 N H ₂ SO ₄ /L deionized water
11 N H ₂ SO ₄	:	306 ml conc. H ₂ SO ₄ /L deionized water

3.8 Pedogenic Indexing

Pedogenic indexing is a method of establishing the uniformity of a parent material deposit. This same method can be used to estimate long term gains and losses in soil P. Since Qu, Zr, and non-carbonate sand plus silt remain relatively unchanged over pedogenesis their content in a given horizon can be used as a reference index against which other less resistant soil constituents can be compared. The premise is that if Zr and P content were uniform throughout the profile at the beginning of soil formation and Zr content hasn't changed, then the change in P content in a horizon can be seen as a net gain or loss relative to the amount of Zr. The formula used to calculate these gains and losses is:

$$\% \text{ gain or loss} = \frac{(\text{weight P in horizon})/(\text{weight Zr in horizon})}{(\text{weight P in C horizon})/(\text{weight Zr in C horizon})} \times 100 \quad (1)$$

The values derived from this equation can be used as a mass-balance evaluation of changes in soil P which have occurred as the result of pedogenesis (St. Arnaud et al., 1988). A value of 80 would indicate 80% of the original P remains in the horizon and 20% has been lost. Several researchers have used this method to determine the net loss of P from the solum of Saskatchewan soils (St. Arnaud et al., 1988, Frossard et al., 1989, Xiao et al., 1991).

The constancy of the ratio of non-carbonate sand plus silt to total zirconium (Zr) or total quartz (Qu) with depth can be used as evidence that soils were developed on a uniform (or randomly variable) deposit.

3.8.1. Total Zr Analysis

1. 100 mg of finely ground soil (100 mesh) was fused with 1 g of lithium metaborate at 1000 °C for 1 hour in a carbon crucible.

2. The fused soil sample was ground by mortar and pestle and then made up to 100 mL of water.

3. The suspension was then analyzed for Zr using ICP (inductively coupled plasma).

3.9 Root Distribution

The distribution of roots with soil depth was determined on a dry weight basis. Roots were sieved out of soil horizons using a 2 mm wire mesh screen and running water. The roots were air dried and weighed, and distributions presented as the percent of total root weight found in each soil horizon.

3.10 Other Chemical Characterization

Soil pH was determined on a 1:1 paste of soil to 0.01M CaCl₂ (McKeague, 1976).

Total nitrogen and phosphate were determined by Autoanalyzer on a wet digest using sulfuric acid and hydrogen peroxide (Thomas et al., 1967). The total P by digestion was compared to the sum of all fractions determined by the Hedley sequential extraction and the total P values were found to be within 5% of each other, confirming the accuracy of our P analysis.

4. RESULTS AND DISCUSSION

4.1 Profile Uniformity

One of the objectives of this study was to quantify the changes in form and distribution of soil P that have occurred as the result of soil development. Few such studies have been undertaken because it is difficult to find soils that occur on deposits uniform enough to allow such evaluations and to establish the original uniformity of the deposit (Santos et al., 1986). Methods developed for determining the nature and amount of minerals present in soil deposits have facilitated the differentiation of parent materials and the evaluation of the nature and intensity of mineral weathering which brings about the changes in form and distribution of mineral elements such as P. However, evaluations of weathering using mineral distribution in soil profiles are often misleading unless the parent material in which the soil was formed was originally of a uniform deposit (St. Arnaud and Sudom, 1981).

It was desirable to find a pattern similar to that seen in the Sudom and St. Arnaud (1971) study in the soils sampled for this present study: consistent particle size distribution in the bottom of the B horizon and in all C horizons of each soil profile (refer to Literature Review section 2.2.2.).

At the Aberdeen location the Knoll soil profile can be seen to have a consistent distribution of particle sizes with depth suggesting a uniform parent material is present (Figure 4.1). In the Aberdeen Depression (2) and Depression (3) soil profiles there was a high degree of variability in particle size distribution in the A and B horizons (Figure 4.2 and Figure 4.3). This was the result of greater weathering intensity and greater clay translocation in the Depression profiles which showed deeper horizon development as compared to the Knoll. The particle size distribution in the bottom six

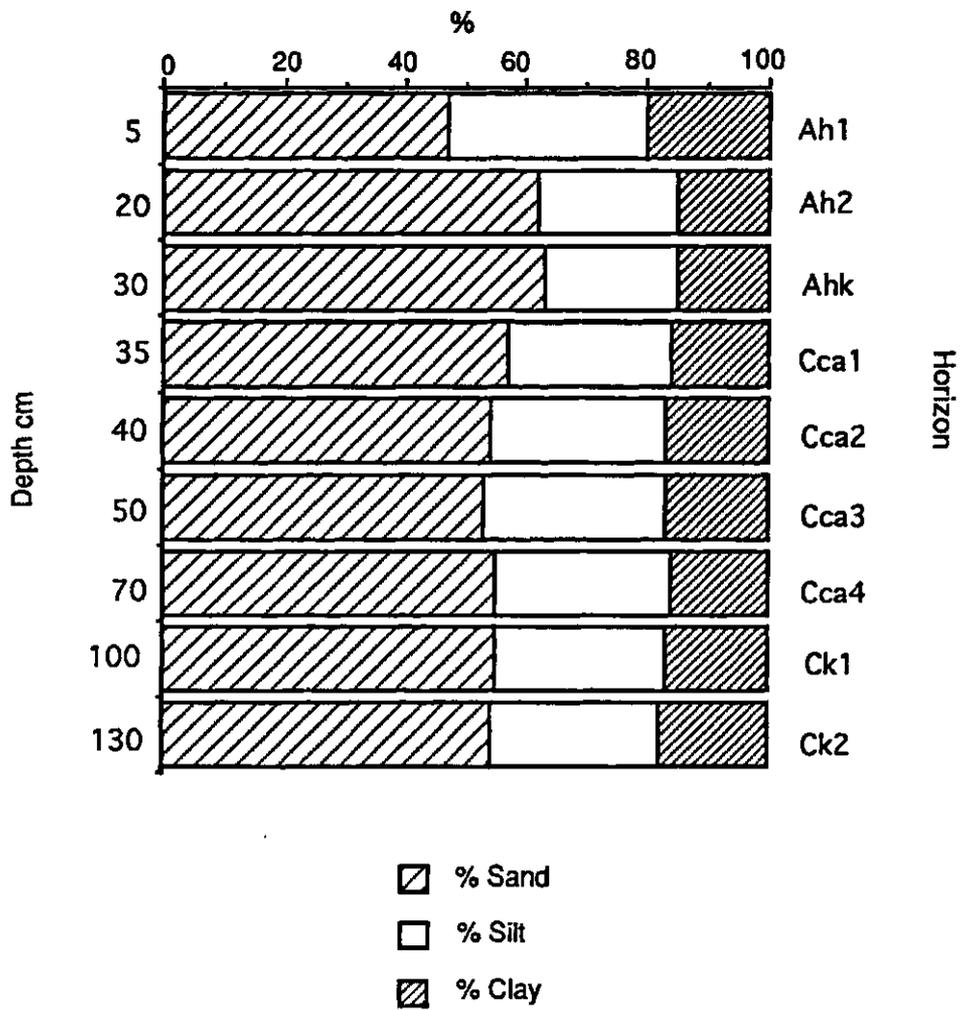


Figure 4.1. Particle size distribution for Aberdeen Knoll site.

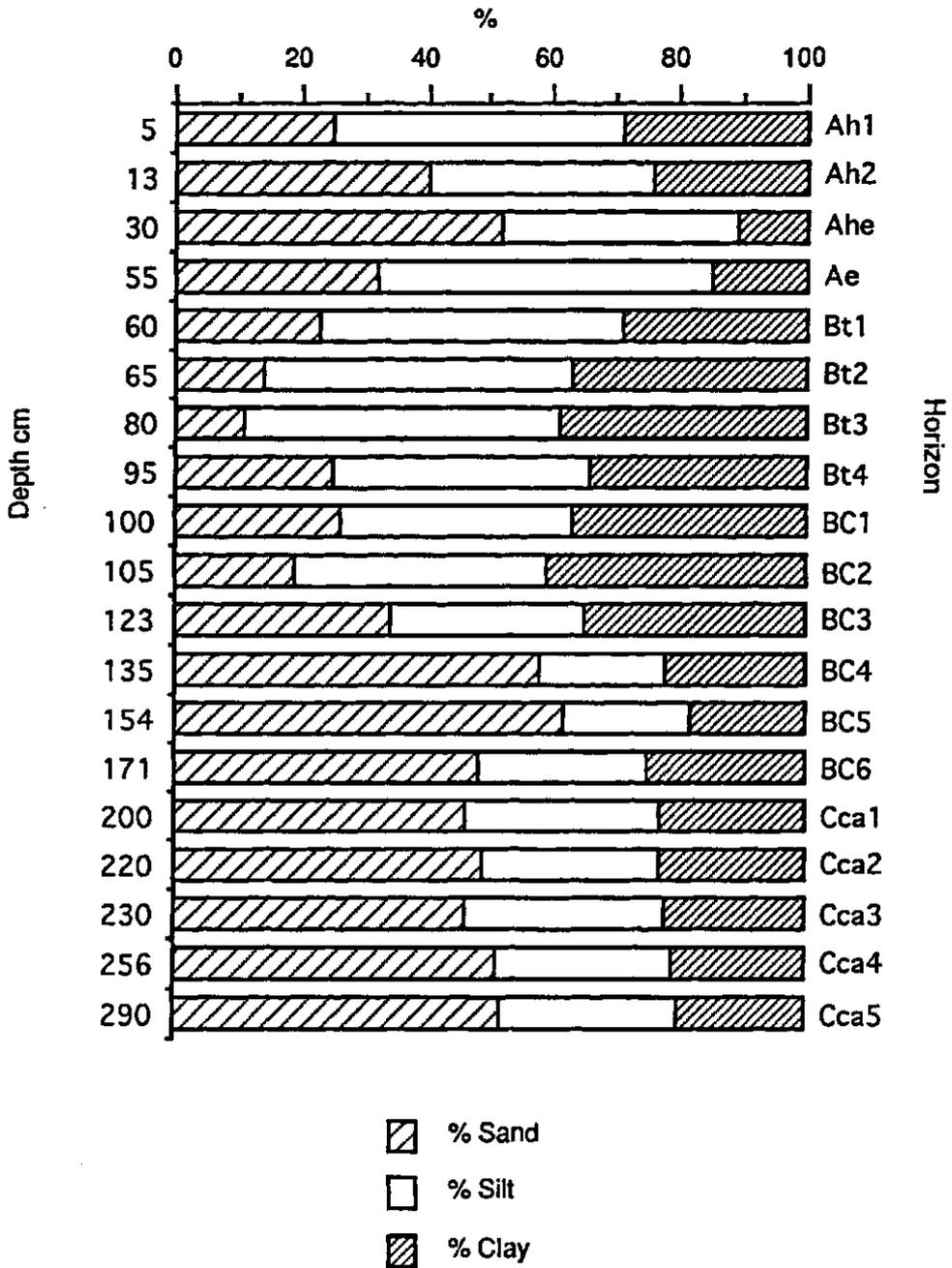


Figure 4.2. Particle size distribution of Aberdeen Depression (2).

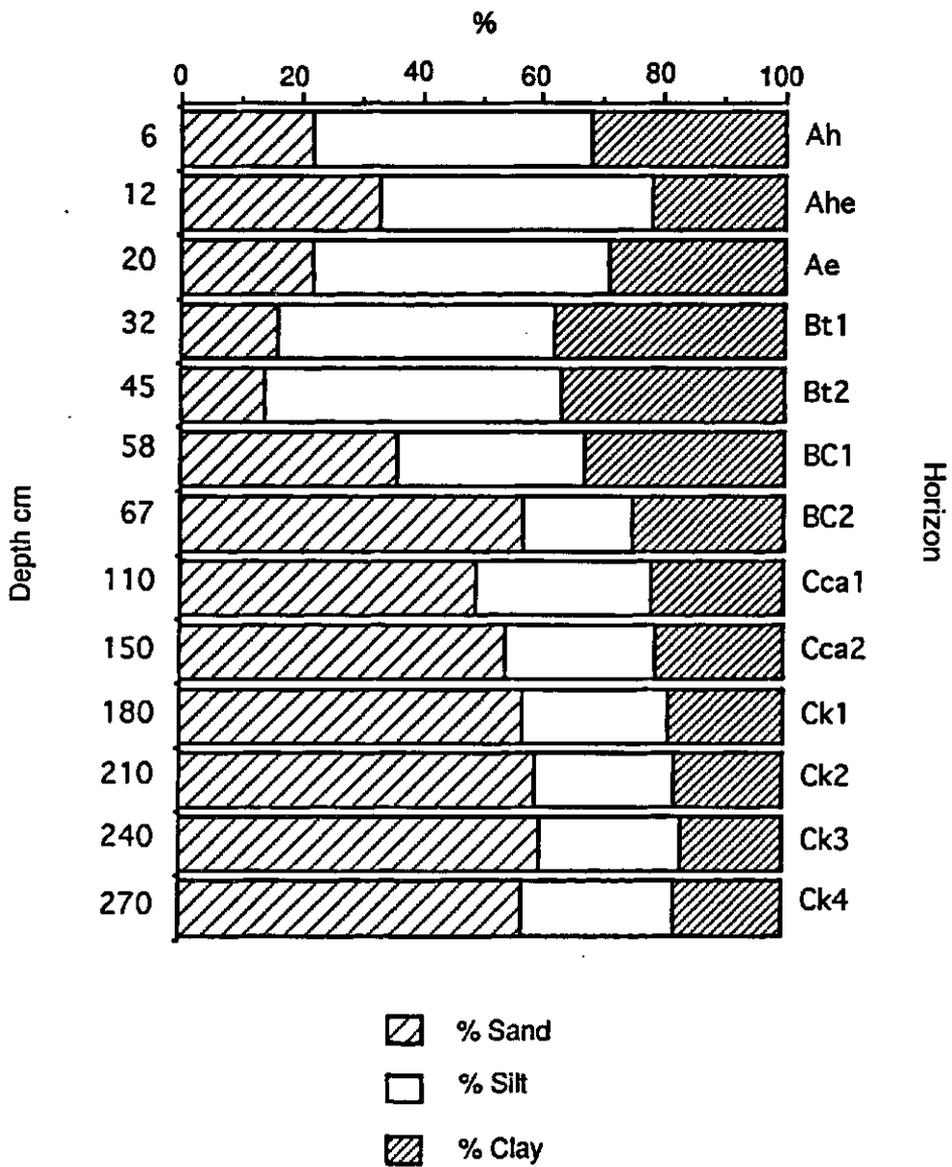


Figure 4.3 Particle size distribution of Aberdeen Depression (3) site.

C horizons of both Depression horizons remained constant with depth indicating that the Aberdeen soil has been developed on a uniform deposit of parent material.

Considering the uniformity of particle size distribution in the Knoll profile, and in the C horizons of the depression profiles, it is likely much of the variability seen in the particle size distribution in the upper solum of the depression soil profiles is the result of soil formation processes. These processes may include the erosion of soil from the mid-slopes, and consequently the sorting of particle sizes in the surface soil horizons of the depression soil profiles. The variability of particle sizes in the depressions is then considered the natural result of soil formation and does not detract from the interpretation of P redistribution.

At the Swift Current location the knoll soil profile appeared to contain a uniform parent material as seen Figure 4.4 which shows a consistent particle size distribution with soil depth. The Swift Current Depression showed little variation in particle size distribution down to the Bt4 horizon (Figure 4.5). A sudden increase in sand content in the Bt5 and Cca1 horizons suggests that some variability in the deposit exists. In the bottom two horizons (Cca2 and Ck) the particle size distribution seems to return to about the same composition as was found in the surface horizons, with sand content being slightly higher and silt being slightly lower. Because the variability of the particle size distribution in the Swift Current soil is relatively small (when compared to Site 1, stratified, of Sudom and St. Arnaud shown in Figure 2.1 of the Literature Review) it was assumed that there was no significant stratification in the parent material, and that the degree of variability which exists is not enough to effect the P redistribution pattern.

Figure 4.6 shows the textural composition of the Spiritwood Native soil profile. In the A and upper B horizon of the Spiritwood soil there was a higher percentage of silt than the underlying horizons. The greater silt content can be explained as the result of weathering processes causing the physical breakdown of sand to silt in this Luvisolic profile (St. Arnaud, 1976). The lower B and all C horizons show a very consistent

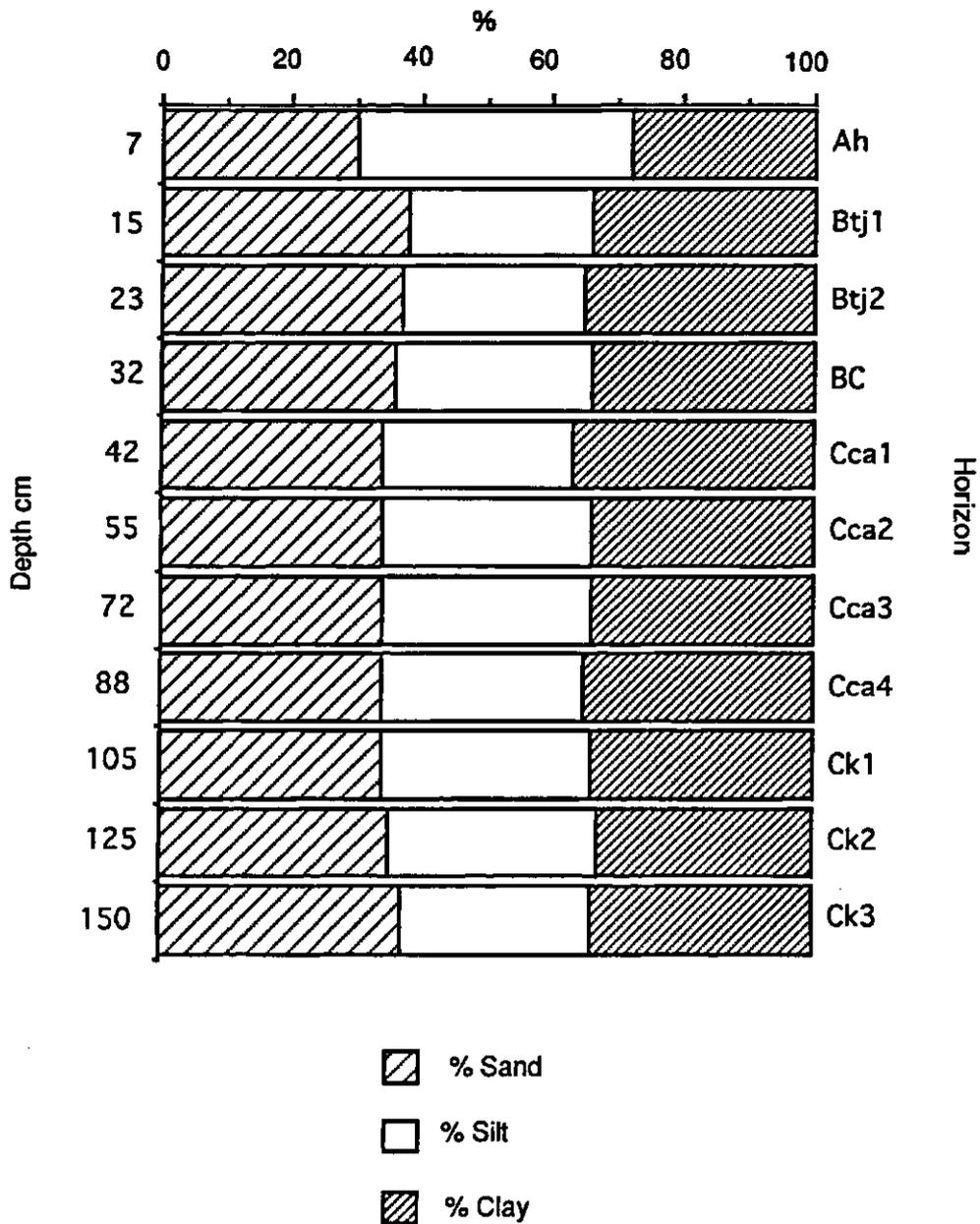


Figure 4.4 Particle size distribution of Swift Current Upland site.

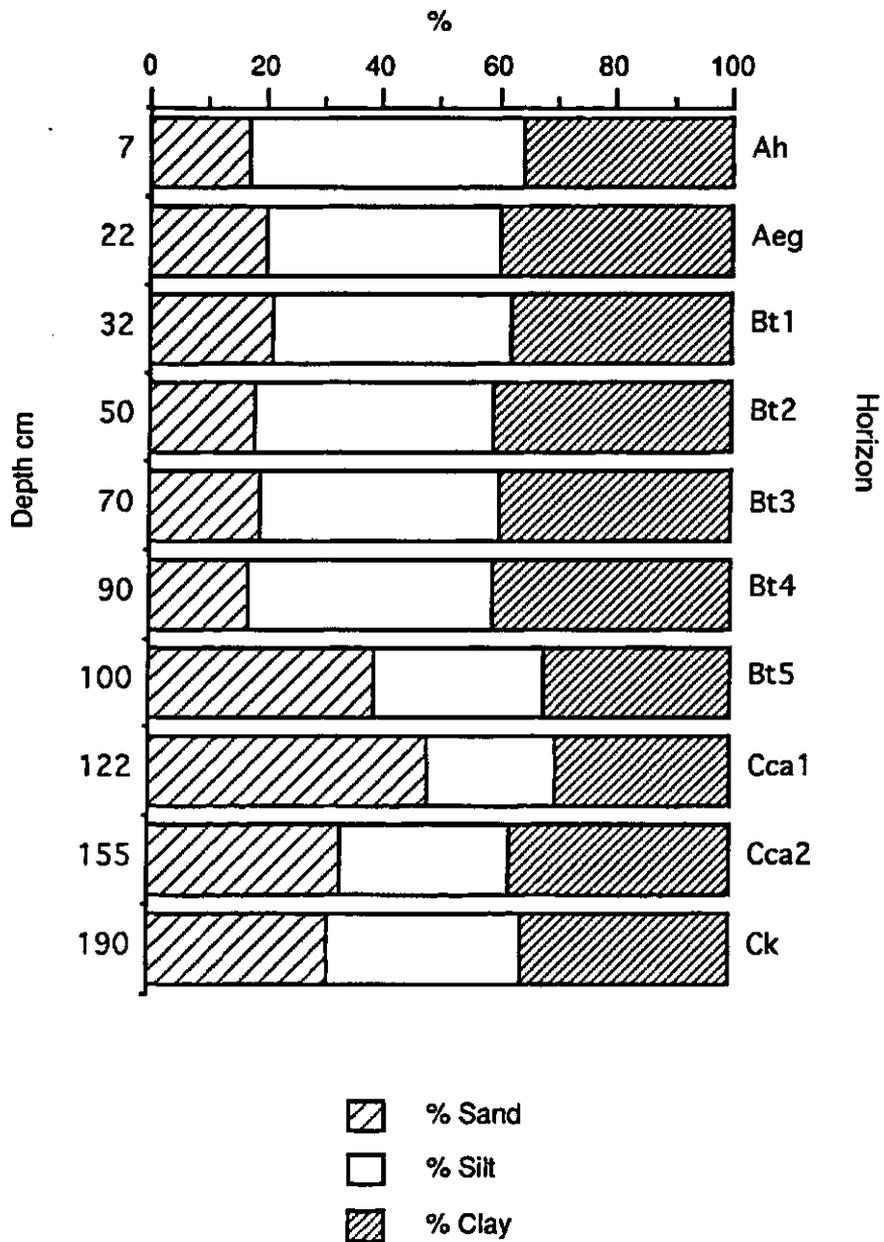


Figure 4.5. Particle size distribution for Swift Current Depression.

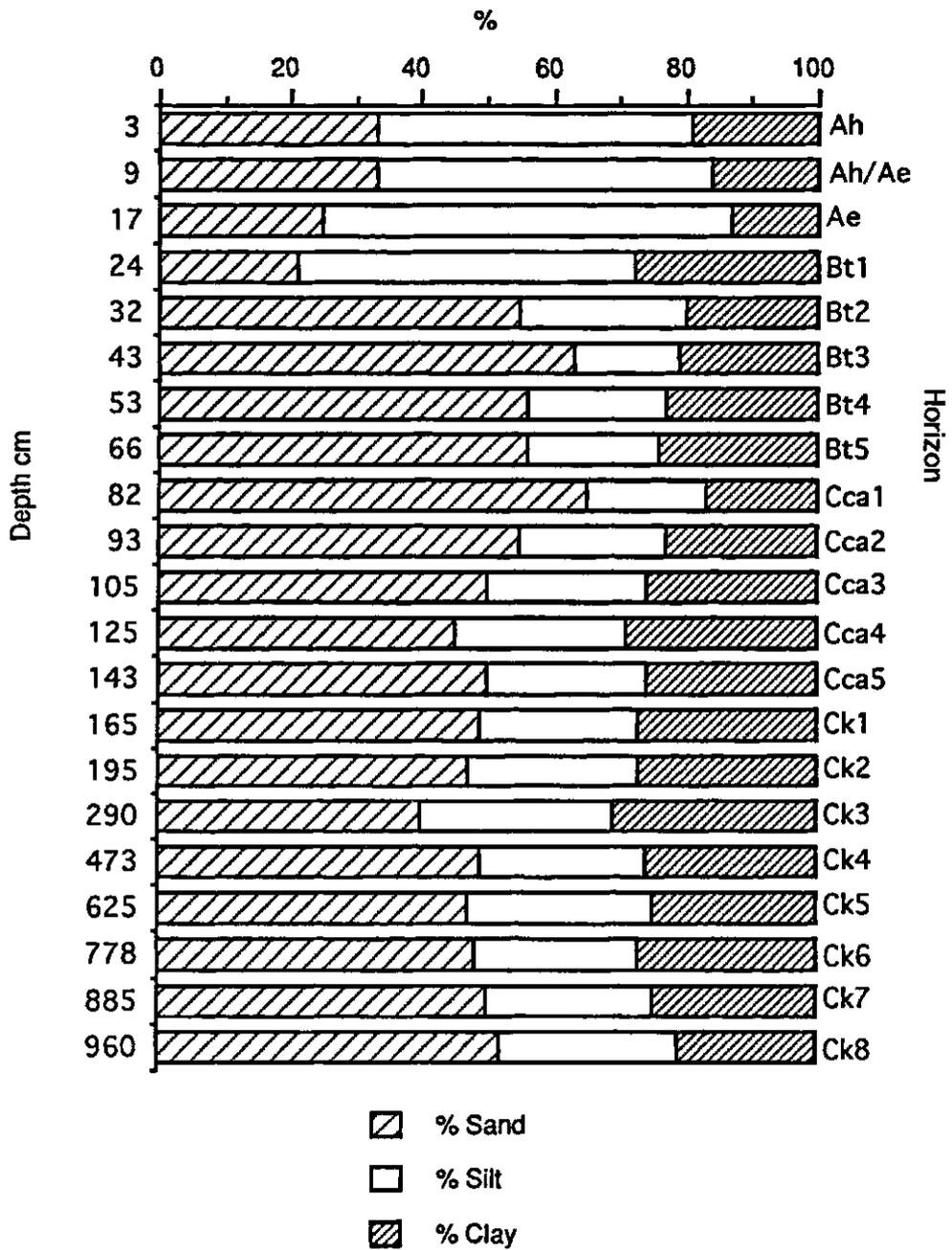


Figure 4.6. Particle size distribution for Spiritwood Native site.

particle size distribution indicating that the profile is of a uniform parent material deposit. The Spiritwood Cultivated soil profile demonstrated a greater degree of variability (Figure 4.7). Some of this variability is attributed to soil disturbance which occurred during the time the land was cleared and also as the result of continual disturbance related to agricultural practices. Since the C horizon shows a consistent particle size distribution it was determined that a uniform deposit of glacial till was originally present.

Further verification of parent material uniformity can be obtained by the relative proportion of highly resistant minerals (pedogenic indexing) in relation to soil depth. The ratio of ZrO_2 to non-carbonate sand plus silt was determined and plotted with soil depth following the procedure of Santos et al. (1986). The ratio of ZrO_2 to non-carbonate sand plus silt (on a weight basis) consistently ranged from between 2×10^3 and 4×10^3 which indicates that fairly uniform variability existed at all three locations and that no stratification was apparent (Figure 4.8). Thus, it was concluded that the parent material deposits of soils sampled were suitable for the purpose of relating P distribution patterns with soil depth to soil forming processes.

4.2 Profile Descriptions

As stated earlier the soil profiles used in this study were selected within the Province along an environmental gradient and within the landscape at the top and bottom slope positions. One example was also taken under native as well as disturbed conditions. The physical and chemical properties of the soil profiles (Tables 4.1, 4.2 and 4.3) indicated that the intensity of weathering processes changed significantly with topography and only marginally between soil zones. The depression (2) profile from Aberdeen was clearly the most strongly developed profile of the seven used in this study, while the Aberdeen Knoll profile was the least developed. Since these profiles represented the extreme conditions of soil formation and were also situated in the center

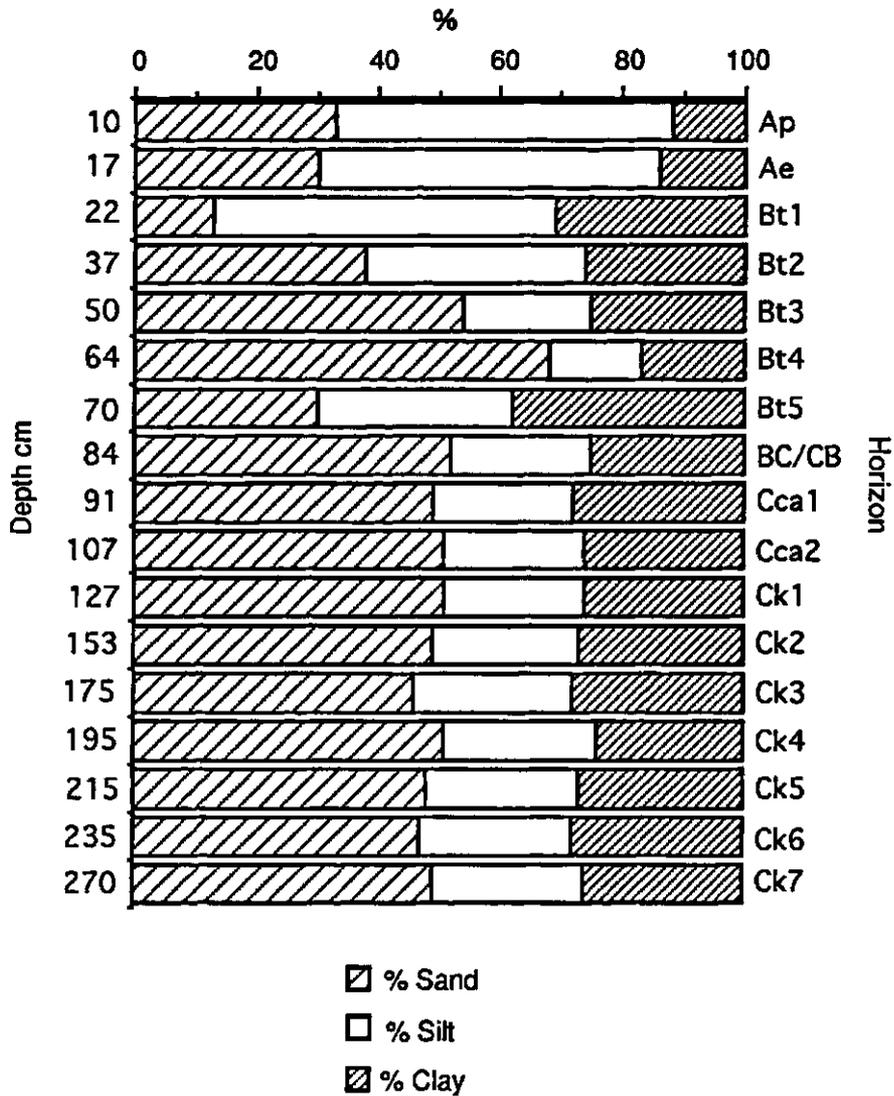


Figure 4.7 Particle size distribution of Spiritwood Cultivated site.

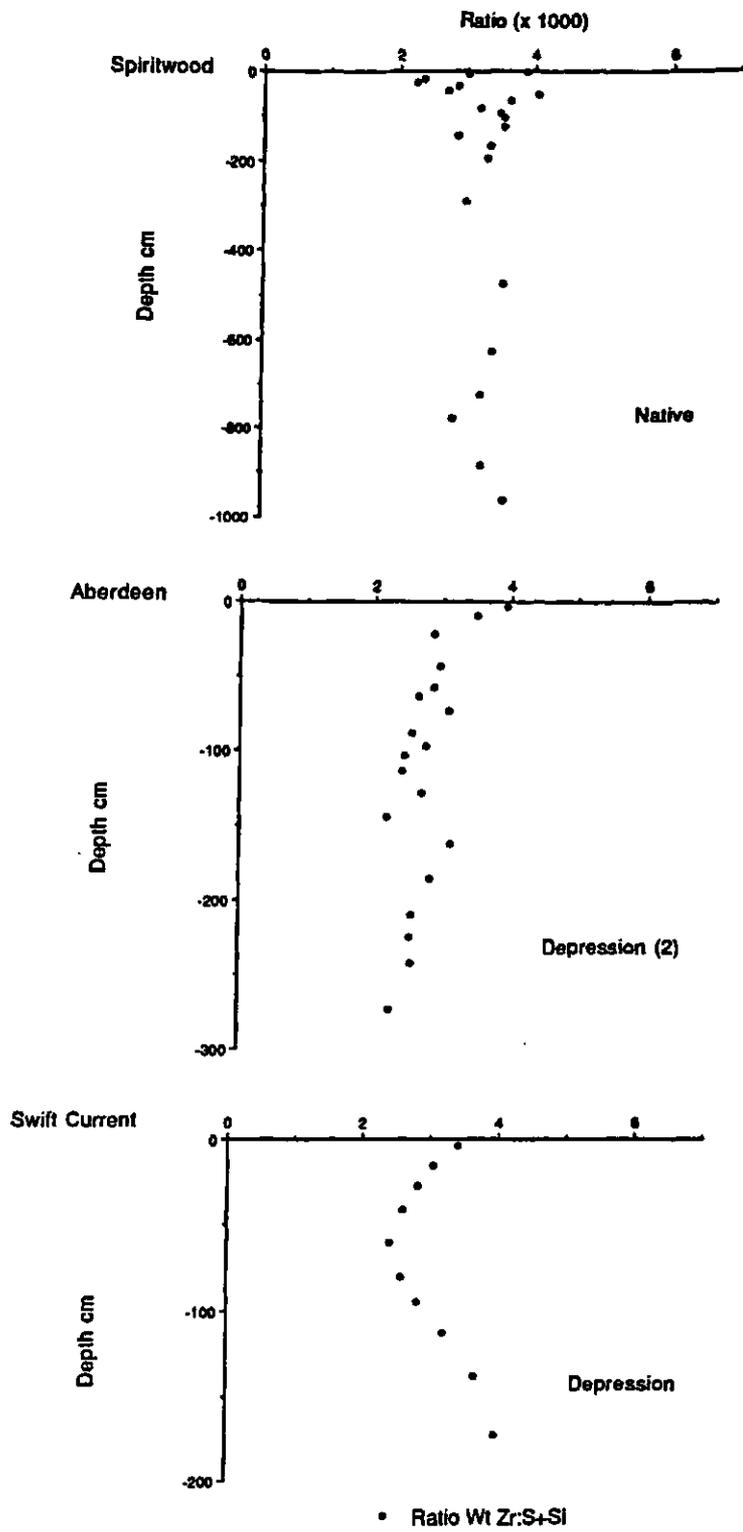


Figure 4.8 The ratio of ZrO_2 :non-carbonate sand plus silt in soil profiles as a determination of parent material uniformity.

of the three locations making up the environmental gradient, the Aberdeen site was described first and the southern and northern sites were discussed in comparison to it.

4.2.1 Aberdeen Sites

The Aberdeen Depression (2) profile was deep with well defined and thick Ah, Ae, Bt, and Cca horizons (Table 4.1). The development seen in the horizons of this soil serves as evidence of the pedogenic processes which have created the present profile. The Ae horizon was 25 cm thick, and showed the gray color of a strongly leached eluvial horizon (Figure 3.4). The clay content of the Bt horizon (Bt1 through Bt5) was much higher than that of the Ae horizon, indicating that clay has translocated from the Ae into the Bt as the result of leaching (Figure 4.2). The absence of CaCO_3 in the A and B horizons and the large accumulation of carbonates in the C horizon confirms the strong leaching regime in this soil. All these characteristics indicate that this depression has collected large quantities of water which have leached through this profile and have provided the driving force of soil formation.

Depression (3) was sampled to a depth of 270 cm and did not exhibit the same degree of soil formation as Depression (2). This profile was well developed containing very distinct soil horizons, but the decreased horizon thickness as compared to Depression (2) suggests less water has leached through this profile. Although both depression profiles experience the same annual precipitation, the amount of water which enters the soil system is much different due to differences in the slope length, slope gradient, and basin size which make up the topography around the depressions. Depression (2) had a steeper gradient and consisted of a larger catchment basin than depression (3) which was made up of a shallow gradient and smaller catchment basin. Thus, the size of the area around the depression contributing to runoff influences the amount of water which will leach through a depression profile. This also suggests that

Table 4.1 Aberdeen soil profile descriptions and selected characteristics.

	Depth cm	Horizon	Bulk density Mg/m ³	Inorg. C g/kg	Org. C g/kg	pH (CaCl ₂)	Roots g/horizon	Roots % total
Aberdeen								
Knoll	0-5	Ah1	0.93	0.8	45.3	6.6	4.5104	47.0
	5-20	Ah2	1.25	5.5	33.3	7.1	2.5119	26.0
	20-30	Ahk	1.25	21.9	19.7	7.5	0.8980	9.3
	30-35	Cca1	1.36	30.8	9.4	7.6	0.2795	2.9
	35-40	Cca2	1.36	30.2	5.5	7.7	0.3279	3.4
	40-50	Cca3	1.36	29.2	3.7	7.9	0.5159	5.4
	50-70	Cca4	1.70	25.4	4.5	8.2	0.4842	5.0
	70-100	Ck1	1.70	21.6	4.3	8.3	0.1035	1.1
	100-130	Ck2	1.70	21.6	2.9	8.1	0.0047	0.1
Depression (2)	0-5	Ah1	0.55	0.2	83.4	5.1	17.4742	72.0
	5-13	Ah2	0.90	0.1	57.7	5.1	4.0365	17.0
	13-30	Ahe	1.56	0.0	8.9	4.6	1.8775	7.7
	30-55	Ae	1.56	0.0	2.3	5.1	0.4660	1.9
	55-60	Bt1	1.57	0.1	4.2	5.4	0.0413	0.2
	60-65	Bt2	1.57	0.3	6.1	5.5	0.0419	0.2
	65-80	Bt3	1.57	0.3	11.0	6.1	0.1438	0.6
	80-95	Bt4	1.57	0.2	10.6	6.5	0.1597	0.7
	95-100	BC1	1.63	0.0	4.6	6.9	0.0088	0.0
	100-105	BC2	1.63	0.0	5.4	7.1	0.0077	0.0
	105-123	BC3	1.63	0.2	4.4	7.1	0.0428	0.2
	123-135	BC4	1.63	4.2	2.1	7.1	0.0056	0.0
	135-154	BC5	1.63	8.4	1.9	7.2	0.0135	0.1
	154-171	BC6	1.63	10.0	2.4	7.2	bd	bd
	171-200	Cca1	1.67	19.1	1.1	7.3	bd	bd
	200-220	Cca2	1.67	21.0	0.1	7.3	bd	bd
	220-230	Cca3	1.67	19.5	0.4	7.3	bd	bd
	230-256	Cca4	1.67	19.4	0.1	7.4	bd	bd
	256-290	Cca5	1.67	19.6	0.1	7.4	bd	bd
Depression (3)	0-6	Ah	0.69	0.6	86.6	5.2	nd	nd
	6-12	Ahe	1.32	1.2	29.3	5.3	nd	nd
	12-20	Ae	1.47	0.4	12.4	5.3	nd	nd
	20-32	Bt1	1.46	0.3	15.9	5.3	nd	nd
	32-45	Bt2	1.46	0.1	15.1	5.4	nd	nd
	45-58	BC1	1.59	0.4	7.1	5.9	nd	nd
	58-67	BC2	1.59	13.4	5.1	6.9	nd	nd
	67-110	Cca1	1.71	28.9	6.4	7.3	nd	nd
	110-150	Cca2	1.71	26.5	2.3	7.5	nd	nd
	150-180	Ck1	1.92	20.4	3.6	7.6	nd	nd
	180-210	Ck2	1.92	21.8	0.3	7.6	nd	nd
210-240	Ck3	1.92	18.8	2.4	7.6	nd	nd	
240-270	Ck4	1.92	21.1	1.7	7.6	nd	nd	

bd (below detection)

nd (not done)

local topography will greatly influence the degree of soil development and dictate the redistribution pattern of soil constituents.

The knoll profile was sampled to a depth of 130 cm and contained a Cca horizon from 30-70 cm, and the Ck horizon below 70 cm (Table 4.1). The amount of CaCO_3 accumulation which is seen in this Cca horizon can be accounted for by translocation from the A horizon above to within 10% (0.40 g cm^{-2} of inorganic carbon was lost from the A horizon and 0.36 g cm^{-2} of inorganic carbon was gained by the Cca horizon). This suggests that the knoll profile has not experienced significant soil erosion. The lack of soil development (no B horizon) indicates that the knoll profile suffers from a lack of moisture infiltration, presumably as the result of topography facilitating water runoff.

The organic carbon content in the surface horizon of the knoll was 45 g kg^{-1} and for the depressions it was $83\text{-}87 \text{ g kg}^{-1}$, reflecting the increase in vegetation growth in the depressions as the result of higher soil moisture content (Table 4.1). Organic carbon content decreased with soil depth in all the Aberdeen profiles with the exception of the Depression (2) profile which showed a subsoil accumulation of between 6 and 11 g kg^{-1} at a soil depth of $65\text{-}95$ cm in the Bt3 and Bt4 horizons (Table 4.1). As very little root mass (0.3 g/horizon or 1.5% of total dry root weight) was found at this depth the accumulation is attributed to leaching of organic matter into these horizons.

In both the knoll and Depression (2) profiles, roots were concentrated in the 0 to 20 cm soil depth, making up 73% and 89% of the total dry root weight found and the maximum rooting depth found was about 120 cm (Table 4.1). There was a greater percentage of roots found below 20 cm of the knoll profile (27%) than the depression profile (11%). This may be the result of more roots having to grow deeper for water in the knoll soil where moisture is more limiting than in the depression soil.

4.2.2 Swift Current

In the Brown soil zone near Swift Current two native grassland profiles were sampled, an upland and adjoining depression (Table 4.2). The Swift Current depression contained a distinct Aeg horizon putting it in the Eluviated Brown great group and making the profile formation similar to the Aberdeen depressions.

The organic carbon contents in the top 7 cm were 32 g kg^{-1} in the knoll soil profile and 80 g kg^{-1} in the depression soil profile (Table 4.2). The level of organic carbon was highest in the A horizon and decreased with soil depth for both soil profiles. In both the knoll and depression profiles roots were concentrated in the 0-23 cm soil depth, making up 79% and 94% of the total dry root weight found in the profile, which was similar to the root distribution found at Aberdeen. Maximum rooting depth was found to be 88 cm in the knoll profile and to 90 cm in the depression profile, with only 1% of the total dry weight of roots found in the horizon of maximum rooting depth.

A greater dry root weight was found in the horizons of the knoll profile than the depression profile. The dry root weight in the top 22 cm of soil for depression was about 17 g, while the upland had a dry root weights of 21 g for a similar soil depth (Table 4.2). Usually lower landscape positions experience higher vegetative productivity, and presumably that includes the production of roots, from the benefit of greater moisture availability. One explanation for greater root mass in the upland profile is the need for more efficient moisture uptake from a limited supply of available moisture. As well a greater turnover time for roots will occur in the upland soil as the result of low moisture conditions inhibiting root decay by microorganisms. Thus, more roots would benefit plants growing on the Upland by probing a greater soil volume for maximum extraction of moisture, and roots would remain in the soil longer before they decay. The depression profile may also have experienced less than

Table 4.2 Swift Current soil profile descriptions and selected soil characteristics.

	Depth cm	Horizon	Bulk density Mg/m ³	Inorg. C g/kg	Org. C g/kg	pH (CaCl ₂)	Roots g/horizon	Roots % total
Swift Current								
Upland	0-7	Ah	1.32	0.2	31.6	6.9	14.5365	56.0
	7-15	Btj1	1.33	0.1	21.9	6.9	3.5121	13.0
	15-23	Btj2	1.33	0.1	14.5	6.9	2.8830	11.0
	23-32	BC	1.35	10.6	17.9	7.2	1.7489	6.4
	32-42	Cca1	1.47	20.2	11.6	7.7	1.1061	4.1
	42-55	Cca2	1.47	20.5	8.4	7.8	0.8996	3.4
	55-72	Cca3	1.47	15.6	5.1	8.1	1.4026	5.2
	72-88	Cca4	1.47	12.8	5.1	8.2	0.1935	0.8
	88-105	Ck1	1.58	8.0	4.4	8.2	0.0369	0.2
	105-125	Ck2	1.58	6.9	3.9	8.2	bd	bd
	125-150	Ck3	1.58	6.9	4.6	8.1	bd	bd
Depression	0-7	Ah	0.99	1.0	79.9	5.2	15.6365	88.0
	7-22	Aeg	1.20	0.6	25.9	4.9	1.0550	5.9
	22-32	Bt1	1.28	1.0	10.4	5.2	0.3390	1.9
	32-50	Bt2	1.46	0.1	10.4	5.6	0.3070	1.7
	50-70	Bt3	1.65	0.0	8.1	6.1	0.2960	1.6
	70-90	Bt4	1.62	0.0	7.5	6.4	0.1141	0.6
	90-100	Bt5	1.62	0.5	7.9	6.7	0.0453	0.3
	104-122	Cca1	1.90	16.7	2.9	7.1	bd	bd
	122-155	Cca2	1.90	13.6	2.3	7.4	bd	bd
	155-190	Ck	1.90	11.5	2.5	7.4	bd	bd

bd (below detection)

maximum root growth due to water logged soil conditions as this profile did show signs of gleying in the A and B horizons suggesting the influence of a high water table.

4.2.3 Spiritwood

In the Gray soil zone south of Spiritwood two profiles were sampled, one under native aspen forest and the other in an alfalfa field (Table 4.3). The native profile was sampled to a depth of 10 m. From 0-305 cm the profile was sampled by intact soil cores and from 395-1005 cm soil was removed with a drilling auger. Both profiles came from an upland position and therefore could not be included in comparisons related to topography as done for Swift Current and Aberdeen.

The organic carbon content of the A horizon of the native profile was 75 g kg^{-1} . The leaf litter (LFH horizon) was not included as only mineral soil was to be considered for phosphorus redistribution analysis. The organic carbon content in the Ap horizon of the cultivated profile was much less than that of the native at only 17 g kg^{-1} as compared to the Ah horizon of the native profile, while the Ae horizons of both profiles had similar organic carbon contents (Table 4.3). The lower organic carbon concentration in the cultivated profile seemed to be the result of bulk density and horizon thickness exaggerating the actual organic carbon content of the native horizon. The native profile had a "fluffy" Ah horizon of only 5 cm in thickness and having a bulk density of 0.50 Mg m^{-3} . In contrast the cultivated profile had an Ap horizon which was 10 cm thick and had a bulk density of 1.39 Mg m^{-3} . The lower organic carbon content of the cultivated horizon is in part the result of cultivation incorporating the surface organic matter to a depth of about 15 cm and thus incorporating it into a much greater soil volume and creating a much lower organic matter concentration when expressed on a weight/weight basis. This can be seen when the weight of organic carbon is calculated for the A horizon of each profile and expressed on a per area basis. The native profile contained 6.9 kg m^{-2} of organic carbon in 5 cm of Ah horizon, while

A1.2 Phosphorus fractionation for Aberdeen soil profiles ($\mu\text{g/g}$ combined)	123
A1.3 Phosphorus fractionation for Aberdeen soil profiles ($\mu\text{g/g}$ % Pt)...	124
A1.4 Phosphorus fractionation for Aberdeen soil profiles ($\mu\text{g/g}$ complete)	125
A1.5 Phosphorus fractionation for Aberdeen soil profiles ($\mu\text{g/g}$ combined)	126
A1.6 Phosphorus fractionation for Aberdeen soil profiles ($\mu\text{g/g}$ % Pt)...	127
A1.7 Phosphorus fractionation for Aberdeen soil profiles ($\mu\text{g/g}$ complete)	128
A1.8 Phosphorus fractionation for Aberdeen soil profiles ($\mu\text{g/g}$ combined)	129
A1.9 Phosphorus fractionation for Aberdeen soil profiles ($\mu\text{g/g}$ % Pt)...	130
A1.10 Zirconium concentration in selected soil profiles.....	131

Table 4.3 Spiritwood soil profile descriptions and selected soil characteristics.

	Depth cm	Horizon	Bulk density Mg/m ³	Inorg. C g/kg	Org. C g/kg	pH (CaCl ₂)	Roots g/horizon	Roots % total
Spiritwood								
Native	0-5	Ah	0.50	0.8	75.4	5.6	8.2297	23.0
	5-12	Ah/Ae	1.41	0.0	14.4	5.0	14.4931	40.0
	12-21	Ae	1.45	1.8	3.2	4.9	7.0870	19.0
	21-26	Bt1	1.70	0.0	7.2	4.8	1.8122	5.0
	26-38	Bt2	1.70	0.1	6.6	4.7	2.7722	7.6
	38-48	Bt3	1.70	0.0	5.1	4.8	0.8383	2.3
	48-57	Bt4	1.70	0.0	6.5	4.8	0.1809	0.5
	57-74	Bt5	1.70	2.4	4.9	5.9	0.4161	1.2
	74-90	Cca1	1.92	13.6	3.8	6.8	0.3626	1.0
	90-95	Cca2	1.92	19.6	4.2	7.0	0.0902	0.3
	95-115	Cca3	1.92	17.6	2.9	7.1	bd	bd
	115-135	Cca4	1.92	14.4	5.4	7.2	bd	bd
	135-150	Cca5	1.92	14.3	1.8	7.3	bd	bd
	150-180	Ck1	1.92	16.8	2.1	7.3	bd	bd
	180-210	Ck2	1.92	16.4	2.6	7.4	bd	bd
	275-305	Ck3	1.92	14.1	3.9	7.5	bd	bd
	395-550	Ck4	1.92	11.7	4.1	7.5	bd	bd
	550-700	Ck5	1.92	11.6	4.3	7.4	bd	bd
	700-855	Ck6	1.92	12.9	3.7	7.5	bd	bd
	855-915	Ck7	1.92	13.7	4.5	7.5	bd	bd
915-1005	Ck8	1.92	16.7	1.7	7.5	bd	bd	
Cultivated	0-10	Ap	1.39	1.2	16.8	5.6	7.3272	70.0
	10-17	Ae	1.53	0.0	13.1	5.7	0.6060	5.8
	17-22	Bt1	1.70	1.1	5.9	5.7	0.3535	3.4
	22-37	Bt2	1.70	0.0	5.6	5.7	1.2794	12.0
	37-50	Bt3	1.70	0.6	3.6	5.6	0.5024	4.8
	50-64	Bt4	1.70	2.6	3.2	6.1	0.2400	2.3
	64-70	Bt5	1.70	13.1	2.5	6.5	0.0295	0.3
	70-84	BC/CB	1.80	18.8	2.7	7.1	0.0203	0.2
	84-91	Cca1	1.87	23.1	2.8	7.3	0.0090	0.1
	91-107	Cca2	1.87	19.9	3.4	7.5	0.0550	0.5
	107-127	Ck1	1.90	14.8	3.1	7.5	0.0079	0.1
	127-153	Ck2	1.90	15.2	3.2	7.5	bd	bd
	155-175	Ck3	1.90	14.2	3.9	7.4	bd	bd
	175-195	Ck4	1.90	12.8	2.6	7.5	bd	bd
	195-215	Ck5	1.90	13.7	2.5	7.5	bd	bd
215-235	Ck6	1.90	15.1	2.9	7.5	bd	bd	
235-270	Ck7	1.90	11.9	3.3	7.5	bd	bd	

bd (below detection)

the cultivated profile contained 3.4 kg m^{-2} of organic carbon in 10 cm of Ap horizon. This means that the amount of organic carbon in the native Ah horizon was reduced by 51% as the result of about 50 years of cultivation. This is comparable to the findings that organic carbon in luvisols cultivated for 13 to 52 years decreased by 26 to 58% of the original concentrations (Ellert, 1990).

Roots were concentrated in the top 22 cm of soil in both profiles, containing 80% of the total dry roots by weight. The maximum rooting depth in the native profile was 95 cm with less than 3% of the total dry weight of roots being found below 48 cm (Table 4.3). In the cultivated soil the maximum depth at which roots were found was 127 cm with only 3% of the total dry weight of roots being found below 50 cm. It appears very few roots are able to grow into the lower Bt and upper Cca horizons since over 95% are usually found in the A and upper B horizons.

The root distributions and total rooting depth was very similar among all the soil profiles used in this study regardless of topography, environmental gradient, or vegetation (trees or grassland). Consistently most of the roots were concentrated in the top 20 cm of soil and maximum rooting depth reached around 1 m. The amount of roots found within individual profiles, as total dry weight, was variable and appeared to be determined by soil moisture conditions which were controlled by topography and environmental gradient.

4.2.4. Comparison Of Sites

The knoll at Aberdeen showed much less soil development (no B horizon) than the Swift Current knoll. This suggests that while both soil profiles were developed on diverging (convex) landscape positions the Aberdeen knoll has experienced more water runoff, and as a result less water has infiltrated the soil inhibiting soil formation processes.

The organic carbon contents in the Aberdeen soils were higher than those found at Swift Current for both landscape positions reflecting the environmental gradient. The southern site experiences less annual precipitation, more wind and higher mean temperatures resulting in more evapotranspiration and less available soil moisture. The result is lower vegetative production and consequently a lower organic carbon content of the soil. At the Aberdeen site higher annual precipitation and cooler temperatures apparently allow the native vegetation to contribute more organic carbon to the soil profile.

The Ae horizon in the Swift Current depression profile was 15 cm thick as opposed to the 25 cm thick Ae in the Aberdeen Depression (2) profile. This might be expected as lower effective precipitation in the Brown soil zone would leave less water for leaching in the Swift Current soil. The Ae horizon in the Aberdeen Depression (3) profile was only 8 cm thick (Table 4.1). The total depth to the carbonate accumulation layer (Cca horizons) was also deeper in the Swift Current Depression profile than the Aberdeen Depression (3) profile. This implies that topography has a greater control over leaching related soil formation processes than the environmental gradient. The only way in which a soil profile from a drier region could demonstrate greater soil formation than a soil profile from a wetter region is by receiving a greater amount of water resulting from large amounts of runoff due to topography.

Comparisons of weathering intensity at the three locations were based on: depth to carbonate accumulation, A horizon thickness, and organic carbon content. The carbonates in both the cultivated and native profiles from Spiritwood were leached to a greater depth than the carbonates in the Swift Current upland, the Aberdeen knoll as well as the Aberdeen Depression (3) profile. Both of the Spiritwood soil profiles, the Swift Current upland and Aberdeen knoll profiles were all on divergent (convex) landscape positions. In this regard the environmental gradient becomes evident in that the wetter northern soils appear to have experienced greater leaching than the southern

locations which are drier. In the case of the Aberdeen Depression (3) profile the added moisture due to topography was not enough to compensate for the environmental gradient, as carbonates were found at 67 cm in the Aberdeen profile and at 84 and 74 cm for the cultivated and native profiles from Spiritwood.

Anderson (1987) considered that, within the grassland region, increased moisture is accompanied by gradual increase in soil organic matter content and greater soil weathering. This finding is consistent with the trends found between Swift Current and Aberdeen. When the grassland is replaced by forest the organic matter content and thickness of the A horizon decreases and a forest litter layer builds up. The A horizon of the Spiritwood native soil profile was thinner and had a lower organic carbon content than the A horizons of the Aberdeen knoll and Depression (3) profiles which is consistent with the findings of Anderson (1987). This suggests that the soil profiles used in this study can be considered representative of the regions and typical of the environmental gradient from along which they were taken.

4.3 Phosphorus Distribution

4.3.1 Total Phosphorus Distribution in Soil Profiles

Since the parent materials of soils used in this study were uniform deposits of glacial till, the original distribution of P is assumed to have been fairly uniform. This implies that any deviation from a uniform pattern of P distribution found in the present profiles has been the result of soil forming processes. The total P (Pt) distribution patterns in the soil profiles (Figure 4.9) show that all the soil profiles have undergone different degrees of soil development, as none demonstrated a uniform distribution of P with depth.

In order to quantitatively determine the amount of Pt redistribution which has occurred in the solum as the result of soil formation processes, the original level of Pt

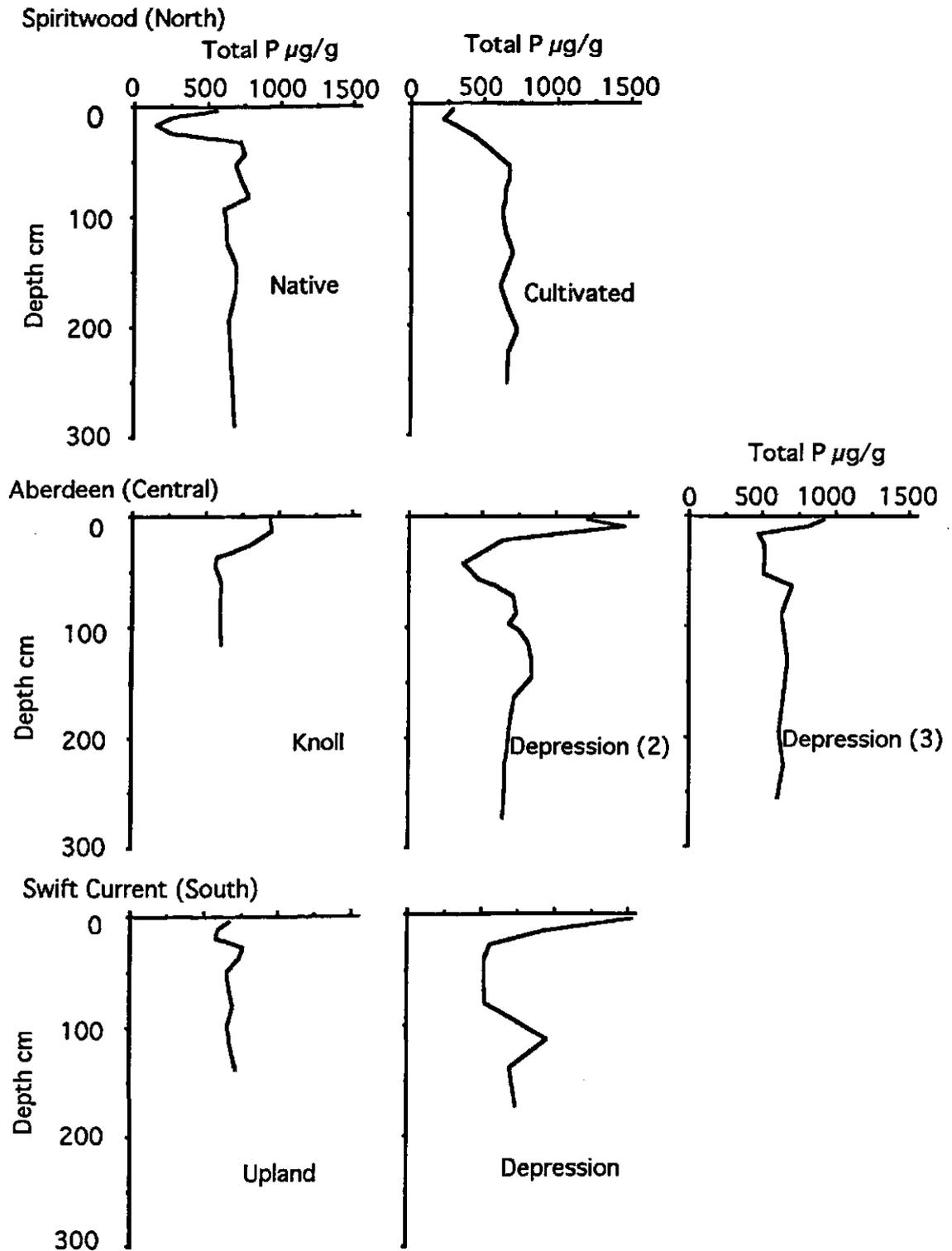


Figure 4.9 Total P distribution in soil profiles from Swift Current, Aberdeen, and Spiritwood.

in the parent material must be considered. The solubility and mobility of CaCO_3 is greater than that of P in soil solution. Therefore the lowest depth of CaCO_3 accumulation (Cca horizon) marks the maximum depth to which P mobility could have occurred. Thus, below the Cca horizon the pattern of Pt concentration is considered the natural variation inherent in glacial till parent material. The Pt concentrations in the parent material of individual soil profiles were found to vary by as little as $7 \mu\text{g g}^{-1}$ ($597\text{-}604 \mu\text{g g}^{-1}$) in the Aberdeen Knoll to as much as $76 \mu\text{g g}^{-1}$ ($649\text{-}725 \mu\text{g g}^{-1}$) in the Spiritwood Cultivated soil profile, with an intermediate range of $40 \mu\text{g g}^{-1}$ ($698\text{-}738 \mu\text{g g}^{-1}$) in the Swift Current Depression. The average amount of Pt in the Swift Current, Aberdeen and Spiritwood parent materials were $700 \mu\text{g g}^{-1}$, $640 \mu\text{g g}^{-1}$, and $680 \mu\text{g g}^{-1}$ respectively, which are typical for Saskatchewan.

Deviations from the original level of Pt above the Cca horizon indicate Pt redistribution. By calculating the amount of Pt found in a horizon of the solum and then subtracting the minimum and maximum amounts of original Pt found in the parent material, a range in Pt redistribution can be quantitatively determined. Below is the equation for calculating the maximum Pt accumulation (or minimum depletion) per horizon. In order to calculate the minimum Pt accumulation (or maximum depletion) the maximum concentration of Pt found in the Ck horizon would be substituted for the minimum $\mu\text{g g}^{-1}$ Pt in Ck horizon seen below:

$$\begin{aligned}
 & (\text{soil wt. A hor.} \times \mu\text{g g}^{-1} \text{ Pt in A hor.}) \\
 & - (\text{soil wt. A hor.} \times \text{min. } \mu\text{g g}^{-1} \text{ Pt in Ck hor.}) \qquad (2) \\
 & = \text{max. P accum. (or min. P depletion) in A horizon}
 \end{aligned}$$

This mass balance approach to determining the maximum and minimum amount of Pt redistribution can be used to estimate the net gain or loss of Pt in the solum, as well as estimate the amount of Pt being accumulated or depleted from soil horizons within the solum as the result of soil formation processes. The amounts of Pt determined to have

been redistributed in soil horizons as the result of soil formation processes were expressed as g m^{-2} and are presented in Table 4.4.

Deviations from the original level of Pt in the solum could be found in all the soil profiles examined in this study (Figure 4.9). Accumulations of Pt were found in the surface soil horizons in all the grassland soil profiles with the exception of the Swift Current Upland soil profile. The amount of Pt making up the surface horizon accumulation varied greatly between sites. The largest concentrations of P were found in the Aberdeen Depression (2) and Swift Current Depression soil profiles both of which held about $1500 \mu\text{g g}^{-1}$ Pt as well as high organic carbon contents of 83 and 80 g kg^{-1} respectively in the Ah horizon. Since surface soils typically accumulate organic matter it is likely that the accumulation of Pt is the result of organic P accumulation. This will be examined in more detail below using P fractionation data. The amount of Pt accumulation in the surface horizons were calculated to be between 57 and 61 g m^{-2} for the Aberdeen Depression (2), and between 71 and 79 g m^{-2} for the Swift Current Depression soil profile (Table 4.4).

The Swift Current Upland and Spiritwood soil profiles contained more Pt in the A horizons than the upper B horizons. These were not considered Pt accumulations but rather areas of lesser depletion as the parent material Pt concentrations were greater than those found in the A horizons. Depletion of Pt from the lower A and upper B horizons was found in all the soil profiles with the amount of Pt removed varying considerably between sites. The greatest Pt depletion was found in the Spiritwood Cultivated soil profile which was determined to have lost between 156 and 204 g m^{-2} (or between 25 and 33% of the original Pt) from the upper horizons of the solum. A conservative estimate of P export by crop removal ($\sim 2 \text{ g m}^{-2} \text{ yr}^{-1}$ for a 2690 kg ha^{-1} wheat crop, Saskatchewan Agriculture, 1987) over 50 years of cultivation is about 100 g m^{-2} . This would suggest that there has been a loss of Pt which can not be accounted for by crop removal alone. This loss of Pt amounts to between 8 and 16% of the original level.

Table 4.4 Maximum and minimum P redistribution in soil profiles.

Site	Soil Depth cm	Type of redistribution	Pt 1992	Min. Pt original	Max. Pt original	Horizon (gain or loss)	Solum (net gain or loss)
<i>g m⁻²</i>							
Spiritwood							
Native	0-26	Depletion	62	172	185	-110 to -123	-25 to -83
	26-90	Accum.	664	579	624	40 to 85	
	90-210	PM	1202	1176	1268	neg	
Cultivated	0-50	Depletion	254	410	458	-156 to -204	-150 to -210
	50-70	Accum.	189	183	205	-6 to 6	
	70-270	PM	1972	1938	2165	neg	
Aberdeen							
Knoll	0-35	Accum.	297	206	208	89 to 91	89 to 91
	35-130	PM	746	746	755	neg	
Depression (2)	0-13	Accum.	114	53	57	57 to 61	73 to 164
	13-65	Depletion	317	420	450	-103 to -130	
	65-171	Accum.	700	591	633	110 to 200	
	171-290	PM	1322	1223	1310	neg	
Depression (3)	0-12	Accum.	75	59	63	12 to 16	19 to -67
	12-58	Depletion	285	344	364	-58 to -79	
	58-110	Accum.	440	416	441	0 to 23	
	110-270	PM	1614	1542	1632	neg	
Swift Current							
Upland	0-23	Depletion	151	163	177	-12 to -26	7 to -19
	23-42	Accum.	158	139	151	7 to 19	
	42-150	PM	932	898	975	neg	
Depression	0-22	Accum.	221	142	150	71 to 79	-24 to -82
	22-90	Depletion	453	595	629	-142 to -176	
	90-122	Accum.	221	184	194	27 to 37	
	122-190	PM	256	249		neg	

PM - Parent material

neg - negligible as parent material provided the background level of original Pt.

There were also large subsoil depletion zones of Pt in all the grassland depression soil profiles. The greatest P depletion was determined to have occurred in the Swift Current Depression soil profile which lost between 142 and 176 g m⁻² Pt. The Aberdeen Depression (2) soil profiles was determined to have lost between 103 and 130 g m⁻² while the Depression (3) soil profile lost between 58 and 79 g m⁻². The amount of Pt seen as a removal from depletion zones implies the Pt has been redistributed to other horizons of the soil. In all the grassland depression soil profiles the amount of Pt determined to have been removed from depletion zones is greater in magnitude than their corresponding surface accumulation zones. Since the removal of Pt from the depletion zone can not be completely accounted for by the accumulation of Pt in the surface horizons, some of the Pt which has been moved out of the depletion zone must have moved to horizons below. By adding the Pt gain, found in the surface accumulation, to the Pt loss, found in the depletion zone, one can quantitatively estimate how much of the Pt has been lost to the subsoil accumulation. These losses amounted to between 61 and 109 g m⁻² (or 10-17% of original Pt from depletion zone) in the Swift Current Depression, between 40 and 70 g m⁻² (or 10-16% of original Pt from depletion zone) in the Aberdeen Depression (2), and between 42 and 67 g m⁻² (or 12-19% of original Pt from depletion zone) in the Aberdeen Depression (3) soil profile.

These depletion zones occurred between soil depths of 10 and 90 cm (Figure 4.9). The greatest proportion of roots was found in the top 20 cm of soil for all soil profiles, while the greatest rooting depth was about 100 cm. Since roots are known to remove P from the soil and move it up into the above ground plant tissue it is likely that at soil depths between 10 and 50 cm, P uptake due to roots is significant. Below the 50 cm soil depth very few roots were found in any of the soil profiles which would suggest that P depletion below 50 cm is more likely the result of P translocation due to leaching than removal by roots.

One of the hypotheses of this study was that subsoil accumulations of P would be found in landscape positions collecting water from surrounding areas (depressions) with good drainage, which could be identified by strong Ae horizons. All the depression soil profiles were indeed found to contain Ae horizons and subsoil P accumulations at depth.

The Aberdeen Depression (2) and Swift Current Depression profiles both contained pronounced Pt accumulations in the subsoil. In the Aberdeen Depression (3) profile the accumulation of Pt in the surface soil, and the subsoil accumulation of P were considerably smaller and not as deep as the other depression profiles (Figure 4.5). The Aberdeen Depression (2) soil profile had a large Pt accumulation of between 110 and 200 g m⁻² which occurred over the greatest soil depth (from 80 cm down to 160 cm soil depth). The Swift Current Depression had a large subsoil P accumulation of between 27 and 37 g m⁻² but it was smaller in thickness (from 100 cm down to 150 cm soil depth) as compared to Aberdeen Depression (2). The Aberdeen Depression (3) soil profile had only a modest subsoil Pt accumulation of between 0 and 23 g m⁻², which was found in a thin soil horizon (from 60 cm down to 90 cm soil depth) closer to the surface than either of the other two depression soil profiles. Thus, the Aberdeen Depression (3) soil profile which showed weaker soil development also showed less P redistribution relative to the Aberdeen Depression (2) and Swift Current Depression profiles which showed strong soil development. This suggests the redistribution of soil P, as the result of soil forming processes, is controlled more by the effects of local topography than the conditions of the environmental gradient for the soils examined in this study.

A mass balance was used in order to develop a complete account of the mass of Pt in the soil solum. The Aberdeen Knoll and Aberdeen Depression soil profiles were determined to have received a net gain in Pt in the range of 89 to 91 g m⁻² for the knoll and 39 to 150 g m⁻² for the depression. The Swift Current soil profiles and the

Aberdeen Depression (3) soil profile were found to contain Pt redistribution values which ranged from negative, indicating a net loss, to positive indicating a net gain of Pt in the solum. Since the negative values were larger in magnitude than the positive values it is likely that these soil profiles have lost a small portion of their original Pt from the soil solum. The Spiritwood and Swift Current Depression soil profiles all showed a clear loss of Pt from the soil solum.

4.4 Phosphorus Fractions In Soil Profiles

The Hedley sequential extraction method of P determination allows the total P pool to be broken down into nine different fractions (Total P fractionation results found in Appendix). The various organic and inorganic fractions which make up the total P pool also show distribution patterns with profile depth. The results of the P fractionation analysis can be found in the Appendix presented as $\mu\text{g g}^{-1}$ complete, $\mu\text{g/g}$ some fractions combined, and combined P fractions as % of total P. The HCl-Pi fraction, thought to be primary Ca-P from parent material, made up the largest single fraction of total P, accounting for up to 82% of the total P in C horizons (Appendix).

4.4.1 Phosphorus Composition Of Parent Material

It was important to establish that the depth of soil sampled in all the soil profiles contained the maximum depth to which soil formation had occurred. To meet this requirement an unweathered parent material in the C horizon was essential. It was mentioned in the Materials and Methods section that this included reaching the Ck horizon. However, an unweathered parent material requires some definition as most parent materials found in Saskatchewan have undergone some degree of weathering prior to the last glaciation and hence the soils are not made up of 100% primary P minerals.

A common finding in glacial till parent materials (unweathered since the last glaciation) of Saskatchewan is the presence of secondary phosphorus minerals. Typically about 20-25% of total P in Ck horizons is found in secondary forms while the remaining Pt is in primary Ca-P form (Schoenau et al., 1989, Xiao et al., 1991). This is the result of weathering which took place prior to the last glaciation. For this reason a total P composition of 20-25% secondary P and 80-75% primary P in C horizons is considered unweathered parent material during the present time frame of soil formation.

In the seven soil profiles examined for this study primary P (1M HCl Pi) made up between 71 and 82% of total P in C horizons, which is within the expected range for parent materials unweathered since the end of the last glaciation (Tables A1.3, A1.6, and A1.9 of Appendix). This leads to the conclusion that all the soil profiles used in this study were sampled to a depth which included all the soil which had been exposed to soil formation processes since the last glaciation.

4.4.2 Distribution of Phosphorus Fractions In Soil Profiles

In all the soil profiles the HCl-Pi (primary P) showed a consistent distribution pattern of increased concentration with soil depth, with proportions ranging from as low as 7% of Pt in the A horizon to as high as 82% of Pt in the Ck horizon. This is consistent with the findings of other researchers (Roberts et al., 1985, Schoenau et al., 1989 and Xiao et al., 1991), and is explained by greater release of P from primary P minerals due to more intense weathering in surface horizon soils.

One irregularity was found in the HCl-Pi fraction of the Spiritwood native site. At a soil depth of 38-48 cm HCl-Pi concentration ($1263 \mu\text{g g}^{-1}$) was found to be almost double that of the soils sampled directly above ($537 \mu\text{g g}^{-1}$) and below ($477 \mu\text{g g}^{-1}$). Total Ca determination showed that there was also twice as much Ca present at this depth compared to the soils above and below. There may have been a random

inclusion of apatite in this soil layer at the point of sampling. The soil profile of the adjoining cultivated field only a few meters away showed no abnormalities in HCl-Pi concentration. Thus, for the purpose of examining what would be considered a normal distribution pattern of primary P in this soil profile, the HCl-Pi concentration of the 38-48 cm depth was estimated by averaging the values found in the horizons above and below ($507 \mu\text{g g}^{-1}$).

The phosphate weathered from primary P (HCl-Pi) minerals enters soil solution where it is subsequently converted to secondary Pi forms or immobilized by plants and microorganisms to appear as Po (Schoenau et al., 1989). The most bioavailable forms of secondary P are the resin Pi and bicarb Pi fractions which are collectively referred to as labile P. These fractions collectively accounted for up to 14% of Pt in surface horizons and could not be detected at all in most subsoil horizons. In all the profiles sampled labile Pi was found to generally decrease with soil depth. This is attributed to greater weathering intensity occurring near the soil surface and decreasing with depth.

In the Swift Current and Aberdeen Depression (2) sites labile Pi decreased in concentration from the Ah to Ae horizon, increased in concentration from the Ae to Bt and BC horizons, and then decreased steadily to zero in the Cca and Ck horizons. This subsoil accumulation of labile Pi is thought to be the result of the leaching experienced in these profiles. Labile Pi is relatively soluble and would thus be susceptible to deep leaching.

The Pi fraction extracted with NaOH is less labile than the resin and bicarb forms but shows similar trends in distribution, generally decreasing in concentration with soil depth. This fraction accounted for up to 12% of Pt in the A horizons and as low as 1% in Ck horizons of soil profiles. The decreasing level of NaOH Pi with soil depth is the result of the greatest soil weathering occurring in surface soils and decreasing with soil depth. The Aberdeen depression soil profiles were the exceptions showing a greater percentage of NaOH Pi in the Bt horizons than the A horizons. This

may be the result of greater *in situ* weathering occurring in the Bt horizons and/or downward translocation of labile Pi into the Bt horizon from the A horizon, and the subsequent precipitation of Pi with soil colloids which would appear as NaOH Pi.

Hot concentrated HCl (conc. HCl) is used to extract Pi and Po fractions which the original Hedley procedure left unextracted, and which has been found to account for up to 60% of Pt in the residue (Tiessen and Moir, 1993). In the soil profiles sampled conc. HCl Pi and Po accounted for about 20% of Pt. The concentration of the conc. HCl Po fraction was generally greater in surface horizons than subsoil horizons while the concentration of the HCl Pi fraction was generally greater in subsoils than surface horizons, but neither showed a consistent distribution pattern with depth.

The conc. HCl extraction is a relatively new modification to the Hedley sequential extraction method used on temperate soils, and is generally poorly understood. These fractions consist of Pi and Po forms which are very resistant to extraction, most of which are relatively unavailable to plants and microbes due to their physical positioning within the surface coatings and lattice structure of secondary minerals. Some of the Po fraction consists of unextractable P held in particulate organic debris which may be rapidly mineralized by soil fauna and flora (Magid et al., 1993). The conc. HCl hydrolyses cellulose in the residual fraction and will release such resistant Po. Thus, part of this Po fraction should be considered much more bioavailable than the highly resistant Pi fraction.

The last fraction to be extracted was the residual P which is removed with a H₂SO₄ digest. The concentration of the residual fraction was generally constant with soil depth showing only slightly higher concentrations in surface horizons. This fraction is believed to be made up primarily of inorganic P which is part of the lattice structure of primary minerals, as most of the secondary minerals and soil coatings would have been destroyed by the previous extraction solutions. Thus, the concentration of residual P is more a function of soil mineralogy and less affected by

pedogenic processes. This fraction is considered to be completely insoluble in soil solution and thus unavailable for biological uptake.

The bicarb, NaOH, and conc. HCl extraction's all contain an organic P (Po) fraction which have been combined and referred to as "sum Po" in Tables A1.3, A1.6, and A1.9 of the Appendix. The percent of Pt in the Po fractions were found to be greatest in surface horizons and decreased with soil depth. The greatest Po was found in the Ah horizon of the Aberdeen Depression (2) soil profile at 1034 $\mu\text{g g}^{-1}$ (71% of Pt) and in the Swift Current Depression soil profile at 942 $\mu\text{g g}^{-1}$ (62% of Pt). The largest amount of Po was located in the top 30 cm of each soil profile, this is the same soil depth in which most of the organic carbon content and total dry root weight was found. This suggests the importance of biocycling to the accumulation of Po by roots and microorganisms in the surface soil.

4.4.3 Phosphorus Transformations and Translocations

In order to better visualize the transformations and translocation of soil P, various fractions were combined and graphed versus soil depth. In Figures 4.10 to 4.16 HCl-Pi has been graphed down the left hand side, representing the original form of P (Primary P) in parent material which is not the result of weathering transformations. This clearly demonstrates how weathering intensity decreases with soil depth, leaving the greatest amount of Ca-P (Primary P) intact in the unweathered Ck horizon. On the right hand side of the bar graphs secondary P has been divided into three general groups representing various degrees of bioavailability (Labile Pi, Resistant Pi, and Organic P). The secondary forms of P can be used to examine the degree of transformation and translocation which have occurred as the result of soil formation.

The resin Pi and bicarb Pi fractions represent the most bioavailable P and are therefore referred to as labile Pi. Bicarb Po, NaOH Po, and conc. HCl Po are grouped

Aberdeen Depression (2)

Aberdeen Knoll

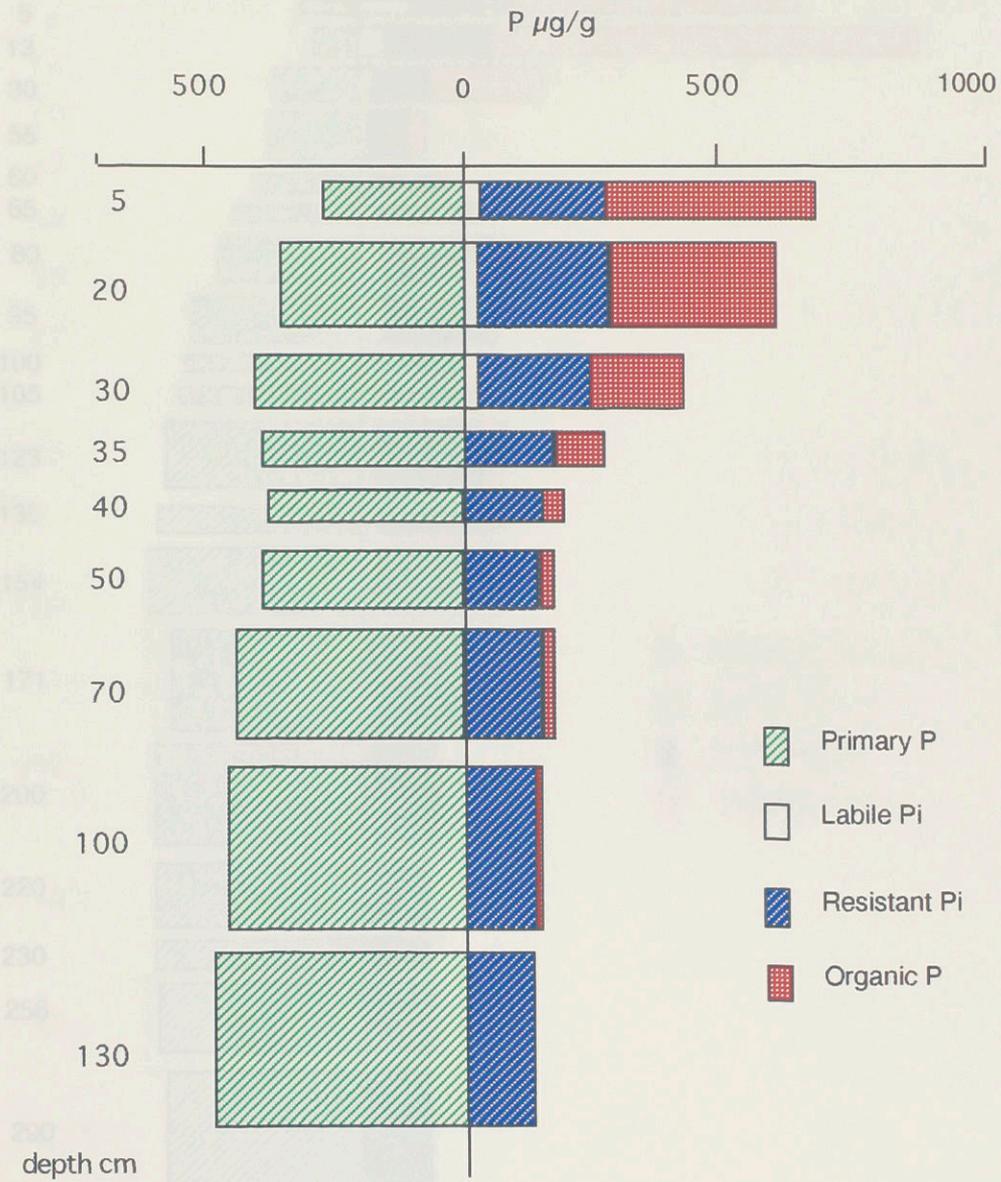


Figure 4.11 Distribution of various P fractions with soil depth for the Aberdeen Depression (2).

Figure 4.10 Distribution of various P fractions with soil depth for the Aberdeen Knoll.

Aberdeen Depression (2)

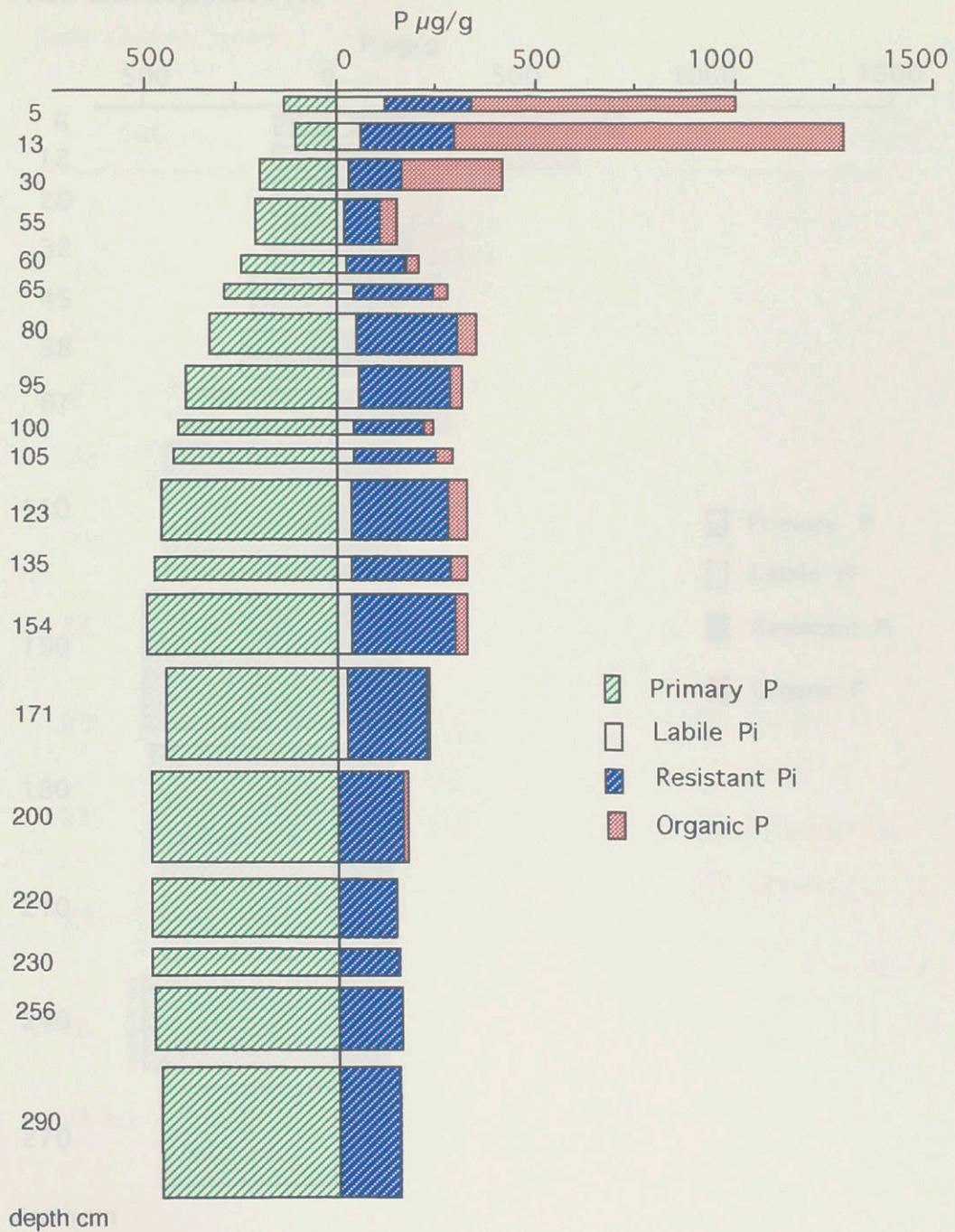


Figure 4.11 Distribution of various P fractions with soil depth for Aberdeen Depression (2).

Aberdeen Depression (3)

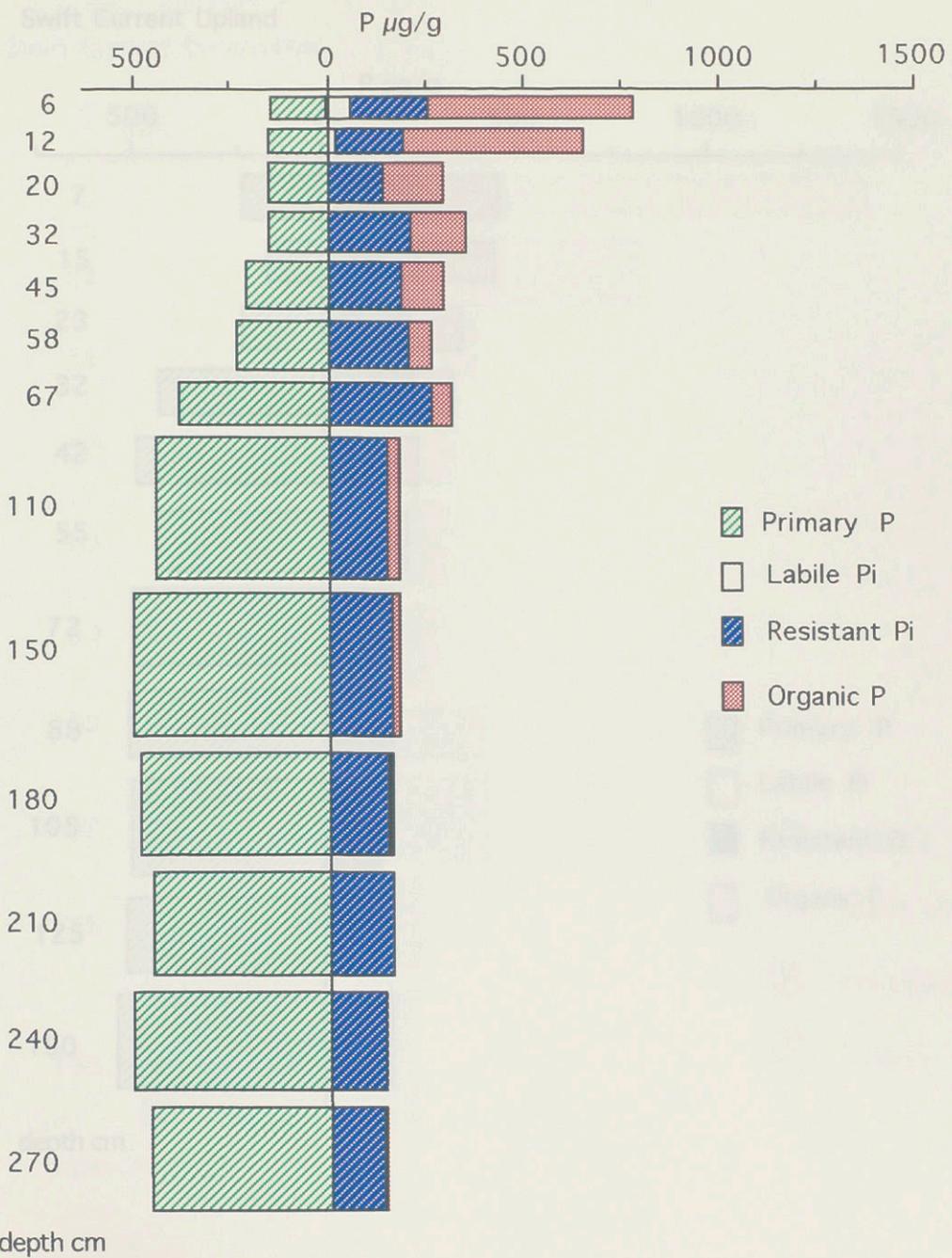


Figure 4.12 Distribution of various P fraction with soil depth for Aberdeen depressions.

Swift Current Upland

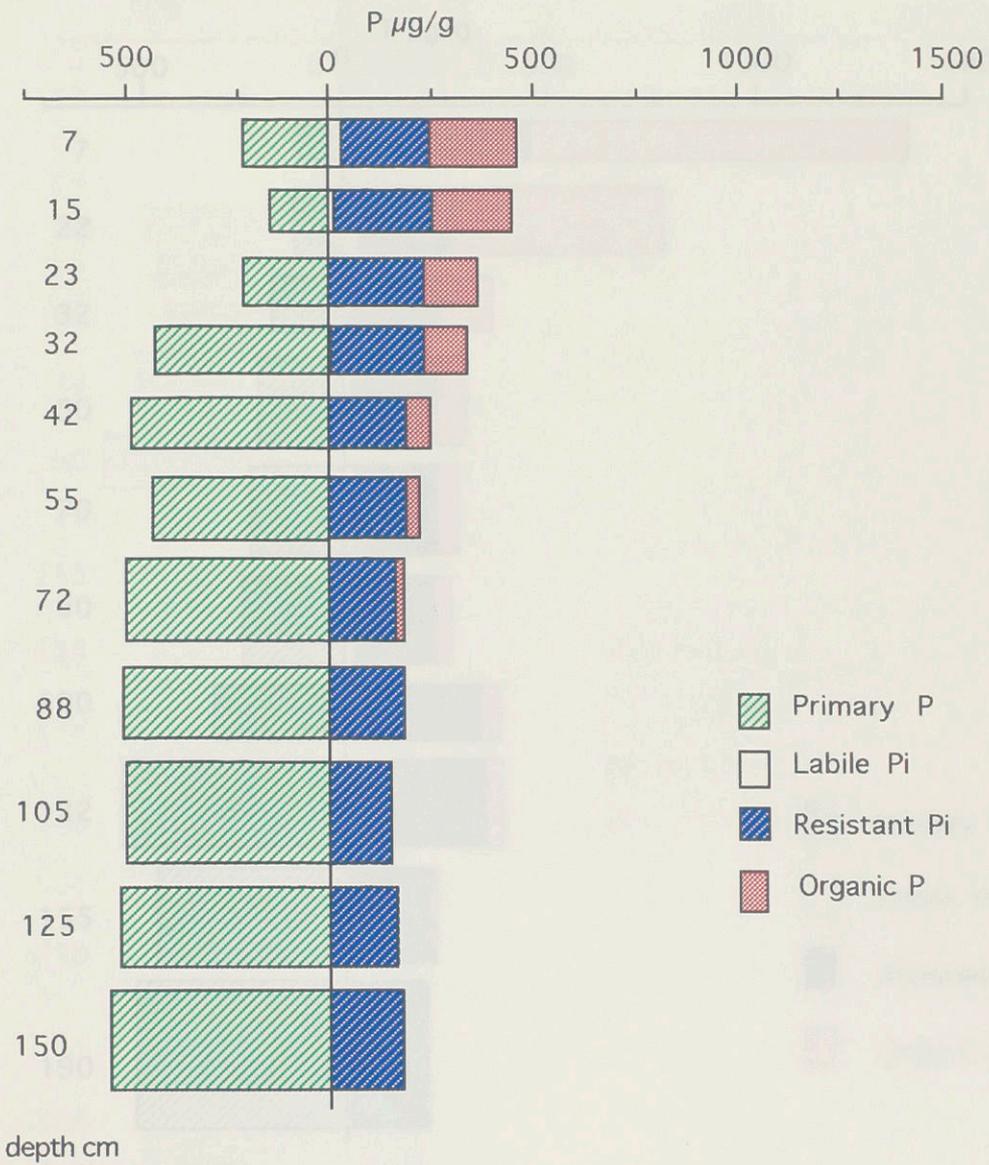


Figure 4.13 Distribution of various P fractions with soil depth for Swift Current Upland.

Swift Current Depression

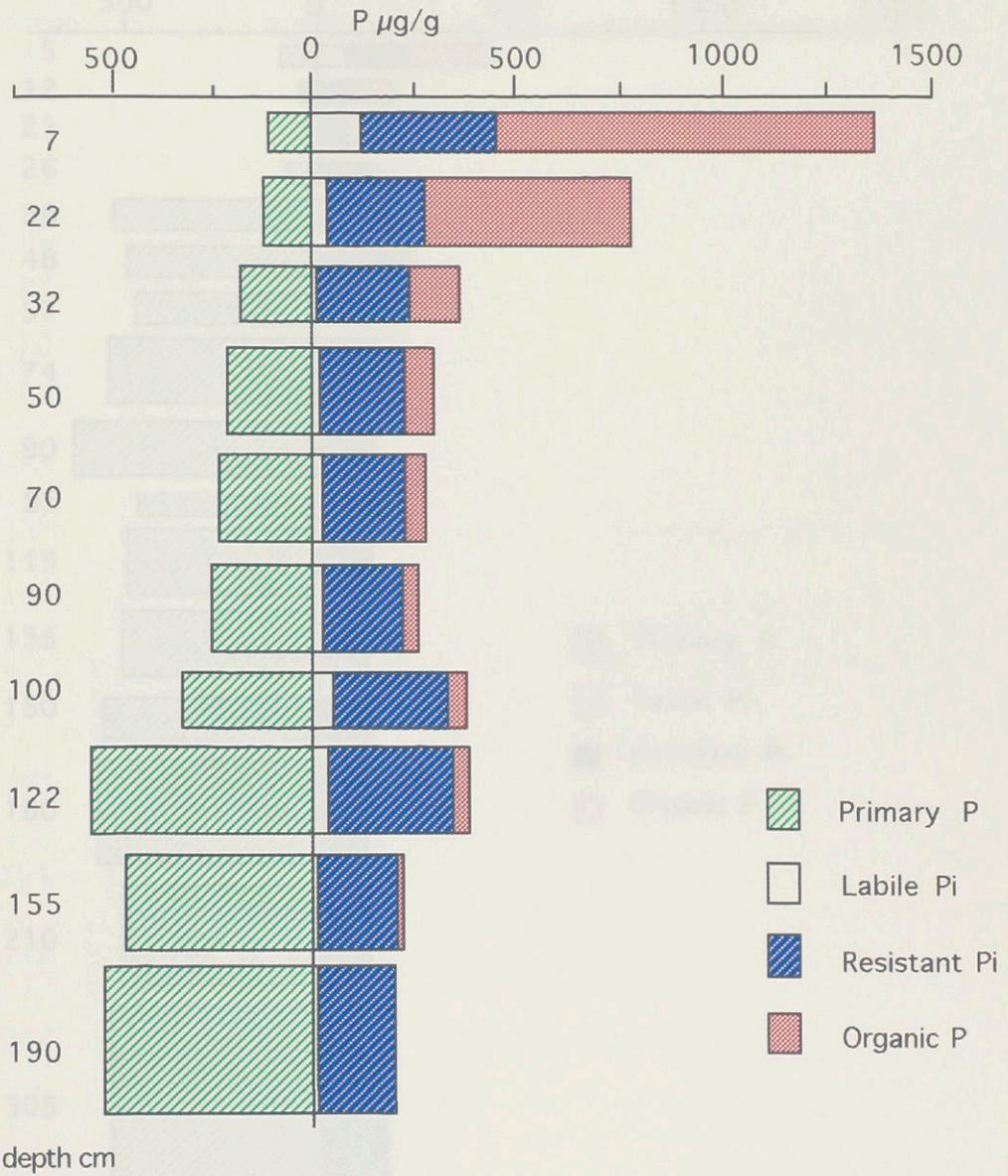


Figure 4.14 Distribution of various P fractions with soil depth for Swift Current Depression.

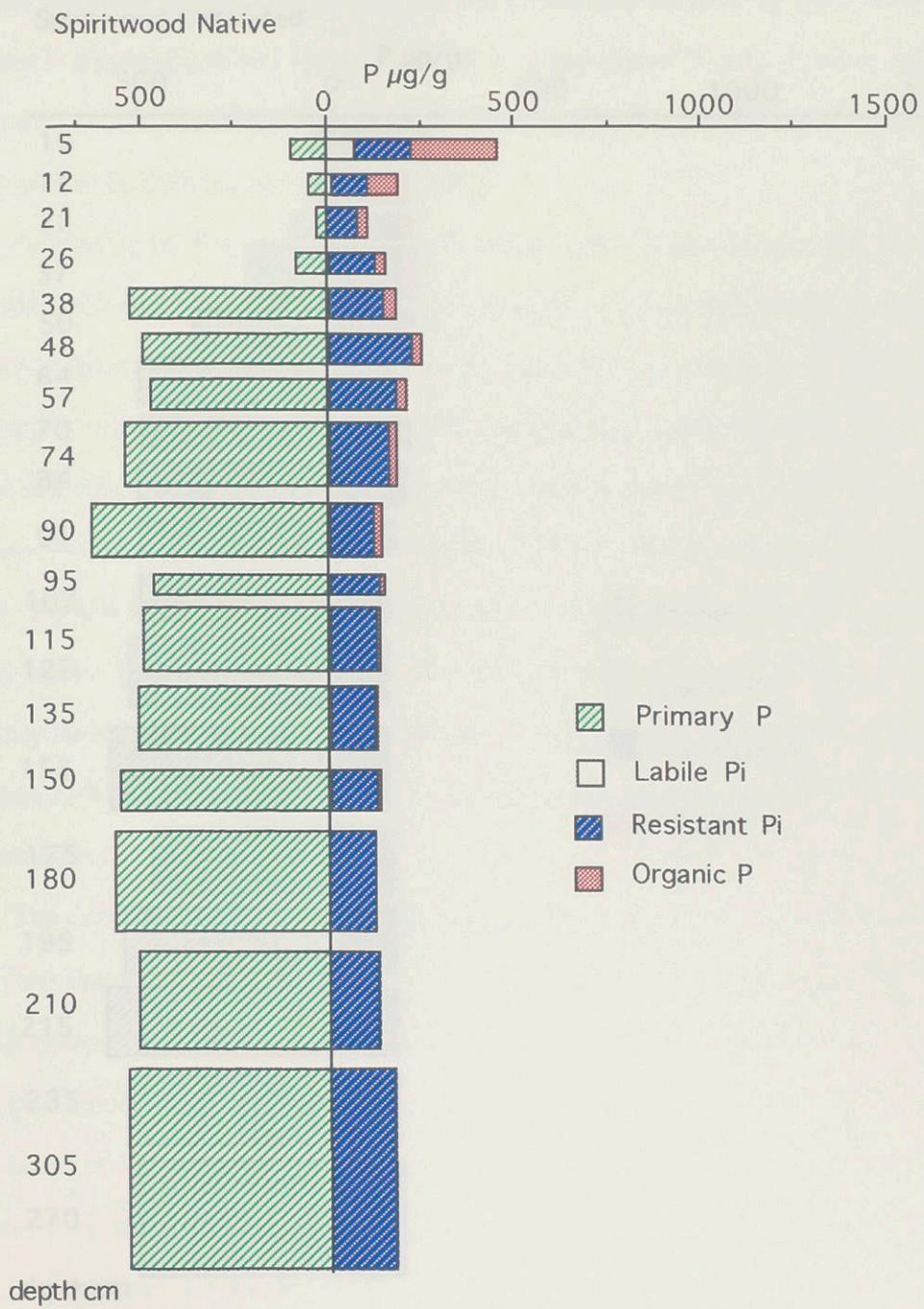


Figure 4.15 Distribution of various P fractions with soil depth for Spiritwood Native.

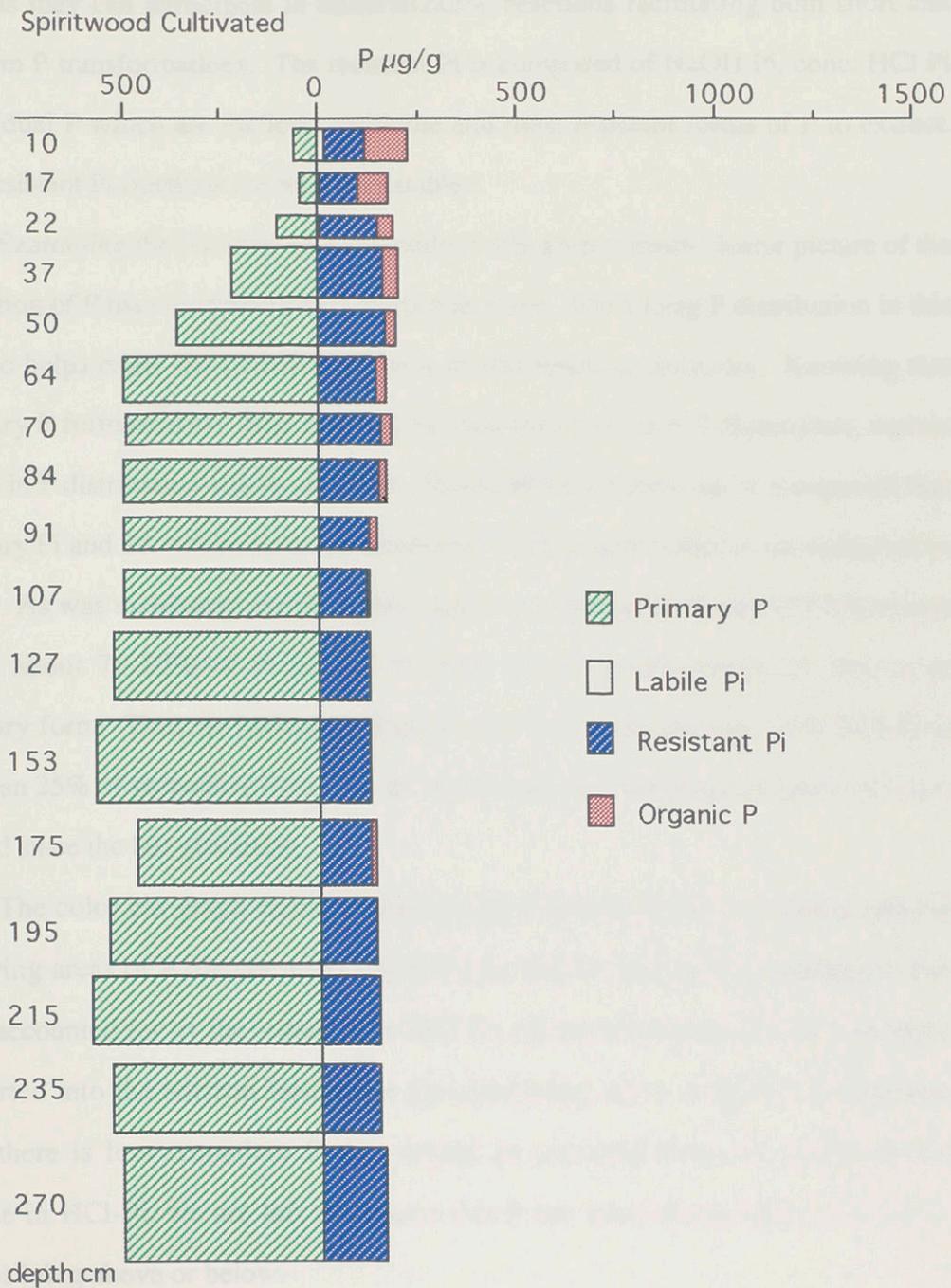


Figure 4.16 Distribution of various P fractions with soil depth for Spiritwood Cultivated.

together as organic P of various stability and represent the next most bioavailable P forms, as they can participate in mineralization reactions facilitating both short and long-term P transformations. The resistant Pi is composed of NaOH Pi, conc. HCl Pi and residual P which are the least available and most resistant forms of P to extract. These resistant Pi fractions are relatively stable.

Examining the fractions of soil P collectively gives a much clearer picture of the distribution of P than examining each P fraction alone. Examining P distribution in this way also helps relate the observed patterns to soil forming processes. Knowing that secondary P formation can only occur at the expense of primary P dissolution, certain patterns in P distribution can be expected. Where HCl-Pi is depleted, it is expected that secondary Pi and Po will be found in quantities which counter balance the reduction in HCl-Pi. As was mentioned earlier in this chapter, the parent materials of Ck horizons contain about 75-80% of Pt in HCl-Pi form while the remaining 25-20% is in secondary form. Thus, in horizons which show a shift from less than 75% HCl-Pi to more than 25% of secondary forms it is an indication that soil formation processes have occurred since the last glaciation.

The color bar graph format for analyzing P transformations is also helpful in identifying areas of P translocation. In horizons that contain more secondary P than can be accounted for by the reduction in HCl-Pi, we are left to assume that P has been transported into the horizon from other horizons lying above or below. In horizons where there is less secondary P than would be expected from the corresponding decrease in HCl-Pi, we are left to assume that P has been transported out to either horizons lying above or below.

In the Aberdeen Knoll and Swift Current Upland soil profiles the concentration of secondary P forms were highest in the top 30 cm of soil and decreased with soil depth (Figures 4.10 and 4.13). This is the result of plant roots removing labile P from the subsoil and transporting P to above ground plant tissue and roots in surface soil, as

over 75% of the dry root weight was also found in the top 30 cm of soil. When plant tissue dies it is subsequently returned to the soil surface as decaying organic matter resulting in its accumulation in the surface soil. The organic carbon content of the Aberdeen Knoll was 45 g kg^{-1} and the Swift Current Upland contained 31 g kg^{-1} of organic carbon. A similar distribution in secondary P can be seen in the surface horizons of these profiles with Aberdeen containing more P_o as well as total secondary P when compared to Swift Current (Figure 4.10 and 4.13). Due to low soil moisture conditions primary P mineral weathering was restricted to a shallow soil depth. The effect of the environmental gradient can be seen in the depth to which primary P weathering was observed at Swift Current and Aberdeen. The Aberdeen knoll profile which experiences greater precipitation is seen to have experienced a deeper (down to 70 cm) and more consistent degree of primary P weathering (Figure 4.10). The Swift Current upland soil profile which experiences greater soil moisture deficit over the growing season has experienced primary P weathering to about 55 cm (Figure 4.13).

In the Swift Current area moisture deficit is lowest in May and June but increases from the beginning of July until fall because of high temperatures and hot winds. Decreased moisture availability results in vegetative growth reaching a peak in June and then decreasing until fall. This allows for only a short growing season and as a result, very little organic matter production and removal of subsoil P can take place. Low soil moisture conditions that generally prevail over the growing season will also decrease the amount of primary P weathering which can occur. Decreased weathering will reduce the amount of secondary P formation, some of which would contribute to the labile P pool. Thus, the accumulation of organic matter and organic P in the surface soil, or the removal of P by roots in the subsoil, will not proceed as rapidly as in the wetter soils of the Swift Current depression and Aberdeen soils.

On the other hand at Aberdeen soil moisture conditions are more favorable than at Swift Current over most of the growing season. This allows for steady vegetative

growth over a longer time resulting in greater organic matter build up and organic P accumulation. The more moist soil will also allow for more primary P weathering to occur, and thus increasing the amount of P in the labile pool, through secondary P formation. The greater vegetation would increase the removal of labile P from the subsoil. Growing roots will continually remove P from the lower solum and cycle P in the upper A horizon where rooting density is highest.

The amount of primary P in the surface soil horizon was greater than that of the soil horizon directly below in the Swift Current Upland, Aberdeen Depression (2) and the Spiritwood Native soil profiles (Figures 4.13, 4.11, 4.15). At Swift Current and Spiritwood it may be that because surface soil horizons are often the driest, due to their susceptibility to evaporation, there is less primary P weathering occurring here. In the Aberdeen Depression (2) soil profile the higher primary P concentration in the surface horizon may be the result of soil erosion moving soil with a high P content from other parts of the landscape into this depression. This appears to be a logical conclusion as this soil profile did not appear to suffer from a shortage of soil moisture and was seen to have received a net gain in Pt above the estimated original level.

4.4.4 Subsoil Phosphorus Accumulations

Accumulations of secondary P were found in the subsoil of all the soil profiles, except for the Swift Current Upland and Aberdeen Knoll. Some profiles showed greater subsoil accumulations than others. It appeared that the most well developed soils, those experiencing the greatest leaching and weathering intensity, showed the most pronounced subsoil accumulations of secondary P. The profiles from Aberdeen Depression (2) and the Swift Current Depression showed the greatest accumulation of secondary P in the subsoil.

The Ae horizon of the Aberdeen Depression (2) profile contained the least Pt and secondary P of all horizons sampled which is likely the result of intense weathering

and leaching (Figure 4.11). This was accompanied by two distinct subsoil accumulation peaks of P which occurred as the result of the intense leaching environment. The first peak occurred at a soil depth of 65-80 cm, and the second at a soil depth of 105-154 cm. This pattern was seen most clearly in the secondary P fractions, with the secondary Pi forms making up the bulk of the accumulation. To a lesser degree this bimodal accumulation pattern is also seen in Aberdeen Depression (3) (Figure 4.12).

It was my hypothesis that in soil profiles such as Aberdeen Depression (2), which have clearly developed as the result of strong weathering and leaching environments, the subsoil P accumulation will be made up mostly of Po forms. As discussed in the Literature Review, the most mobile form of P is believed to be Po. However, the secondary P in the accumulation zones (Bt and upper Cca horizons) of the Aberdeen Depression (2) soil profile were primarily made up of Pi forms. The organic P fractions are relatively small compared to the Pi fractions in these horizons (Figure 4.11).

The first P accumulation in the Aberdeen Depression (2) soil profile was found in the same horizons (Bt1 to BC2) as a subsoil organic carbon accumulation (Table 4.1) and a region of high clay content (Figure 4.2). Despite the high organic carbon content in these horizons the P accumulation was made up of predominantly resistant Pi forms. There was also a small labile Pi accumulation in these horizons. The secondary P peaks did not coincide with the clay peaks. This would suggest that P was not moving in organic form or by clay movement but possibly as labile P forms and becoming more resistant with time.

The second zone of P accumulation in the Aberdeen Depression (2) profile was found in the horizons lying directly above the inorganic carbon (CaCO₃) accumulation layer (Cca horizon). The accumulation of secondary Pi was also made up primarily of resistant Pi forms. These horizons do not contain a high organic carbon content or an

accumulation of clay. There was a significant amount of labile Pi in the horizons that contained secondary P accumulation. Since resistant Pi is considered stable and immobile, its accumulation must be the result of labile Pi leaching through the soil profile in soil solution and then reacting with Fe, Al, and Ca to form reaction products of greater stability. This suggests that soil moisture conditions may contribute to some active transformations maintaining labile Pi in a soluble form, and preventing the precipitation of Pi by reactive soil colloids.

At soil depths greater than 50 cm the amount of Po decreased and became almost undetectable. This suggests that some Po is leaching to these soil depths as the root distribution in these horizons is low and the additions of Po from decaying roots is unlikely. Thus, another possible means of Pi accumulation occurring in the subsoil is by Po leaching and by mineralization reactions converting the Po to Pi. The leaching of Po into the subsoil and subsequent mineralization to secondary Pi forms would result in the accumulation of secondary Pi and cause Po to remain at low concentrations. However, the mineralization of Po to Pi is unlikely in these horizons as the microbial population, which is required for mineralization reactions, is very small below soil depths of 1 m (refer to Figure 2.2 of Literature Review). Thus, the accumulation of secondary P in the subsoil appears to be the result of some Po leaching but primarily as the result of labile Pi being translocated down into the subsoil.

In the Aberdeen Depression (3) profile the total P distribution exhibited a small, single zone of P accumulation in the subsoil. However, the secondary P fractions showed that two small accumulation zones of secondary P existed. The first P accumulation is seen at a soil depth of 20-32 cm and the second at depth of 58-67 cm (Figure 4.12). The accumulations were both smaller and not as deep as the Depression (2) profile P accumulations, but similarly they consisted of mostly resistant Pi. The soil horizons of the Aberdeen Depression (3) soil profile which contained high subsoil P concentrations did not contain high organic carbon contents (Table 4.2) or clay

accumulation (Figure 4.3) but did contain low Po and high resistant Pi concentrations. This suggests that, as in the Depression (2) soil profile, the Depression (3) soil profile may have formed a subsoil P accumulation as the result of Pi leaching. This may have occurred as soluble P leaching followed by precipitation and formation of secondary resistant Pi.

The Swift Current Depression profile shows one zone of accumulation of subsoil Pt which peaks at a soil depth of 104-122 cm (Figure 4.14). This accumulation was comprised of two horizons of secondary P accumulation (Bt5-95 cm, and Cca1-113 cm) and one horizon of slightly higher primary P (Cca1-113 cm). The accumulations of P did not coincide with accumulations of Po (Figure 4.14) or high clay content (Figure 4.5). This accumulation may be the result of leached labile Pi being precipitated by the high inorganic carbon (CaCO_3) content in this horizon (Table 4.2) to form secondary Ca-P compounds identified as primary P in this fraction. The secondary P accumulation is made up of mostly resistant Pi forms which may be the result of the formation of reaction products from leached labile Pi.

The Swift Current Depression profile did contain a distinct Ae horizon, which could be identified visually by its platy structure and whitish color, but the concentration of Po ($522 \mu\text{g g}^{-1}$) and organic carbon (26 g kg^{-1}) in the Ae horizon was greater than that found in the Ae horizons of the other depression soil profiles. Where intense leaching has occurred, it is expected that the most soluble and mobile soil constituents (two of which are Po and organic carbon) would be leached out of the Ae horizon. This would indicate that while some leaching is occurring in the Swift Current Depression soil profile having formed an Ae horizon as well as a P accumulation, intense leaching is being prevented by the fluctuating high water table present in this soil.

The Spiritwood cultivated soil showed very small Pt accumulations deep in the C horizon (Figure 4.16). These appeared to be solely the result of inherent variability

within the parent material as the secondary P fractions remained fairly constant in concentration while variability was observed in the primary P (HCl-Pi) concentration at soil depths greater than 91 cm, in the C horizon (Figure 4.16). Secondary P concentrations did vary in the A and B horizon of the cultivated profile, with the greatest portion being made up of resistant forms of Pi. These variations are not reflected in the Pt distribution and thus do not constitute a significant trend or pattern in P redistribution.

In the native profile at Spiritwood a subsoil accumulation can be seen in the distribution patterns of Pt as well as secondary P (Figure 4.15). The accumulation occurs in the horizon (Bt3) which was found to have unusually high HCl-Pi and Ca concentrations. The Po fractions are found only in the surface horizons (Figure 4.15) and clay content is seen to be highly variable and not related to the secondary P peaks. This could suggest that leached P is being precipitated by the high concentration of Ca and/or the accumulation is the result of *in situ* weathering of the high primary P content. As seen in the accumulations at the other sites, the bulk of the secondary P is found in resistant forms.

4.5 Phosphorus Gains and Losses In Soil Profiles

It was one of the objectives of this thesis to quantitatively determine the losses or gains of P in the horizons of soil profiles. Using the pedogenic index equation (refer to section 2.5.2) it was possible to determine the net loss or gain of P in the solum of soil profiles. Zirconium oxide was used as the stable index mineral (Table A1.10 in the Appendix). Based on this calculation the Swift Current Depression soil profile lost 28% of its original P, the Aberdeen Depression (2) soil profile gained 14% above the original level of P, and the Spiritwood Native soil profile lost 7% of its original P from the solum (Figure 4.17). The mass balance calculations which were used to determine the range of P redistribution also exhibited similar trends to those found by pedogenic

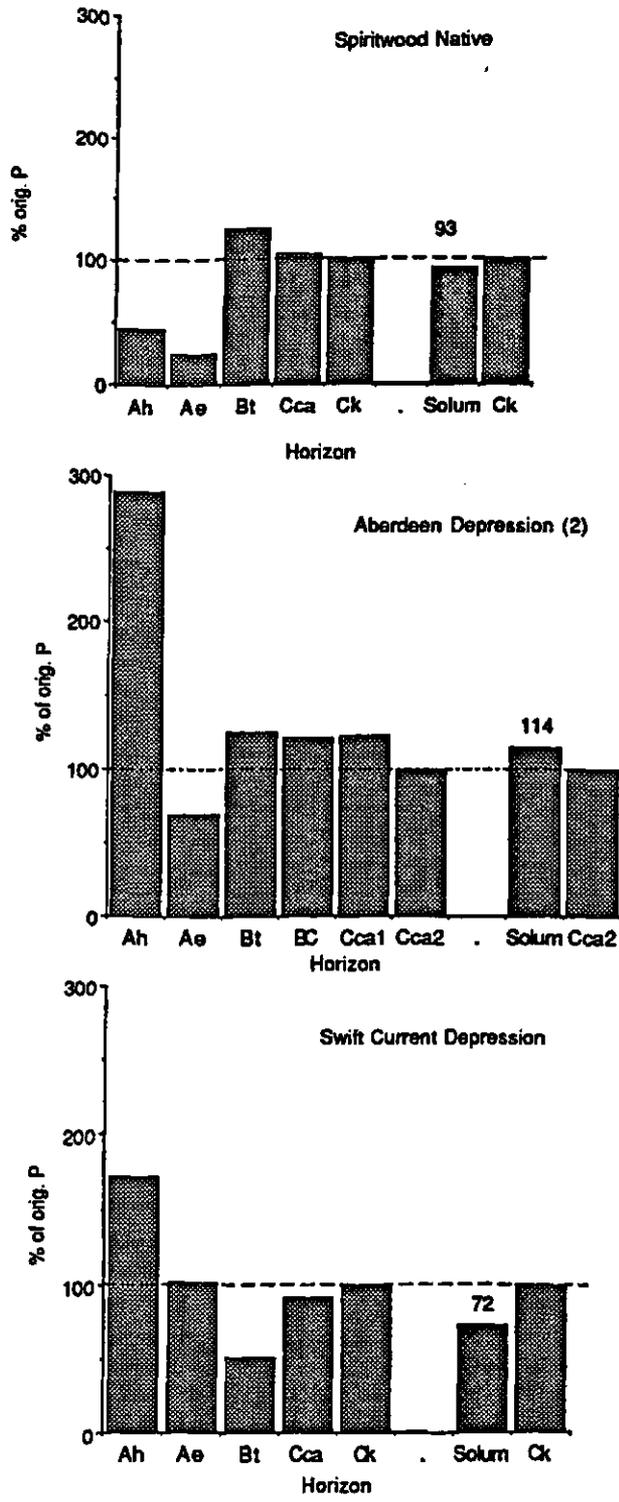


Figure 4.17 The % gain or loss of P in the various horizons of the soil profiles determined by pedogenic indexing (ZrO₂ index mineral).

indexing. The mass balance calculation showed that the Swift Current Depression lost between 24 and 82 g m⁻² of Pt, the Aberdeen Depression (2) gained between 73 and 164 g m⁻², and the Spiritwood Native soil profile lost between 25 and 83 g m⁻² from the solum (Table 4.4). These results indicate that soil forming processes have resulted in a net loss of P from the soil profiles of Swift Current and Spiritwood while soil forming processes have resulted in a net gain of P in the Aberdeen soil profile.

Typically a net loss of P is expected from soil profiles. As P transformation and translocation proceed with time some P is lost through erosion, ground water flow, and organic matter export. Frossard et al. (1989) found that two grassland soils from Saskatchewan had lost 20% of their original P. St. Arnaud et al. (1988) reported that the more weathered forest soils of Saskatchewan have lost up to 40% of their original P from the solum. This research suggested that greater P loss could be expected from the solum of forest soils as compared to grassland soils. This was not true for the soils used in the present study as the grassland depression appeared to have lost more of its original P than the forest soil.

The Aberdeen Depression (2) soil profile appeared to have gained more P than was originally present. This could be the result of an influx of P from surface or subsurface lateral water flow as soluble ions in solution or as P associated with soil colloids as part of particulate erosion. However, the Aberdeen Knoll was also found to contain more Pt in the solum than was originally present as calculated by mass balance. This contradicts the idea that Pt has been lost from the knoll and accumulated in the Depression. It may be that Pt has been removed from other parts of the surrounding landscape accounting for the gain found in the Depression. Some possible explanations for Pt additions to a knoll position could be: animal behavior patterns related to grazing in one area and moving to another to defecate, or the accumulation of Pt as fire ash which may have collected on the knoll after episodes of local bush fires.

The 7% loss of the original P from the Spiritwood Native soil profile to a depth of 210 cm was low compared to the findings of St. Arnaud (1989), who found the solum of the same soil to contain 79% of the original P, indicating a loss of 21%. St. Arnaud sampled to a soil depth of 1.37 m, while we sampled to a depth of 10 m. When the pedogenic index was calculated using the full 10 m soil profile the solum was determined to contain 99% of its original soil P. This may indicate that the small amount of P lost from the top 2 m of soil may have accumulated below this depth without producing discernible accumulations, or that the budget becomes less reliable as greater soil depth (with its inherent variability) is included in the calculation.

Other causes of P loss in the Spiritwood Native soil may be related to the amount of P held in the LFH layer which was not measured, P held in the standing trees and understory, as well as deep leaching of P into the ground water. The LFH layer of a similar location and vegetation stand was determined to contain as much as 9 g m⁻² (Xiao et al., 1990). The amount of P held in standing vegetation has been estimated to be approximately 3-5 g m⁻² by Van Cleve et al. (1983). A water sample was removed from the 10 m hole after soil cores had been removed from the Spiritwood Native site. The water was analyzed for P and was found to contain 0.05 µg mL⁻¹ P, which accounts for a potential loss of 10-20 g m⁻² P due to deep leaching into the ground water over the time of soil formation. This suggests that of the 25 to 83 g m⁻² of P lost from the Native solum between 22 and 35 g m⁻² can be accounted for.

A possible cause of P loss from the Spiritwood Cultivated site may be the removal of the P rich LFH layer, top soil, and tree vegetation during to time the land was cleared. With the use of heavy equipment the forest was likely cleared by pushing the trees and underbrush into piles and then burning the piles. This would result in an accumulation of P as ash in a local area and a net loss of P from a much greater area.

5. CONCLUSIONS

My hypothesis was that subsoil accumulations of P could be found in soil profiles of water collection landscape positions and good drainage. It was thought that because well-drained soil profiles experience a considerable amount of leaching that they would translocate P down into the subsoil. It was my conclusion that up to 20% of the original P making up the horizons of depletion zones was translocated down into the subsoil by the soil formation process of leaching.

It was also hypothesized that part of the P accumulation at depth could be the result of roots either moving P down into the subsoil through living roots or more likely the decomposition of dead roots could increase the concentration of P in the subsoil. There was no evidence to support the hypothesis that living roots translocate P down into the subsoil. The root distribution patterns found in the soil profiles suggest that there were very few roots (<3% of total dry root weight) present in the subsoil, and in all cases more than 75% of all roots were concentrated in the top 20 cm of soil. Combined with the literature evidence that the microbial population below 1 m in soil depth is too small to allow much decomposition and mineralization of organic matter to occur.

The soil profiles used in this study were selected along an environmental gradient with the idea that as one moved to regions which had lower moisture deficit soil formation processes would become more intense and the P accumulation would be found at greater soil depth. My results did not support this thought. It appeared that the influence of local topography on the flow of runoff water into catchment basins (depressions) was greater than the influence of the environmental gradient governing the amount of annual precipitation and water deficit.

Researchers (Schoenau and Bettany, 1987, and Frossard et al., 1989) have shown that P_o is more mobile than P_i in the soil environment of Saskatchewan. For this reason it was expected that the P accumulations found in subsoil's would be largely be made up of P_o forms. However, I found that P accumulations were largely in the form of secondary resistant P_i . This was not associated with clay accumulation. It was concluded that the accumulation of resistant P_i in the subsoil may be the result of soluble P_i leaching and subsequent formation of reaction products with Ca, Fe and Al. This would result in the formation of an increasing amount of resistant P_i with time.

With the use of the pedogenic indexing calculation it was possible to estimate the net gains and loss of soil P experienced by soil horizons as the result of soil formation processes. It was determined that the Swift Current Depression and Spiritwood Native soil (to a depth of 210 cm) lost approximately 28% and 7% , respectively, of their original P from the soil solum. The Aberdeen Depression (2) soil with steeper slopes was shown to have gained approximately 14% more P in the solum than was present originally, probably derived from P-enriched soil eroded from the surrounding landscape.

Using a mass balance approach it was also possible to estimate a range of Pt redistribution among soil horizons in a given soil profile. In the Aberdeen Depression (2) soil profile which showed the greatest soil formation also demonstrated the greatest Pt redistribution. The mass balance calculation determined that there had been more Pt moved out of the depletion zone (between 103 and 130 $g\ m^{-2}$) than could be accounted for in the surface soil Pt accumulation (between 57 and 61 $g\ m^{-2}$). This suggested that there has been Pt movement, or redistribution, occurring from the upper B horizon down into the lower Bt and BC horizons. This soil profile was also determined to have experienced a net gain of Pt from the original level of Pt as indicated by the concentrations in the parent material. This was consistent with the pedogenic indexing results indicating an influx of Pt to this soil profile. The Spiritwood Cultivated soil

profile was found to have lost between 150 and 210 g m⁻² Pt, of which only 100 g m⁻² could be accounted for by crop removal. This suggests that between 8 and 16% of the original Pt in the solum has been lost to processes other than crop harvesting.

6. BIBLIOGRAPHY

- Acton, D.F. and J.G. Ellis. 1978. Soils of the Saskatoon map area 73B. University of Saskatchewan, Extension Division, Saskatoon.
- Agbenin, J.O. and H. Tiessen. 1993. Phosphorus transformations in a toposequence of Lithosols and Cambisols from semi-arid NE Brazil. *Geoderma* in press.
- Aguilar, R., and R.D. Heil. 1988. Soil organic carbon, nitrogen, and phosphorus quantities in northern great plains rangeland. *Soil Sci. Soc. Am. J.* 52:1076-1081.
- Anderson, D.W. 1987. Pedogenesis in the grassland and adjacent forests of the Great Plains. *Adv. Soil Sci.* 7:53-93.
- Anderson, D.W. 1988. The effect of parent material and soil development on nutrient cycling in temperate ecosystems. *Biogeochemistry* 5:71-97.
- Anderson, G., E.G. Williams, and J.O. Moir. 1974. A comparison of the sorption of inorganic orthophosphate and inositol hexaphosphate by six acid soils. *J. Soil Sci.* 25:51-62.
- Ayres, K.W., D.F. Acton, and J.G. Ellis. 1985. The soils of the Swift Current map area 72J. University of Saskatchewan, Extension Division, Saskatoon.
- Bowman, R.A., and C.V. Cole. 1978a. Transformations of organic phosphorus substances in soil as evaluated by sodium-bicarbonate extraction. *Soil Sci.* 125:49-54.
- Bowman, R.A., and C.V. Cole. 1978b. An exploratory method for fractionation of organic phosphorus from grassland soils. *Soil Sci.* 125:95-101

- Bowman, R.A., S.R. Olsen, and F.S. Watanabe. 1978. Greenhouse evaluation of residual phosphate by four phosphorus methods in neutral and calcareous soils. *Soil Sci. Soc. Am. J.* 42:451-454.
- Christiansen, E.A. 1979. The Wisconsinan deglaciation of southern Saskatchewan and adjacent areas. *Can. J. Earth Sci.* 16:913-938.
- Cole, C.V., G.S. Innis, and J.W.B. Stewart. 1977. Simulation of phosphorus cycling in semiarid grasslands. *Ecology* 58:1-15.
- Coupland, R.T. and J.S. Rowe. 1969. Natural vegetation of Saskatchewan. Pages 73-77. In J.H. Richards and K.I. Fung (eds.) *Atlas of Saskatchewan*. University of Saskatchewan, Saskatoon, Saskatchewan.
- Donald, R.G. 1991. Leaching and redistribution of phosphorus in Gray Luvisol soils. Ph. D. Thesis, University of Saskatchewan, Saskatoon, Saskatchewan.
- Edmunds, F.H. 1944. Geology and its relationship to soils in Saskatchewan. In J. Mitchell (ed.) *Soil Survey Report No. 12, Soil Survey of Southern Saskatchewan from Township 1 to 48 inclusive*. University of Saskatchewan, Saskatoon, Saskatchewan.
- Ellert, B.H. 1990. Kinetics of nitrogen and sulfur cycling in Gray Luvisol soils. Ph.D. thesis. University of Saskatchewan, Saskatoon, Saskatchewan.
- Frossard, E., J.W.B. Stewart, and R. J. St. Arnaud. 1989. Distribution and mobility of phosphorus in grassland and forest soils of Saskatchewan. *Can. J. Soil Sci.* 69:401-416.
- Godfrey, C.L. and F.F. Riecken. 1954. Distribution of phosphorus in some genetically related loess-derived soils. *Soil Sci. Soc. Am. Proc.* 18:80-84.
- Hannapel, R.J., W.H. Fuller, Bosma, S., and J.S. Bullock. 1964. Phosphorus movement in a calcareous soil: 1. Predominance of organic forms of phosphorus in phosphorus movement. *Soil Sci.* 97:350-357.

- Hannapel, R.J., W.H. Fuller, and R.H. Fox. 1963. Phosphorus movement in a calcareous soil: II. Soil microbial activity and organic phosphorus movement. *Soil Sci.* 97:421-427.
- Hedley, M.J., J.W.B. Stewart, and B.S. Chauhan. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Sci. Soc. Am. J.* 46:970-976.
- Honeycutt, C.W., R.D. Heil, and C.V. Cole. 1990. Climatic and topographic relations of three great plains soils: II. Carbon, nitrogen, and phosphorus. *Soil Sci. Soc. Am. J.* 54:476-483.
- Lindsay, W.L., and P.L.G. Vlek. 1977. Phosphate minerals. in *Minerals in Soil Environments*, J.B. Dixon and S.D. Weed, eds., Soil Science Society of America, Madison, Wisconsin, pp. 639-672.
- Magid, J., H. Tiessen, and L.M. Condron. 1993. Dynamics of organic phosphorus in soils under natural and agricultural ecosystems.
- McKeague, J.A. 1976. *Manual on soil sampling and methods of analysis*. Soil Research Institute of Canada. Publ. Agr. Canada.
- McKenzie, R.H. 1989. Mechanisms controlling soil phosphorus dynamics in chernozemic and luvisolic soils. Ph.D. thesis Dept. Soil Science, University of Saskatchewan, Saskatoon, Saskatchewan.
- Metha, N.C., J.O. Legg, Goring, C.A.I., and C.A. Black. 1954. Determination of organic phosphorus in soils. I. Extraction method. *Soil Sci. Soc. Am. Proc.* 18:443-449.
- Miller, R.W., and R.L. Donahue. 1990. The development of soils. Chapter 1 In *Soils: An Introduction to Soils and Plant Growth*. Prentice Hall, Englewood Cliffs, NJ.

- Mitchell, J., H.C. Moss, and J.S. Clayton. 1950. Soil survey of Saskatchewan covering the agriculturally settled areas north of township 48: Report No. 13 University of Saskatchewan, Saskatoon.
- Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta* 27:31-36.
- Paul, E.A., W.E. Lowe, Biederbeck, V.O., and J.R. Willard. 1973. Soil Microorganisms: I. Population dynamics of bacteria and actinomycetes. In Matador Project Technical Report No. 37. University of Saskatchewan, Saskatoon, Saskatchewan.
- Richards, J.H., and K.I. Fung. 1969. Atlas of Saskatchewan. University of Saskatchewan, Saskatoon, Saskatchewan.
- Ritchie, J.C. 1975. The late-Quaternary vegetational history of the Western Interior of Canada. *Can. J. Bot.* 54:1793-1818.
- Roberts, T.L., J.W.B. Stewart, and J.R. Bettany. 1985. The influence of topography on the distribution of organic and inorganic soil phosphorus across a narrow environmental gradient. *Can. J. Soil Sci.* 65:651-665.
- Roberts, T.L., and J.R. Bettany. 1985. The influence of topography on the nature and distribution of soil sulfur across a narrow environmental gradient. *Can. J. Soil Sci.* 65:419-434.
- Roscoe, B. 1960. The distribution and condition fo soil phosphate under old permanent pasture. *Plant and Soil* XII, 1:17-29.
- Runge, E.C.A., and F.F. Riecken. 1966. Influence of natural drainage on the distribution and forms of phosphorus in some Iowa prarie soils. *Soil Sci. Soc. Amer. Proc.* 30:624-630.
- Russell, R.S. 1977. Plant root systems. Thier functions and interaction within the soil. McGraw Hill Book Company, London.

- Santos, M.C.D., R.J. St. Arnaud, and D.W. Anderson. 1988. Quantitative evaluation of pedogenic changes in Boralfs (Gray Luvisols) of east central Saskatchewan. *Soil Sci. Soc. Am. J.* 50:1013-1019.
- Saskatchewan Agriculture. 1987. General recommendations for fertilization in Saskatchewan. Agdex 541. Soils and Crops branch, Saskatchewan.
- Schoenau, J.J., J.W.B. Stewart, and J.R. Bettany. 1989. Forms and cycling of phosphorus in prairie and boreal forest soils. *Biogeochem.* 8:223-237.
- Shively, S.B., and J.E. Weaver. 1939. Amount of underground plant materials in different grassland climates. *Nebraska Conservation Bulletin* No. 21.
- Simonson, R.W. 1959. Outline of a generalized theory of soil genesis. *Soil Sci. Soc. Amer. Proc.* 23:152-156.
- Singer, M.J., and D.N. Munss. 1987. *Soils an introduction*. Macmillan Publishing Company, New York.
- Smeck, N.E. 1973. Phosphorus: an indicator of pedogenic weathering processes. *Soil Sci.* 115:199-206.
- Smeck, N.E., and E.C.A. Runge. 1971. Phosphorus availability and redistribution in relation to profile development in an Illinois landscape segment. *Soil Sci. Soc. Am. Proc.* 35:952-959.
- Spencer, V.E., and R. Stewart. 1934. Phosphate studies: 1. Soil penetration of some organic and inorganic phosphate. *Soil Sci.* 28:65-79.
- St. Arnaud, R.J. 1976. Pedological aspects of glacial till. P.133-155. In R.F. Legget (ed.) *Glacial till*. R. Soc. Can. Spec. Publ. 12. R. Soc. Can., Ottawa.
- St. Arnaud, R.J., J.W.B. Stewart, and E. Frossard. 1988. Application of the 'pedogenic index' to soil fertility studies, Saskatchewan. *Geoderma*, 43:21-32.

- St. Arnaud, R.J., and E. P. Whiteside. 1963. Physical breakdown in relation to soil development. *J. of Soil Sci.* 14:267-281.
- Stewart, J.W.B., and H. Tiessen. 1987. Dynamics of soil organic phosphorus. *Biogeochemistry.* 4:41-60.
- Strong, W.L. 1984. Below-ground ecology of boreal forests in the Hondo-Lesser Slave Lake area, Alberta. Ph.D. thesis. University of Alberta, Edmonton, Alberta.
- Sudom, M.D. and R.J. St. Arnaud. 1971. Use of quartz, zirconium, and titanium as indices in pedological studies. *Can. J. Soil Sci.* 51:385-396.
- Thomas, R.L., R.W. Sheard, and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using single digest. *Agron. J.* 59:240-243.
- Tiessen, H. 1991. Characterisation of soil phosphorus and its availability in different ecosystems. *Trends in Soil Science* 1:83-99.
- Tiessen, H., J.R. Bettany, and J.W.B. Stewart. 1981. An improved method for the determination of carbon in soils and soil extracts by dry combustion. *Commun. In Soil Science And Plant Analysis.* 12:211-218.
- Tiessen, H., T.L. Roberts, and J.W.B. Stewart. 1983. Carbonate analysis in soils and minerals by acid digestion and two-endpoint titration. *Commun. In Soil Science And Plant Analysis.* 14:161-166.
- Tiessen, H., J.W.B. Stewart, and C.V. Cole. 1984. Pathways of phosphorus transformations in soils of differing pedogenesis. *Soil Sci. Soc. Am. J.* 48:853-858.
- Tiessen, H., and J.W.B. Stewart. 1983. The biogeochemistry of soil phosphorus. *Planetary Ecology.* 39:463-472.

- Tiessen, H., and J.O. Moir. 1993. Characterization of available P by sequential extraction. Chapter 10, pp 75-86 *In Soil Sampling and Methods of Analysis*, M.R. Carter, Ed., Can. Soc. Soil Sci., Lewis Publishers, London.
- Van Cleve, K.L., L. Oliver, R. Schlentner, L.A. Viereck, and C.T. Dryness. 1983. Productivity and nutrient cycling of taiga forest ecosystems. *Can. J. For. Res.* 13:747-766.
- Walker, T.W., and A.F.R. Adams. 1958. Studies on soil organic matter: 1. Influence of phosphorus content of parent materials on accumulations of carbon, nitrogen, sulfur, and organic phosphorus in grassland soils. *Soil Sci.* 85:307-318.
- Walker, T.W., and J.K. Syers. 1976. The fate of phosphorus during pedogenesis. *Geoderma*, 15:1-19.
- Williams, J.D.H., T. Mayers, and J.O. Nriagu. 1980. Extractability of phosphorus from phosphate minerals common in soils and sediment. *Soil Sci. Soc. Am. J.* 44:462-465.
- Williams, J.D.H., and T.W. Walker. 1969a. Fractionation of phosphorus in a maturity sequence of New Zealand basaltic soil profiles. 1. *Soil Sci.* 107:22-30.
- Xiao, X.J., D.W. Anderson, and J.R. Bettany. 1991. The effect of pedogenetic processes on the distribution of phosphorus, calcium, and magnesium in Gray Luvisols. *can. J. Soil Sci.* 71:397-410.

7. APPENDIX

Table A1.1 Phosphorus fractionation for Aberdeen soil profiles.

Depth cm	Resin	Bicarb	Bicarb	NaOH	NaOH	1M HCl	conc. HCl	conc. HCl	Residual	Sum
	Pi	Pi	Po	Pi	Po	Pi	Pi	Po	P	P
Knoll										
0-5	19	12	10	29	224	266	131	166	78	936
5-20	9	6	9	9	106	349	155	213	92	947
20-30	11	13	5	3	27	397	138	151	74	818
30-35	2	4	3	1	8	389	115	83	55	660
35-40	0	4	1	1	2	377	98	40	49	572
40-50	2	2	1	1	2	391	97	25	42	563
50-70	1	0	1	1	1	437	100	20	44	604
70-100	1	0	0	2	0	454	93	8	39	597
100-130	0	1	0	1	1	474	87	2	38	604
Depression (2)										
0-5	90	37	118	74	463	146	87	124	75	1214
5-13	48	22	207	78	676	106	96	152	76	1460
13-30	11	10	43	48	211	208	42	14	54	642
30-55	6	7	12	17	30	214	34	6	45	371
55-60	15	11	6	30	19	261	68	11	57	478
60-65	24	18	7	54	19	300	104	11	56	592
65-80	31	23	9	74	28	340	131	14	62	712
80-95	34	23	5	83	15	400	101	10	61	732
95-100	30	16	4	39	11	423	82	10	65	680
100-105	31	18	3	53	17	437	101	23	64	748
105-123	25	15	2	44	15	466	143	33	69	812
123-135	25	16	2	45	11	489	156	29	62	834
135-154	20	15	1	51	4	500	168	22	56	837
154-171	12	11	0	35	2	466	134	9	49	718
171-200	8	7	0	19	1	491	111	10	43	690
200-220	5	4	0	11	0	500	103	1	47	672
220-230	4	2	0	8	0	486	110	1	44	654
230-256	3	2	0	7	0	477	113	5	43	651
256-290	3	2	0	6	0	471	116	1	44	644
Depression (3)										
0-6	43	20	87	36	321	137	89	117	73	923
6-12	13	8	83	36	327	158	71	52	64	813
12-20	6	4	19	16	117	151	68	28	64	471
20-32	8	5	14	25	76	159	115	44	69	515
32-45	7	5	11	24	61	215	94	40	64	520
45-58	5	4	5	23	23	242	126	23	57	508
58-67	3	3	2	19	15	386	177	34	66	705
67-110	2	1	1	3	5	443	91	29	58	634
110-150	3	1	1	4	2	500	107	13	45	676
150-180	3	3	2	4	3	486	107	1	35	644
180-210	4	1	1	5	1	451	113	2	38	616
210-240	3	1	1	4	0	500	100	1	39	647
240-270	2	3	0	6	1	466	103	3	29	611

Table A1.2 Phosphorus fractionation for Aberdeen soil profiles.

	Depth cm	Horizon	Labile P _i	NaOH P _i	conc. HCl P _i	Residual P	Sum P _o	1M HCl P _i	Sum P
Knoll	0-5	Ah1	31	29	131	78	400	266	936
	5-20	Ah2	15	9	155	92	328	349	947
	20-30	Ahk	24	3	138	74	183	397	818
	30-35	Cca1	7	1	115	55	93	389	660
	35-40	Cca2	4	1	98	49	44	377	572
	40-50	Cca3	4	1	97	42	27	391	563
	50-70	Cca4	1	1	100	44	21	437	604
	70-100	Ck1	1	2	93	39	8	454	597
	100-130	Ck2	1	1	87	38	3	474	604
Depression (2)	0-5	Ah1	127	74	87	75	705	146	1214
	5-13	Ah2	70	78	96	76	1034	106	1460
	13-30	Ahe	21	48	42	54	269	208	642
	30-55	Ae	13	17	34	45	48	214	371
	55-60	Bt1	26	30	68	57	36	261	478
	60-65	Bt2	42	54	104	56	37	300	592
	65-80	Bt3	54	74	131	62	50	340	712
	80-95	Bt4	57	83	101	61	30	400	732
	95-100	BC1	46	39	82	65	25	423	680
	100-105	BC2	49	53	101	64	43	437	748
	105-123	BC3	40	44	143	69	50	466	812
	123-135	BC4	41	45	156	62	42	489	834
	135-154	BC5	36	51	168	56	27	500	837
	154-171	BC6	24	35	134	49	11	466	718
	171-200	Cca1	15	19	111	43	11	491	690
	200-220	Cca2	9	11	103	47	2	500	672
	220-230	Cca3	6	8	110	44	1	486	654
230-256	Cca4	5	7	113	43	5	477	651	
256-290	Cca5	5	6	116	44	1	471	644	
Depression (3)	0-6	Ah	63	36	89	73	525	137	923
	6-12	Ahe	21	36	71	64	463	158	813
	12-20	Ae	9	16	68	64	163	151	471
	20-32	Bt1	13	25	115	69	133	159	515
	32-45	Bt2	12	24	94	64	112	215	520
	45-58	BC1	9	23	126	57	51	242	508
	58-67	BC2	6	19	177	66	51	386	705
	67-110	Cca1	3	3	91	58	36	443	634
	110-150	Cca2	5	4	107	45	15	500	676
	150-180	Ck1	6	4	107	35	6	486	644
	180-210	Ck2	5	5	113	38	4	451	616
210-240	Ck3	4	4	100	39	1	500	647	
240-270	Ck4	5	6	103	29	4	466	611	

Table A1.4 Phosphorus fractionation for Swift Current soil profiles.

Depth cm	Resin	Bicarb	Bicarb	NaOH	NaOH	1M HCl	conc. HCl	conc. HCL	Residual	Sum
	Pi	Pi	Po	Pi	Po	Pi	Pi	Po	P	P
	<i>µg/g</i>									
Upland										
0-7	19	11	8	23	108	210	125	96	71	672
7-15	11	5	12	14	107	143	135	79	89	594
15-23	8	3	8	12	70	209	136	51	83	580
23-32	6	5	5	8	41	420	139	60	84	766
32-42	3	3	2	4	18	480	125	36	66	738
42-55	1	3	1	3	9	431	122	30	59	659
55-72	0	3	1	4	4	486	114	11	49	672
72-88	0	4	0	10	4	506	123	8	44	699
88-105	0	6	0	11	3	497	100	3	40	660
105-125	0	6	0	13	2	509	114	2	36	682
125-150	0	6	0	14	3	531	118	3	41	717
Depression										
0-7	72	52	253	180	589	111	86	100	77	1521
7-22	22	16	114	73	370	114	97	38	74	918
22-32	10	10	18	36	76	179	119	33	82	564
32-50	10	10	10	28	46	216	108	23	74	525
50-70	13	13	6	31	29	238	109	17	69	524
70-90	20	15	4	33	18	256	104	18	62	531
90-100	32	20	4	51	21	334	178	20	66	727
104-122	20	21	2	47	10	557	206	32	56	952
122-155	4	4	1	12	4	471	144	8	50	698
155-190	4	4	0	11	3	523	146	5	43	738

Table A1.5 Phosphorus fractionation for Swift Current soil profiles.

	Depth cm	Horizon	Labile	NaOH	conc. HCl	Residual	Sum	1M HCl	Sum
			Pi	Pi	Pi	P	Po	Pi	P
						<i>µg/g</i>			
Upland	0-7	Ah	30	23	125	71	212	210	672
	7-15	Btj1	16	14	135	89	198	143	594
	15-23	Btj2	12	12	136	83	129	209	580
	23-32	BC	11	8	139	84	105	420	766
	32-42	Cca1	7	4	125	66	57	480	738
	42-55	Cca2	4	3	122	59	40	431	659
	55-72	Cca3	3	4	114	49	17	486	672
	72-88	Cca4	5	10	123	44	12	506	699
	88-105	Ck1	6	11	100	40	5	497	660
	105-125	Ck2	6	13	114	36	4	509	682
	125-150	Ck3	7	14	118	41	7	531	717
Depression	0-7	Ah	124	180	86	77	942	111	1521
	7-22	Aeg	38	73	97	74	522	114	918
	22-32	Bt1	20	36	119	82	127	179	564
	32-50	Bt2	20	28	108	74	80	216	525
	50-70	Bt3	26	31	109	69	51	238	524
	70-90	Bt4	35	33	104	62	40	256	531
	90-100	Bt5	53	51	178	66	44	334	727
	104-122	Cca1	42	47	206	56	44	557	952
	122-155	Cca2	8	12	144	50	13	471	698
		155-190	Ck	7	11	146	43	8	523

Table A1.6 Phosphorus fractionation for Swift Current soil profiles.

	Depth cm	Horizon	Labile	NaOH	conc. HCl	Residual	Sum	1M HCl
			Pi	Pi	Pi	P	Po	Pi
							%Total P	
Upland	0-7	Ah	4	3	19	11	32	31
	7-15	Btj1	3	2	23	15	33	24
	15-23	Btj2	2	2	23	14	22	36
	23-32	BC	1	1	18	11	14	55
	32-42	Cca1	1	1	17	9	8	65
	42-55	Cca2	1	0	18	9	6	65
	55-72	Cca3	0	1	17	7	2	72
	72-88	Cca4	1	1	18	6	2	72
	88-105	Ck1	1	2	15	6	1	75
	105-125	Ck2	1	2	17	5	1	75
	125-150	Ck3	1	2	16	6	1	74
Depression	0-7	Ah	8	12	6	5	62	7
	7-22	Aeg	4	8	11	8	57	12
	22-32	Bt1	4	6	21	15	23	32
	32-50	Bt2	4	5	20	14	15	41
	50-70	Bt3	5	6	21	13	10	45
	70-90	Bt4	7	6	20	12	8	48
	90-100	Bt5	7	7	24	9	6	46
	104-122	Cca1	4	5	22	6	5	59
	122-155	Cca2	1	2	21	7	2	68
		155-190	Ck	1	2	20	6	1

Table A1.7 Phosphorus fractionation for Spiritwood soil profiles.

	Depth cm	Resin	Bicarb	Bicarb	NaOH	NaOH	1M HCl	conc. HCl	conc. HCL	Residual	Sum
		Pi	Pi	Po	Pi	Po	Pi	Pi	Po	P	P
Native											
						<i>µg/g</i>					
	0-5	47	33	25	31	149	96	67	59	49	554
	5-12	7	4	14	10	58	62	43	10	47	256
	12-21	2	1	5	5	22	33	30	6	44	149
	21-26	2	1	6	7	18	86	68	8	53	250
	26-38	2	1	6	7	16	537	99	11	44	723
	38-48	2	2	5	10	12	507*	159	9	46	751
	48-57	2	2	5	10	13	477	120	9	48	686
	57-74	3	3	3	7	13	543	100	9	47	727
	74-90	1	2	4	2	6	634	80	10	36	775
	90-95	1	1	0	2	4	466	91	6	38	609
	95-115	1	1	0	1	3	494	77	6	41	624
	115-135	1	1	1	1	3	509	76	2	41	634
	135-150	1	1	1	2	2	566	84	2	36	695
	150-180	2	2	1	2	2	566	84	0	36	693
	180-210	1	2	0	3	1	509	92	1	36	645
	275-305	3	3	0	6	2	511	120	1	37	684
	395-550	3	3	0	7	1	494	100	0	35	643
	550-700	3	3	1	9	1	491	104	0	35	645
700-855	3	4	0	8	2	497	116	0	40	666	
855-915	3	4	0	8	1	483	116	0	36	648	
915-1005	3	4	0	7	1	491	113	0	37	653	
Cultivated	0-10	9	7	11	15	59	59	40	33	52	286
	10-17	3	3	7	9	45	48	35	24	50	224
	17-22	2	2	5	8	22	106	81	15	60	302
	22-37	2	2	6	9	19	223	105	10	56	432
	37-50	2	3	3	9	14	354	115	10	51	561
	50-64	4	3	2	7	9	494	92	15	46	672
	64-70	1	1	1	3	6	486	103	15	55	671
	70-84	0	1	2	2	3	480	105	10	46	649
	84-91	0	1	0	1	4	497	80	12	47	643
	91-107	0	1	0	1	2	491	70	9	49	625
	107-127	1	1	0	2	1	520	79	4	41	649
	127-153	1	1	0	2	2	557	83	3	42	692
	155-175	2	2	0	3	3	463	83	6	47	610
	175-195	1	1	0	3	1	526	85	0	44	661
	195-215	2	2	0	4	1	571	104	1	41	725
	215-235	3	2	0	4	1	514	99	0	42	664
235-270	2	2	0	6	1	497	110	0	40	657	

*Average of values taken from horizons directly above and below.

Table A1.8 Phosphorus fractionation for Spiritwood soil profiles.

	Depth cm	Horizon	Labile	NaOH	conc. HCl	Residual	Sum	1M HCl	Sum
			Pi	Pi	Pi	P	Po	Pi	P
Native						<i>µg/g</i>			
	0-5	Ah	80	31	67	49	232	96	554
	5-12	Ah/Ae	12	10	43	47	82	62	256
	12-21	Ae	3	5	30	44	33	33	149
	21-26	Bt1	3	7	68	53	32	86	250
	26-38	Bt2	3	7	99	44	33	537	723
	38-48	Bt3	4	10	159	46	25	507*	751
	48-57	Bt4	4	10	120	48	26	477	686
	57-74	Bt5	5	7	100	47	25	543	727
	74-90	Cca1	3	2	80	36	19	634	775
	90-95	Cca2	2	2	91	38	9	466	609
	95-115	Cca3	2	1	77	41	8	494	624
	115-135	Cca4	2	1	76	41	6	509	634
	135-150	Cca5	2	2	84	36	5	566	695
	150-180	Ck1	3	2	84	36	3	566	693
	180-210	Ck2	3	3	92	36	3	509	645
	275-305	Ck3	6	6	120	37	3	511	684
	395-550	Ck4	6	7	100	35	1	494	643
	550-700	Ck5	6	9	104	35	1	491	645
	700-855	Ck6	6	8	116	40	1	497	666
	855-915	Ck7	6	8	116	36	0	483	648
	915-1005	Ck8	6	7	113	37	0	491	653
Cultivated									
	0-10	Ap	16	15	40	52	103	59	286
	10-17	Ae	6	9	35	50	76	48	224
	17-22	Bt1	4	8	81	60	42	106	302
	22-37	Bt2	4	9	105	56	35	223	432
	37-50	Bt3	5	9	115	51	26	354	561
	50-64	Bt4	7	7	92	46	26	494	672
	64-70	Bt5	3	3	103	55	22	486	671
	70-84	BC/CB	1	2	105	46	15	480	649
	84-91	Cca1	1	1	80	47	16	497	643
	91-107	Cca2	1	1	70	49	12	491	625
	107-127	Ck1	2	2	79	41	6	520	649
	127-153	Ck2	2	2	83	42	5	557	692
	155-175	Ck3	4	3	83	47	10	463	610
	175-195	Ck4	3	3	85	44	2	526	661
	195-215	Ck5	3	4	104	41	2	571	725
	215-235	Ck6	5	4	99	42	1	514	664
	235-270	Ck7	5	6	110	40	1	497	657

*Average of values taken from horizons directly above and below.

Table A1.9 Phosphorus fractionation for Spiritwood soil profiles.

	Depth cm	Horizon	Labile	NaOH	conc. HCl	Residual	Sum	1M HCl
			Pi	Pi	Pi	P	Po	Pi
% Total P								
Native	0-5	Ah	14	6	12	9	42	17
	5-12	Ah/Ae	5	4	17	18	32	24
	12-21	Ae	2	3	20	30	22	22
	21-26	Bt1	1	3	27	21	13	34
	26-38	Bt2	0	1	14	6	5	74
	38-48	Bt3	1	1	21	6	3	68
	48-57	Bt4	1	1	18	7	4	70
	57-74	Bt5	1	1	14	6	3	75
	74-90	Cca1	0	0	10	5	2	82
	90-95	Cca2	0	0	15	6	2	77
	95-115	Cca3	0	0	12	7	1	79
	115-135	Cca4	0	0	12	6	1	80
	135-150	Cca5	0	0	12	5	1	81
	150-180	Ck1	0	0	12	5	0	82
	180-210	Ck2	1	0	14	6	0	79
	275-305	Ck3	1	1	18	5	0	75
	395-550	Ck4	1	1	16	5	0	77
	550-700	Ck5	1	1	16	5	0	76
700-855	Ck6	1	1	17	6	0	75	
855-915	Ck7	1	1	18	6	0	75	
915-1005	Ck8	1	1	16	6	0	75	
Cultivated	0-10	Ap	6	5	14	18	36	21
	10-17	Ae	3	4	16	22	34	21
	17-22	Bt1	1	3	27	20	14	35
	22-37	Bt2	1	2	24	13	8	52
	37-50	Bt3	1	2	21	9	5	63
	50-64	Bt4	1	1	14	7	4	74
	64-70	Bt5	0	0	15	8	3	72
	70-84	BC/CB	0	0	16	7	2	74
	84-91	Cca1	0	0	12	7	2	77
	91-107	Cca2	0	0	11	8	2	79
	107-127	Ck1	0	0	12	6	1	80
	127-153	Ck2	0	0	12	6	1	81
	155-175	Ck3	1	0	14	8	2	76
	175-195	Ck4	0	0	13	7	0	80
	195-215	Ck5	0	0	14	6	0	79
215-235	Ck6	1	1	15	6	0	77	
235-270	Ck7	0	1	17	6	0	76	

*Average of values taken from horizons directly above and below.

Table A1.10 Zirconium concentration in selected soil profiles.

Site	Soil Depth cm	Horizon	Zr ppm
Spiritwood Native	0-5	Ah	210
	5-12	Ah/Ae	280
	12-21	Ae	370
	21-26	Bt1	320
	26-38	Bt2	280
	38-48	Bt3	290
	48-57	Bt4	190
	57-74	Bt5	210
	74-90	Cca1	260
	90-95	Cca2	220
	95-115	Cca3	210
	115-135	Cca4	200
	135-150	Cca5	260
	150-180	Ck1	220
	180-210	Ck2	220
	275-305	Ck3	230
	395-550	Ck4	210
	550-700	Ck5	220
700-855	Ck6	260	
855-915	Ck7	230	
915-1005	Ck8	220	
Aberdeen Depression (2)	0-5	Ah1	180
	5-13	Ah2	220
	13-30	Ahe	310
	30-55	Ae	290
	55-60	Bt1	250
	60-65	Bt2	240
	65-80	Bt3	200
	80-95	Bt4	260
	95-100	BC1	230
	100-105	BC2	240
	105-123	BC3	270
	123-135	BC4	280
	135-154	BC5	350
	154-171	BC6	220
	171-200	Cca1	230
	200-220	Cca2	250
220-230	Cca3	260	
230-256	Cca4	260	
256-290	Cca5	300	

Table A1.10 contin. Zirconium concentration in selected soil profiles.

Site	Soil Depth cm	Horizon	Zr ppm
Swift Current	0-7	Ah	190
Depression	7-22	Aeg	200
	22-32	Bt1	220
	32-50	Bt2	230
	50-70	Bt3	250
	70-90	Bt4	230
	90-100	Bt5	240
	104-122	Cca1	220
	122-155	Cca2	170
	155-190	Ck	160

