REPORT #
RRTAC 91-4

SOIL PHYSICAL PROPERTIES

IN

RECLAMATION

by

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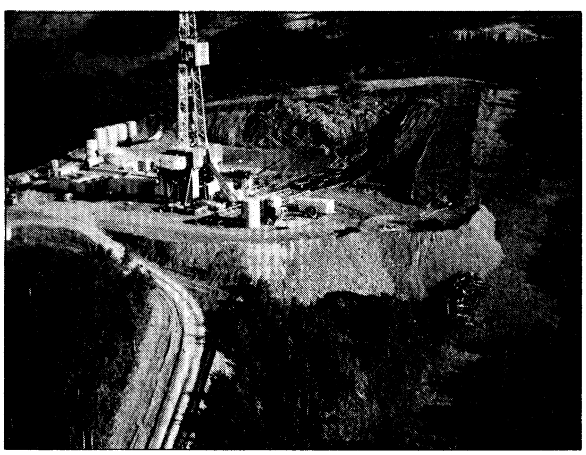

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DISCLAIMER

This report is intended to provide government and industry staff with up-to-date technical information to assist in the preparation and review of Development and Reclamation Approvals, and development of guidelines and operating procedures. This report is also available to the public so that interested individuals similarly have access to the most current information on land reclamation topics.

The opinions, findings, conclusions, and recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of government or industry. In particular, the threshold values in Section 16.3 are presented for discussion purposes only, and are not meant to be regulatory in nature. Mention of trade names or commercial products does not constitute endorsement, or recommendation for use, by government or industry.

REVIEWS

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effects on the soil ecosystem and what preventative, ameliorative, and/or remedial measures are possible

4. Conduct a soil physical properties workshop, involving professionals in Alberta to obtain and disseminate information available from their experience and/or research.

From the workshop, it was determined that routine use of soil physical characterizations was limited by a generally poor working knowledge of soil physical properties and how they are measured. The literature abounds with both theoretical and applied considerations of soil physical properties but little research examined the impacts of industrial disturbances on those properties for Alberta, or Canada in general. Much more information exists for the USA but it is not always possible to extrapolate those results to Canada. Thus an attempt was made to translate the literature into a document that could improve the working knowledge of soil physical properties and clarify the issues related to measurement.

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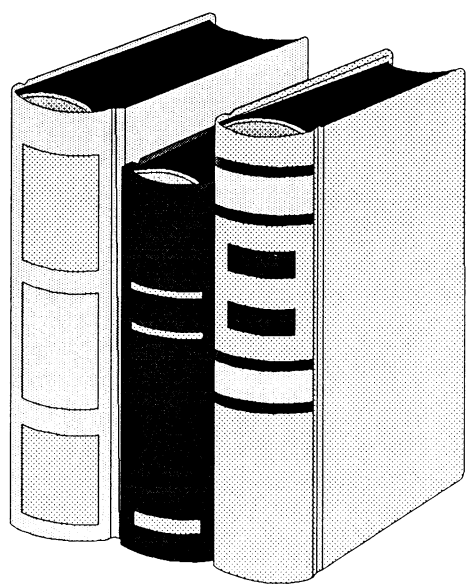
PART I

LITERATURE REVIEW AND DISCUSSION



'Where shall I begin, please your Majesty?' he asked.
'Begin at the beginning,' the King said, gravely,
'and go on till you come to the end:
then stop.'
Lewis Carroll 1832-1898
Alice's Adventures in Wonderland

1. INTRODUCTION

To provide coordinated direction for reclamation research in Alberta, the need to review the current understanding and the role of soil physical properties in soil disturbance related activities was identified. Surface coal mining, pipeline and wellhead construction, oil sands extraction, timber harvesting, and agricultural production activities alter the landscape to some degree and their cumulative effect has changed, and will continue to change, the soil resources of the province of Alberta. The nature and severity of these alterations are dependent upon inherent soil properties as affected by disturbance type and the success of reclamation and management practices.

Doll (1987) believed, "the goal of reclamation should be the establishment of a permanently stable landscape, aesthetically and environmentally compatible with the surrounding undisturbed land". Restoration of the productivity of reconstructed soil is a complicated problem. Nielsen et al. (1983) stated "In the past, management has been judged on annual measurements of crop productivity, and not on measurements taken below the soil surface that could be used to signal the long term consequences of management of present-day soil and water resources". The emphasis on chemical fertility has often resulted in neglect of soil physical properties that combine with chemical properties for optimum, sustainable, soil productivity. However, it is often soil physical properties that present the main limitations to reclamation of disturbed lands (Albrecht and Thompson 1982; King and Evans 1989; McSweeney and Jansen 1984). The over-emphasis on chemical fertility is attributable, to some extent, to the lack of reliable, quantitative descriptions of soil physical properties in the field. While studying soil physical properties in the laboratory using soil cores and repacked samples has yielded much information on core and repacked samples, there are limited guarantees that such information can be applied to the landscape (White 1988). In spite of soil physical properties being recognized as one of the critical productivity limiting factors in reclamation, soil chemical properties are still often used as the only criteria of reclamation success because of difficulties in characterizing soil physical properties (Omodt et al. 1975).

Often soil scientists, reclamation specialists, and agrologists concerned with management of disturbed lands are forced to seek answers to their questions regarding soil physical properties in a style once described by Oscar Wilde as "Chaos, illumined by flashes of lightning". Measurement of soil physical properties in the field is difficult; subject to spatial and temporal variability, time and length scales, and nonsteady, multidimensional velocity fields in a three phase system. Every soil physical property and process is also modified by weather phenomena (rainfall, frost, solar radiation, and drought), erosion, and human manipulation (management). Often the inability to characterize spatial variability prevents researchers from accurately matching soil use requirements to soil characteristics and, therefore, from predicting soil performance and behaviour. Soil physical properties and processes are closely interconnected, further complicating their measurement. It is also easy to understand why field measurement of soil physical properties has been described as a "challenge that few have ever accepted" (Nielsen and Biggar 1967). While that challenge is still evident in the measurement of many soil physical properties, the current challenge is related to selection of those soil physical property measurements that will best answer our questions, and the measurement techniques that will best provide that information. We must simplify a complex system by concentrating on the factors which appear to have the greatest and most direct bearing upon the problem at hand.

In the view of White (1988) "What properties we need to know and how we measure them are related directly to the questions we are attempting to answer". Through a Soil Physical Properties Workshop held in November 1990 for people in Alberta working with soil physical properties, and an extensive literature review, the authors have attempted to identify what questions have been answered, what questions remain unanswered, and what soil physical properties and measurement techniques are best suited to meeting information needs within Alberta. The objective of this review is not to provide a methodology manual or theoretical treatise on soil physics, but rather to assess the various properties and composite parameters and processes in a manner that hopefully will clarify, not confound. The report contains a brief overview of field related measurement methodology and spatial and temporal variability for each soil physical property, followed by a review of soil physical property interrelationships, the effects of development/ management activities on these properties, and the prevention/amelioration/remediation/acceptance strategies employed in dealing with changes in the physical property. Recommendations for future research follow a summary of physical properties most affected by reclamation activities and differences by disturbance type.

Finally, a word to those who view the introduction of the topic of soil physics as an opportunity to leave the room. Isaac Asimov (1969) recalled his initial reaction to physics in OPUS 100:

> "I once took a course in high school physics which, for some reason forever buried in the murky mind of the teacher, began with a long and detailed study of the incandescent lamp. I never recovered. I did poorly in the course, naturally, and I did not do remarkably well in my one college course in the science, either. Press the button marked physics in my brain and the first free-association response is electric lights. Fooey."

Asimov's reaction is shared by many. He overcame his electric light damage through the arduous task of writing a three volume work on understanding physics. Clearly, the appropriate application of soil physical property analysis for management purposes does not require such extreme measures. The following report is directed toward renewed incentive and direction for the use of soil physical properties analysis in the management of disturbed lands.

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To see a World in a Grain of Sand,
And a Heaven in a Wild Flower,
Hold Infinity in the palm of your hand,
And Eternity in an hour.
William Blake 1757-1827
Auguries of Innocence

2. TEXTURE

2.1 INTRODUCTION

Soil texture is defined as the relative proportions of the various sizes of particles in a soil. Qualitatively the term represents the "feel" of the soil material, whether coarse and gritty or fine and smooth. Quantitatively, the term denotes the measured distribution or proportions of particle sizes. Texture is a relatively permanent, natural attribute of the soil and is most often used to characterize its physical makeup.

The traditional method of characterizing particle size is to divide particles into three textural fractions: sand, silt, and clay (Hillel 1982). Individual particles in a soil sample are separated and measured after dispersion of aggregates. Measures of particle size are expressed as a percentage of soil material contained in the particle size range (textural fraction). Particle size varies widely from stones and rocks (> 2.0 mm diameter) to submicron clays (< 1 μm diameter). Various disciplines use different particle size limits to classify and evaluate soil for specific purposes. Thus variations occur in the particle size limits chosen to separate sand, silt, and clay, and in the percentage of sand, silt, and clay chosen to define a textural class. Gee and Bauer (1986), McKeague (1978), and Sabey et al. (1987) compared various classification schemes, while Shirazi and Boersma (1984) and Shirazi et al. (1988) provided a unified quantitative analysis for soil texture.

Textural separates impart distinct characteristics to a soil. There are other particle size classification systems but the following one is commonly used. The sand fraction is characterized by large particle size (0.05 mm to 2.0 mm diameter), small surface area per unit weight, low chemical activity, lack of plasticity, low total pore space, adequate aeration, low water-holding capacity, and few plant available nutrients. Clays are characterized by relatively small particle size (< 0.002 mm diameter), large surface area to weight ratio, hardness when dry, plastic and moldable when moderately wet and sticky when wet, high total pore space, usually small pores, high water holding capacity, chemically active when moist, and many available plant nutrients if not too weathered. Clays with shrinking and swelling characteristics (e.g., montmorillonite) impart considerable variability to this fraction. Silt particles (0.002 mm to 0.05 mm diameter) have properties intermediate between sand and clay (Sabey et al. 1987). The coarse fraction (> 2.0 mm) imparts variable characteristics to soils dependent upon type, size, and degree of weathering.

2.2 PARTICLE SIZE ANALYSIS

Measurement of the size distribution of individual particles in a soil sample, called particle size analysis (PSA) or mechanical analysis, is accomplished by dispersion of soil aggregates and separation of individual particles according to size limits. Soil particles can be separated with graded sieves down to diameters of approximately 0.05 mm. To separate finer particles, sedimentation methods (hydrometer or pipette) based on Stoke's law are used (Hillel 1980). Chemical and physical dispersion pretreatments are necessary to break down aggregates in most soils. Chemical pretreatments may also be required to remove organic matter, iron oxides, carbonates, and soluble salts.

Laboratory procedures are performed on loose samples with sample size dependent on soil structure and maximum size of fragments present. Gee and Bauer (1986) provide suggested sample sizes dependent upon particle diameter. They also reviewed laboratory procedures as did McIntyre and Loveday (1974) and McKeague (1978). Sabey et al. (1987) discussed particle size analysis in relation to reclaimed mine soils and overburden in the western United States.

Once the relative proportions of sand, silt, and clay are determined, a textural triangle is used to assign a qualitative textural term, incorporating all three values to classify the soil texture (e.g., loam, silt loam, sand).

2.2.1 Accuracy And Efficiency

The accuracy and efficiency of particle size determination is largely dependent upon the method of laboratory analysis. There is no general "best" method of particle size analysis. The appropriate method depends on the soil being analysed, purpose of the analysis, time constraints, and available equipment. If a textural categorization is required (e.g., loamy sand), the hydrometer method is generally sufficiently accurate. However, if a precise determination of percent clay is required, the pipette method is required. Sieving may also be used in conjunction with either the hydrometer or pipette methods to determine subcategories of sand. No method yields absolute results and all are empirical. Different methods of chemical and physical pretreatment will also affect results (Gee and Bauer 1986; McKeague 1978).

2.3 SPATIAL AND TEMPORAL VARIABILITY

Different sizes of soil particles result from weathering of parent material and vary according to pedogenesis associated with environment and landscape position. Localized pockets of material with variable particle size, such as sand lenses, can occur.

Coefficients of variation (CV) for soil texture are summarized in the Appendix. CV's for sand, silt, and clay fractions fall in the medium range of variation. Mausbach et al. (1980) found clay content could be estimated within $\pm 5\%$ clay (95% confidence level) by one to four samples in loess soils, two to eight samples in glacial drift soils, and four to twenty-four samples in illuvial and residual soils. Jury (1986) found the number of samples required to estimate percent sand or clay within a fraction, f = 10, 20, or 50% of the mean at the 95% confidence level, assuming spatial independence of properties and a CV of 40%, to be 64, 16, and 3, respectively.

2.4 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Size fractions play a fundamental role in the formation of physical, physiochemical, and chemical properties of soils because of their various degrees of firmness, chemical composition, and structural makeup. Coarse fractions increase the size of spaces between particles which facilitate movement of air and drainage water. However, they do not aggregate well and are thus prone to erosion; their water holding capacities are often low, promoting droughtiness. Silt particles have a tendency to stick together or to adhere to other particles, influencing soil crust formation after wetting. The fine clay fraction is colloidal in nature and has surface charges influencing sorption capacity of water and available nutrients. Clay particles adsorb water and hydrate, causing the soil to swell upon wetting and shrink upon drying. Because of its large surface area per unit mass and its resulting physiochemical activity, clay is generally the decisive fraction most influencing soil behaviour (Hillel 1980). Loam and silty materials in coal spoil banks are most productive because of good aggregation, drainage, aeration, available nutrients, and water holding capacity (Haynes and Klimstra 1975). Clay soils may be less productive due to poor drainage, poor aeration, increased compactibility, and high crusting potential.

Soil texture is the predominant determinant of water holding capacity in most agricultural soils (Saxton et al. 1986). Hydraulic conductivity is affected by soil texture through porosity. For example, gravelly or sandy soils with large pores can have saturated hydraulic conductivities much greater than clay soils with narrow pores, although total porosity of clay soils is generally greater than that of sandy soils.

Soil texture is directly related to soil structure in that structure is the spatial arrangement of elementary soil particles into compound particles, aggregates, or peds and the stability of these units. Coarse textured soils tend to be more granular in structure, whereas soils high in clay particles tend to group themselves in structural units of secondary particles or aggregates. Differences in texture are a major cause of variation in soil bulk density from one soil to another.

Soil texture indirectly influences plant root systems through effects on mechanical impedance and by modifying soil water, aeration status, and nutrient content and availability. Root growth is generally affected more in coarse textured than fine textured soils due to lower fertility, lower unsaturated hydraulic conductivity, and lower water storage (Glinski and Lipiec 1990). This was exemplified by higher progressive root growth and shallower rooting depth of wheat in sandy than loamy soils in India (Prihar and Gajri 1982).

Plant root growth will in turn affect soil texture. Modifications in particle size distribution and clay fraction composition can occur in the rhizosphere through accelerated disaggregation of compound shale fragments into component silt/clay particles (Glinski and Lipiec 1990).

2.5 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

Texture may be affected by development/management activities if subsurface materials are brought to the surface and/or surface materials incorporated into the subsurface. Increased stoniness may result from bringing rocks to the surface (Mutrie and Wishart 1989). This has often been reported in the literature on pipeline trenching, mining, forestry, and agricultural operations.

Particle size may be affected in mine overburden at the spoil-atmosphere interface. Down (1975) reported finding smaller particle sizes on spoil surfaces during the first 21 years after mining in Great Britain, after which aggregation tended to change it to larger sizes. These textural changes were very small at depths of 10 cm and nonexistent at 20 cm. Texture also varies with distance downslope on larger mine spoil piles as heavier (coarser) materials end up at the pile base.

Clay content was the only soil physical characteristic of spoil at the Whitewood Mine that significantly affected productivity through its association with water holding capacity (Edwards and Schumacher 1989). At the Syncrude and Suncor mines north of Fort McMurray, cover of agronomic plant species increased significantly with clay in years two and five but there was no relationship between cover of native invaders and clay content (Hardy BBT Ltd. 1990).

2.6 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

In reclamation activities, some mixing of soil horizon material is likely, often resulting in textural changes. This can not normally be prevented, but measures to minimize the problem can be practiced. In most cases, if care is taken to minimize the problem, remedial measures may not be necessary. This may be a positive change, such as when sand is mixed with clay soils.

To minimize mixing of topsoil and subsoil, topsoil should be stripped and stockpiled wherever the pipeline right-of-way (r-o-w) is graded (Mutrie and Wishart 1989). In Alberta, such practices must be followed. The stripped area should be wider at locations where a deeper and/or wider ditch is required (such as at road crossings, rail lines, foreign lines, watercourses, and side bends) or where the ditch is being excavated by a backhoe.

Considerations important in planning reclamation of strip mined areas include the prevention of perched water tables and soil anaerobosis which result when fine textured impervious materials are placed under coarser materials (Omodt et al. 1975). Where clay overlies sandy material, water will not enter the sand until the clay is close to saturation since the matric suction in the sand is markedly lower than that in the clay. The placement of materials with highly erodible textures in exposed positions or sloped areas should also be avoided (Sims et al. 1984).

The reclamation process may also include amendments to improve soil texture. Fedkenheuer (1980) found amending well drained sandy soil with peat at Syncrude improved texture to a loamy sand or sandy loam. In such a case, the peat would have had a substantial clay and silt content in order to effect a change in mineral texture.

2.7 PERSPECTIVE

Texture is a fundamental soil property and thus knowledge of it is essential to the understanding and interpretation of all soil physical properties and changes incurred in them through various development/management activities. In order to categorize a soil and to make comparisons among different research projects, texture should be determined for all study sites. Although some people are highly skilled at manual texturing, this is not recommended for reclamation research. The hydrometer method is recommended, being easy and reliable for textural determinations. Pipette analysis may be warranted where clay content is high and interest is focussed on that fraction. Pipette analysis is also generally used to confirm classification of a soil.

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Ay, now the plot thickens very much upon us.
George Villiers 1628-1687
The Rehearsal

3. BULK DENSITY

3.1 INTRODUCTION

Soil bulk density (D_b) is the ratio of the mass of dry soil solids to the total bulk volume of the soil. Bulk volume includes volume of the solids and the pore space. Mass is determined after drying to a constant weight at 105°C; volume is that of the field sample (Blake and Hartge 1986) and is either known (core method) or must be determined (clod and excavation methods).

Measures of bulk density are expressed in SI units (kg m^{-3}) and/or units derived from them. Mg m^{-3} is the preferred unit. Derived units, such as Mg m^{-3}, tonnes m^{-3}, or g cm^{-3} are numerically equivalent. D_b values range from 0.90 to 1.80 Mg m^{-3} (900 to 1800 kg m^{-3}). In commercial and engineering applications, Db is often expressed in lb ft^{-3} (Blake and Hartge 1986).

Measurement of D_b is influenced by soil water content and, particularly in expansive soils, water content measurements should accompany the D_b determination (Blake and Hartge 1986; McIntyre and Loveday 1974). If particle density is known, soil porosity can be calculated and an indirect indication of aeration status can be determined (McIntyre and Loveday 1974). Many soil analyses and nutrient values are converted from a gravimetric (mass) to volumetric basis using D_b (Blake and Hartge 1986). Different methods have different manpower and capital costs.

3.2 CORE METHODS

Core methods are among the most commonly used direct methods of sampling for D_b. A cylindrical metal sampler is hammered, driven at constant speed (hydraulic pressure), or augered into the soil to obtain a sample that can be analyzed in sections or increments (Raper and Erbach 1987). Sampler design varies from thin-walled metal cylinders to cylindrical sleeves fitted with removable sample cylinders constructed of various materials. Sample cylinders are carefully removed to obtain a relatively undisturbed and known volume of soil in situ. Further laboratory measurements such as pore-size distribution, infiltration, or hydraulic conductivity can then be conducted on the undisturbed core. Blake and Hartge (1986), McIntyre and Loveday (1974), and McKeague (1978) provided core sampling procedures. Common methods, suitable soil types, analyses performed, core dimensions, and efficiency and accuracy are presented in Table 3.1.

3.2.1 Accuracy And Efficiency

Specific research applications have prompted development of a variety of soil sampling devices (Erbach 1987). Two basic designs, the thin walled open probe and the double cylinder

Table 3.1. Core methods for bulk density sampling.

Referenced Method	Soil Types And Conditions	Analyses	Core Dimensions	Accuracy And Efficiency
1. Manual Pressure Methods:				
Lutz 1947 Double cylinder	Piedmont and coastal plains of widely varying properties	Bulk density Water content	6 cm x 4.2 cm 6 cm x 3.8 cm	Compression/fracturing in hard dry or sticky compact soil
Holowaychuk 1965 Serrated open edge probe	Organic deposits	Bulk density	14.6 x 35.56 cm	Only to 35 cm, frozen organic matter free of stones and rocks
Revut and Rode 1969	Small core - dense soils Large core - loose arable soils	Bulk density		
Pikul et al. 1979 Open probe	Top 10 cm summerfallow Silt loam	Bulk density Water content	5 cm x 20 cm	Performance determined by loose layer overlying compact
Tuttle et al. 1984 Open probe	Loamy sands and clay, samples, root cores on remote forest sites	Bulk density	7.62 cm x 45.0 cm	Some compaction on soils near field capacity
Doran and Mielke 1984 Double cylinder	Fine silty loam Silty clay loam	Bulk density	2.54 cm x 31.5 cm	Cores not retainable for further analyses
Sharma and De Datta 1985 Open probe	Well puddled surface soils	Bulk density	7.5 cm x 30 cm	Designed for well puddled soils
2. Auger Methods:				
Kelly et al. 1947	Moist soils	Bulk density Water content Permeability	5 cm x 180 cm	Dry soil slips from tube, stones limit operation, See Raper and Erbach 1987 for remediation
Buchelle 1961	Seedbed physical environment Sandy loam and silt loam	Bulk density Water content	8.5 cm x 30 cm to 90 cm depth	

Table 3.1. Core methods for bulk density sampling (continued).

Referenced Method	Soil Types And Conditions	Analyses	Core Dimensions	Accuracy And Efficiency
3. Hammer Methods:				
Uhland 1949	Loams	Permeability	7.6 cm x 7.6 cm	
Jamison et al. 1950 Sliding hammer open probe	Cecil clay Davidson loam		9.5 cm x 6.5 cm	Manual pressure - loose soils Hammer - compact soils
Jensen et al. 1960 Open probe	Silty clay loam, plastic wet, very hard dry soils			Reduced crop damage and compaction
Goit and Sheppard 1976 Open probe	Shallow frozen soils	Water content Bulk density	3.18 cm x 60 cm 20 cm increments	No consolidation or stone damage, soil freezes to core
Srivastava et al. 1982	Large undisturbed soil and root samples in clay and loam	Root mass Bulk density	25.5 cm x 7.6 cm x 60 cm depth	Compaction was less than conventional methods
4. Hydraulic Pressure Methods:				
Mielke 1973	Beef cattle feedlots underlying sandy and silty clay loams	Water content and movement	10.2 cm x 122 cm	Silicone spray lubricant used
Schickendanz et al. 1973	Loamy sands to clay		Various tips	Adaptable and mobile
Bausch et al. 1977	In tall standing crop, various lateral and vertical distances	Bulk density Water content	5.11 cm diameter 30 cm increments	Efficiency reduced in dry or high clay content soils
Dyck et al. 1977	Root zone of cereal crops		15 cm x 122 cm	Slight compaction
Ginn et al. 1978 Probe and hydraulic system	Cores in standing crops Sandy loam and clay	Bulk density Water content	10 cm x 125 cm Lateral span 100 cm	Can obtain cores from standing crops in wet and dry systems
Swallow et al. 1987 Double cylinder metal core with PVC lining	Establish encased micro-plots and obtain large cores	Infiltration Plant growth Charcoal rot	25 cm x 1.2 m core 7.6 cm x 1.2 m	Rocky, certain types of hard-pan caliche and root materials present problems

Table 3.1. Core methods for bulk density sampling (continued).

Referenced Method	Soil Types And Conditions	Analyses	Core Dimensions	Accuracy And Efficiency
5. Combination Methods:				
Bausch et al. 1977 Vertical pressure and rotary drilling	To obtain soil cores in tall standing crops		5.11 cm x 30 cm to 9 m depth, lateral span 152 cm	Efficiency reduced in dry or high clay soils
Foale and Upchurch 1982 Hydraulic ram and hydraulic jack hammer	Silty clay Fine sandy loam	Root length N movement D_b in nonplastic soils	2.0 to 5.0 x 2 m	
Wells 1959 Hammer and spiral slips Vehicle mounted auger	Red brown rendzinas Terra rosas, black earths Solodized Solonetz		5 cm x 120 cm 5 cm x 180 cm	Compaction, unsuitable for physical analyses and in dry and hard clay or stony soils
Stanek and Silc 1976 Cylindrical cutter, core holder attached to hand drill	Peat	Bulk density Pore space Water holding capacity	7.62 cm x 7.62 cm	
Schuh 1987 Hydraulic probe Maul or post driver	Non-cohesive soils of sand, loamy sand, and sandy loam textures	Bulk density Hydraulic conductivity Permeability Water content	5.3 cm x 6.3 cm to 2.5 m depths	Unsuitable in stony or gravelly soils, sample loss on coarse Cave in of auger holes before sampling
Ruark 1985 Sliding hammer with open probe and double cylinder core with plastic sleeve	Cores for root and nutrient determination over wide range of soil conditions	Root studies Nutrient determinations	Open probe 3.8 cm x 30 cm, double cylinder 6.35 cm x 35 to 50 cm	Hardened cutting tips allow sampling in rocky and heavily rooted soils
Tessier and Steppuhn 1990 Double cylinder with hydraulic and manual pressure	Loamy soils	Bulk density	4.75 cm x 30 cm	In clays require lubrication

sampler, operated by hand, continuous hydraulic pressure, intermittent hammering or jacking, or a combination of methods, present varied opportunities to maximize efficiency and accuracy.

Core compaction accounts for the largest error inherent in the method. Tapered sampling tubes provide clearance between the core and the inside of the soil tube reducing core compaction. However, excessive inside clearance can produce lateral deformation, slumping, and shortening of the core. The frictional force required to remove the core from the ground causes disturbances at the core edge and should be minimized through design modifications (McIntyre and Loveday 1974; Raper and Erbach 1987). Hammer-driven sampling increases sample distortion, particularly in soft cohesive soils and may cause plastic deformation of aggregates in a well structured soil rather than fracturing (Stone 1989). Jacking produces volume and plastic deformation in wet cohesive soils and increases compaction in non-cohesive soils. Uninterrupted pushing or hydraulic pressing produces the least compacted, least disturbed samples (McIntyre and Loveday 1974). Raper and Erbach (1987) concluded that an augered soil sampler disturbs the core less than pushed samplers in clay loam soils and Teflon™ coating the sampler tip did not reduce friction or increase accuracy.

To avoid compression or disturbance in heavy, compact, or plastic soils, core diameters should exceed 7.5 cm to minimize disturbance at the core edge (Blake and Hartge 1986; Jamison et al. 1950). However, in both very dry and wet medium textured soils, accuracy and efficiency did not increase with smaller diameter cores (2.54 to 4.75 cm) (Doran and Mielke 1984; Tessier and Steppuhn 1990). Nesmith et al. (1986) found larger cores (14.6 cm dia. x 10.1 cm long) more accurate but due to method destructiveness and inefficiency and high correlation of small and large core values, smaller cores (5.4 x 5.9 cm) were preferred.

The largest errors with manual or augered soil cores occur near the surface (0 to 10 cm) (Raper and Erbach 1987). Accuracies are not greater than $\pm$ 0.05 Mg m^{-3} using core methods under favourable conditions (Baranowski 1983). Baranowski (1983) also concluded increasing sample volume from 100 to 250 cm^3 did not affect measurement accuracy. Using one sample per plot, 10, 12, and 30 replications were required to detect a 0.01 Mg m^{-3} difference with 95% probability between tillage, depth, and tillage by depth interaction values, respectively (Elamin 1987 cited by Raper and Erbach 1987). In two different aged forest soil sites, on the North Carolina coastal plain, 5 to 26 samples were required to estimate D_b at a 0.05 probability level within 0.01 Mg m^{-3} using a 7.6 cm diameter core (Terry et al. 1981). Variations between hammering and hydraulic pressure methods significantly affected D_b values, but generally did not affect the ability of core parameters to detect differences in soil structure at specified water contents. Sampling technique may have less effect on structurally degraded soil (Stone 1989).

Coring devices designed to withstand rugged use require complex and heavy driving carts (Dyck et al. 1977; Swallow et al. 1987) and can result in site disturbance. Open probes and double cylinders with cutting edges or augers are not suitable for gravelly soils (Schuh 1987; Wells 1959) but function well in uniform textured soils. Small diameter soil cores (Doran and Mielke 1984) and incremental samplers (Pikul et al. 1979) may limit other analyses due to small sample size.

The core method is relatively capital-economic, requiring a coring device, a balance, and an oven. Manpower costs are high since sample collection is time consuming, particularly for greater depths, which often requires two people. Samples brought to the laboratory and weighed require a twenty-four hour drying period before final weighing; again requiring manpower.

3.3 EXCAVATION METHODS

Excavation, developed by soil engineers for bituminous and gravelly material, is utilized in tillage and forestry research where loose surface soil and stones prevent core and clod use (Blake and Hartge 1986; Flint and Childs 1984). Bulk density is determined by excavating a quantity of soil, determining the volume of the excavation (Table 3.2), then oven drying and weighing the excavated soil. Accuracy in measuring the excavation volume is the limiting factor.

Excavation methods are most useful in soils with loose surface horizons and those with coarse fragments. If water is used to determine volume, the holes can be coated with impermeable flexible liners or a flexible rubber balloon can contain the fluid. The technique limits sampling to level terrain (Flint and Childs 1984), although sand cones can be utilized on slopes (0% to 40%). Sand cones are based on the principle that poured sand settles to a specific D_b, so the weight of the sand poured into the hole indicates volume. Mensuration techniques and bead cone devices (like sand cone but beads are reused) can be used in irregular excavations and on steep slopes with large amounts of coarse fragments, respectively (Blake and Hartge 1986; Flint and Childs 1984).

3.3.1 <u>Accuracy And Efficiency</u>

The American Society for Testing and Materials (ASTM 1982a, b) has specifications for the sand cone and rubber balloon methods. Water and sand methods used on steep slopes require bench cutting to provide a level base, resulting in inaccurate measurement of surface horizons (Flint and Childs 1984). Puncturing the lining in the fluid method can cause measurement errors. Viscous fluid methods are difficult to use (Shipp and Matelski 1964). In fluid and sand methods, difficulty is encountered in ensuring the fluid or sand is level with the bottom of the template placed at the soil surface. Errors in 1 mm of sand level measurement result in an error of 0.01 Mg m^{-3} in D_b of 1.36 Mg m^{-3}. Compaction of sand during measurement, and accuracy and resolution of field measurement scales can present significant problems (Blake and Hartge 1986). Volume measurement using mensuration techniques with a 30 x 30 x 10 cm excavation and 36 depth measures on a 5 cm grid can result in errors of 1% assuming a cumulative error of 1 mm per depth measurement (Blake and Hartge 1986).

Table 3.2. Excavation methods for bulk density sampling.

Referenced Method	Soil Types And Conditions	Analyses	Sample Size	Accuracy And Efficiency
Blake and Hartge 1986 Sand funnel	Soils with loose surface horizons or with appreciable rock content	Bulk density	By coarse fragment size	Must excavate smooth round walls, remove stones, trim roots; difficult to determine when sand or water reaches template bottom and discriminate horizons
Blake and Hartge 1986 Mensuration apparatus	Soils with loose surface horizons or with appreciable rock content	Bulk density	By coarse fragment size	As above, has low accuracy level
Blake and Hartge 1986 Rubber ballon apparatus	Soils with loose surface horizons or with appreciable rock content	Bulk density	By coarse fragment size	As above
Shipp and Matelski 1965 Saran lined	Soils with coarse fragments >3 in diameter	Bulk density	By coarse fragment size	Slow, costly
Flint and Childs 1984 Bead cone	To remove slope limiation and increase volume of rock fragment size sampled	Bulk density	By coarse fragment size	1% accuracy with volumes accommodating rock fragments up to 8.5 cm; requires calibration

3.4 CLOD METHODS

Clod methods are commonly used direct methods of soil sampling. Bulk density is determined by weighing the clod, coating or saturating it with a water repellant substance, then weighing the coated/saturated clod in air and while immersed in a liquid of known density and temperature (Blake and Hartge 1986; McIntyre and Loveday 1974). A portion of the clod is removed and weighed before and after oven-drying at 105°C to calculate D_b as corrected for water content. A summary of common methods, soil types and conditions, analysis, equipment, and notes on accuracy and efficiency is provided in Table 3.3.

3.4.1 Accuracy And Efficiency

Small clods are not representative, as the macropore space between clods and the larger fragments of coarser soils are not included in the measurement. Choosing representative clods from disturbed layers is difficult because of packing by equipment (Blake and Hartge 1986; McIntyre and Loveday 1974). Also, sampling bias towards compact clods that resist deformation during measurement may exist (Shipp and Matelski 1965). Clod methods are not preferred but are utilized in situations where a specialized sampling apparatus is not available. Properties of soils with developed primary structure can be reasonably represented using clods with mass greater than 100 g (oven dry weight) although higher D_b are reported compared to other methods. Larger clods are required for soils with developed secondary and tertiary structure (McIntyre and Loveday 1974). Greater variability and considerably higher D_b are obtained from clods less than 250 cm^3 (McIntyre and Loveday 1974; Shipp and Matelski 1965).

3.5 RADIATION METHODS

Radiation methods were originally designed for determining properties of road beds, fill slopes, and foundations in engineering and construction (Gameda et al. 1987). They provide a rapid means of measuring wet D_b with suitable calibration (Erbach 1987). Radiation (in situ) methods involve measurement of scattered or transmitted gamma rays to obtain the combined density of gaseous-liquid-solid components of the soil mass (called wet D_b). Correction removes the components of density attributable to liquids and gases and yields a D_b measurement (Blake and Hartge 1986; Erbach 1982). D_b can thus be determined from wet D_b by separation of soil water, if its magnitude is known.

Bulk density is determined by measuring the scattering or transmission of gamma rays between a source and detector. This scattering or transmission varies with soil properties, including density. The scattering technique employs a single source and a detector located in either a surface gauge or single probe. Transmission (attenuation) techniques use two rods with the gamma source located in one rod and the Geiger detector in the other. Probes are inserted into

Table 3.3. Clod methods for bulk density sampling.

Referenced Method	Soil Types And Conditions	Analyses	Sample Size	Accuracy And Efficiency
Saran coating	Clods or coarse peds in soils with well developed primary structure	Water retention Bulk density Pore space Swelling characteristics	Representative clod	Difficult to obtain naturally occurring soil masses near surface; higher D_b as no accounting for interclod space
Paraffin wax coating	As above	As above	As above	As above
Kerosene saturation	As above	As above	As above	Kerosene coating used when large clods not obtained or poor aggregation High wetting causes clod distortion

access tubes or into pre-drilled holes in the soil to measure scattered or transmitted radiation. Soil water is measured concurrently to convert D_b to a dry soil basis. The dual source (combined gamma-neutron probe) simultaneously measures density and water with corrections required for dry D_b (Blake and Hartge 1986; Culley and McGovern 1990; Erbach 1987; Gameda et al. 1987). A brief summary of references is provided in Table 3.4.

3.5.1 Accuracy And Efficiency

The gamma-ray methods are rapid and limit soil disturbance. Soane et al. (1971 cited by Erbach 1987) reported that attenuation readings were as accurate as core samples and threefold faster. The single probe is limited by depth (20 to 25 cm), and accuracy in measuring conditions at or near the surface is limited (Erbach 1987). Culley and McGovern (1990) found single and dual combination probes, evaluated in the laboratory and field, gave good results. While the single probe is more influenced by near surface water, both single and dual instruments are equally accurate in determining wet D_b. Factory supplied calibration coefficients for gamma-ray probes have not yielded accurate results (Culley and McGovern 1990; Erbach 1987; Gameda et al. 1987) necessitating the calibration of probes for conditions of most use.

Radiation techniques require a high capital output ($5000 to $12000). However, they are manpower efficient, requiring one person who can take many readings in a short time. This facilitates statistical comparisons at a relatively low cost. Many modern instruments can be directly downloaded to a computer, obviating manual data recording. Radioactive techniques can be used for non-destructive repetitive measurements, thus preserving the physical integrity of a site. Manpower to drill holes and install tubes may be high but is a one-time cost at site establishment.

When using radiation techniques, the operator should be aware of the radiation hazard and adhere to strict safety guidelines. Commercially available equipment has the hazard reduced to safe levels, however it is important to adhere to recommended distances and other conditions described by the manufacturer. The equipment should be checked for radiation leaks on a regular basis. Vehicles transporting radioactive devices must display the appropriate warning signs.

3.6 SPATIAL AND TEMPORAL VARIABILITY

Bulk density variability is primarily related to sample quality and its representativeness of the soil mass under investigation. D_b changes systematically with landscape position, horizon, horizon depth, parent material, and at random (Cassell and Bauer 1975). Parent material, from least to most variable is loess, till, fluvial deposits, tectonic rocks, and drastically disturbed soil materials. Killpack (1982) observed the layer by layer soil replacement in Iowa coal mines caused greater vertical than horizontal variability and variability increased horizontally as lateral measurement distance increased. Good estimates of D_b can be obtained from a relatively small

Table 3.4. Radiation methods for bulk density sampling.

Referenced Method	Soil Types And Conditions	Analyses	Radiation Type	Accuracy And Efficiency
1. Single Source				
Single probe	Fine to medium texture	Bulk density	Gamma	Limited by depth, unsuitable for coarse textures soils
Double probe	Fine to medium texture	Bulk density	Gamma	
2. Dual Source				
Single probe	Fine to medium texture	Bulk density Water content	Gamma Neutron	Limited by depth, limited sphere of accuracy for water determination; useful for rapid profile determination
Double probe	Fine to medium texture	Bulk density Water content	Gamma Neutron	As above

number of samples (Warrick and Nielson 1980; White 1988) as indicated by relatively low CVs (5% to 10%) combined with a normal probability distribution. Field sampling technique requires consideration of intended analyses, cost, and site variability. Data on parent material, texture, and estimated CV ranges are available (Mausbach et al. 1980; Warrick and Nielson 1980; White 1988) to assist in plot design, sample method, and sample size. Mulla et al. (1990), Warrick and Nielsen (1980), and White (1988) presented appraisals of soil property measurement problems and spatial and temporal variability. A summary of D_b CVs is provided in the Appendix.

Year-to-year D_b fluctuations of a poorly drained lacustrine clay loam soil are reported to be independent of differences in soil water at sampling time and sampling technique (Stone and Wires 1990). In the same soil, seasonal effect on D_b was large, less variable, and exceeded any variation due to depth or time of tillage (Bolton et al. 1981). Seasonal fluctuations have been attributed to wetting/drying cycles (Horn 1988). Unexplained, early spring decreases in D_b were observed in forest soils of Southwest Georgia (Haines and Cleveland 1981). Kay et al. (1985) found seasonal variation in excess of 40% within the top 15 cm of an Ontario clay loam soil during freezing.

3.7 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Bulk density is influenced by soil texture, organic matter, soil shrinking and swelling characteristics, soil water, structure, and minerology; as well as sampling point stress history and location within the profile. It is related to strength, trafficability, plant growth, water infiltration, drainage, and the power required to till (draft). Even in extremely compacted soils, D_b remains appreciably lower than particle density, since particles can never interlock perfectly and the soil remains a porous body. Wires et al. (1987) studied silt loams during drying and clearly showed the dependence of D_b on water potential, reinforcing the contention that for comparison purposes, D_b must be expressed at a reference water content or potential.

With increased D_b, decreases occur in porosity, water retention, air diffusivity, and hydraulic properties; soil strength and thermal conductivity increase; pore size distribution will change towards a smaller proportion of large pores. There is an inverse relationship between Bernstein's modulus and the angle of internal soil friction with D_b (Wells and Treeswan 1978). However, Mapa et al. (1986) commented that over some compactive range, hydraulic conductivity as a function of soil matric potential may increase with increased D_b. This is likely due to a reduction in macropores leading to an increase in mesopores which are more conductive at medium water potentials. There is generally a direct relationship between D_b and texture, with D_b maximal in coarse textured soils. Organic matter lowers D_b as soil aggregation increases and/or average particle density is reduced. D_b varies with position in the soil profile, generally increasing with depth as porosity decreases and structure changes occur due to soil overburden. Gupta et al. (1989) presented a review of the effects of compaction (increase in soil density and decrease in fractional air volume) on soil structure. They related changes in density to microscopic structural changes and reviewed the mechanisms involved. D_b alone does not accurately reflect pore size distribution of the soil (Gupta et al. 1990). A reduction in macropore space and restricted water movement creates poor surface and subsurface drainage with resultant poor aeration, water logging, and nutrient and mineral imbalances. The larger number of micropores in fine-textured soils and slow water flow renders these soils most affected by increases in D_b. The lower the soil water diffusivity of a soil, the greater the effect of D_b on soil-water diffusivity (Libardi et al. 1982 and Jackson 1963 cited by Gupta 1989). D_b varies with soil structure, particularly that related to packing and is thus often used as a measure of soil structure.

The density to which a soil can be compacted is dependent upon soil water content as characterized by its Proctor density curve. D_b generally increases with increased soil water, reaching a maximum density and then declining as soil water content approaches saturation (De Kimpe et al. 1982; Saini et al. 1984). Harris (1971) termed soil water content at which maximum compaction occurs the optimum moisture content with values ranging from 25.88% to 38.32%. Saini et al. (1984) developed a compactibility index defining ease with which a soil compacted. Compression indices increased linearly as clay increased up to 33% then remained constant with further increases in clay content (Larson et al. 1980). Type of clay also affected compactibility, in the order of kaolinite < hydrous mica < montmorillonite. Howard et al. (1981) did not find D_b correlated with either silt or clay content, but organic carbon and water content were important.

Wetting and drying effects on soil D_b depend on clay content and activity (Heinonen 1986). Intense swelling upon wetting of dried montmorillonitic soils alleviates compaction in days. In micaceous clay, swelling is less pronounced and takes months with shrinkage cracks contributing permanently to soil water permeability. Wetting and drying have weakest effects in sandy soils.

Bulk density, through its interrelationships with other soil properties such as porosity, water retention, strength, and hydraulic properties (sorptivity, hydraulic conductivity, infiltration) affects plant growth. D_b can affect length, spatial arrangement, and total biomass of plant roots as well as seedling emergence, total biomass, plant growth patterns, and plant physiologic functions. These changes occur indirectly through reduced pore space and restricted soil air and water movement. Since the oxygen partial pressure affects root elongation and interacts with mechanical impedance, root reactions to changes in D_b cannot be totally ascribed to the mechanical constraint exerted on roots (Tardieu 1988). Response to mechanical stresses is affected by the physiological status of the plant such as its water potential, oxygen uptake, and hormonal fluctuations. As a consequence, the entire plant is affected by soil physical properties such as D_b.

The literature contains many references to plant growth limiting D_b values. These values are soil type specific (Carter 1990), with critical D_b for rooting inversely related to % silt and clay (Jones 1983). Veihmeyer and Hendrickson (1948) found sunflower root growth was stopped at a growth-limiting D_b of 1.75 Mg m^{-3} for sandy soils and 1.46 and 1.63 Mg m^{-3} for clay soils. Similarly, Voorhees et al. (1975) found pea root growth stopped at 1.61 Mg m^{-3} in sandy loam but at 1.37 Mg m^{-3} in clay. The increase in D_b tolerable on fine textured clay is different from that for sandy soils which compact to higher density and to a greater extent when dry. Plant roots will, however, penetrate dense sandy soil (1.60 Mg m^{-3}) more easily than clay soil of similar density (Albrecht and Thompson 1982). In clay soils with a high shrink-swell potential, roots can develop freely in zones of weakness between peds (Jones 1983). Small D_b increases on fine textured soil can limit growth due to loss of macropore volume (Doll 1987). Volume and characteristics of the macropore system may be more important for soil functioning than D_b, particularly in layers not annually ploughed (Hakansson 1990). Air dry soil compacted at an applied stress of 173 kPa develops a similar D_b as a soil packed at field capacity and an applied stress of 87 kPa. However, the infiltration rate is 30 times higher for soil packed under the former conditions. Thompson et al. (1987) found the correlation of D_b to root growth was high with an R^2 of 0.81.

Bulk density is in turn affected by plant growth. As roots grow they occupy soil pores, soil particles will be pushed aside, and D_b of the soil near the root will increase within a distance of 1 to 2 mm (Glinski and Lipiec 1990). Large tree roots will affect the soil within a greater distance.

3.8 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

Changes in D_b are dependent on disturbance type and can be linked to loss of topsoil, mixing of topsoil and subsoil, decreased organic matter levels, altered soil hydraulic properties, and increased surface stoniness. The degree of change is directly associated with soil type (especially texture), soil water during the disturbance and replacement, land use, and type of construction activity, particularly the applied load or force.

In most development/management activities, soils are prone to D_b increases from repeated high traffic and heavy construction equipment. Factors affecting D_b include tire characteristics (type, dimension, inflation pressure), load, speed and number of passes, and wheel slip. It is generally believed that compaction close to the soil surface is a function of the tractive device and subsoil compaction is a function of total load (Raghavan et al. 1976; Taylor et al. 1980; Voorhees et al. 1986). These factors are covered in a literature review by Cannon and Landsburg (1990). As the subsoil is often a surface for heavy traffic in mining operations, compaction at this depth occurs due to both causes.

Changes in D_b associated with pipeline construction are most affected by soil type. Culley et al. (1981, 1982) found disturbance increased D_b at all depths over the Sarnia-Montreal pipeline on medium and fine textured soils, but not on coarse textured soils. On sandy clay loams and silty loams, D_b increased in trench (1.24 Mg m^{-3}) and work areas (1.27) compared to undisturbed areas (1.17) due to high clay content and wet conditions during installation. On clay loams, D_b was lower, 1.10, 1.17, and 1.22 Mg m^{-3} in the undisturbed, trench, and work areas, respectively. Halvorson et al. (1980) foundincreases from 1.24 Mg m^{-3} in undisturbed areas to 1.57 Mg m^{-3} in trenches on sandy loam soils but was not changed in clay loams and silty clay loams. Ramsay and Mackenzie (1978), Stewart and Mackenzie (1979), and Shields (1979) found similar trends on clay loams and sands. Shields (1979) reported D_b increased 10% on the r-o-w. De Jong and Button (1973) reported decreased D_b from 1.55 to 1.44 Mg m^{-3} on all zones of the r-o-w in Solonetzic soils. On Chernozemic loams, D_b increased from 1.20 to 1.40 Mg m^{-3}. Season of construction had little effect on compaction levels (Stewart and Mackenzie 1979).

Pipeline construction activity affected D_b in different areas of the r-o-w. On fine loamy sands in semi-arid Oklahoma, D_b was lower in the trench than on the working side and control areas at all depths (Zellmer et al. 1985). On Alberta loam-silt loam textured Solonetzic soils, Naeth et al. (1987) found disturbance increased surface D_b 51% to 82% relative to undisturbed mixed prairie; with trench D_b near 1.60 Mg m^{-3} and work areas at 1.30 to 1.40 Mg m^{-3}. Compared to undisturbed prairie, trenching reduced D_b below 25 cm depth, but increased D_b to 55 cm depth in other parts of the r-o-w. Rowell and Crepin (1981) found compaction a major problem in cultivated Chernozems, particularly over the trench. Landsburg (1989) reported no significant changes in Ap horizon on the work side of either Dark Brown Chernozemic or Solonetzic soils. On the spoil side, D_b increased from an undisturbed 0.82 to 1.09 Mg m^{-3} in the Chernozems and from 1.16 to 1.22 Mg m^{-3} in the Solonetzs. Bulk density increased by as much as 0.79 Mg m^{-3} on the trench in Luvisols near Heart River, Alberta (Cloutier 1988). At 15 and 30 cm, trench D_b was lower than treatment controls due to increased organic matter in the trench and the breaking up of the Bt horizon. D_b in the work area increased from 1.17 to 1.43 Mg m^{-3}. The plow-in technique lead to increased D_b over the trench in the 0 to 15 cm depth the year after construction but not in the second year (Landsburg and Cannon 1989). There were no increases at 15 to 30 cm nor on the two- and three-lift operations four years after construction.

In five of seven projects in Alberta that were reviewed, D_b increased. There were no differences between stripped and nonstripped topsoils in Luvisols and Chernozems or in two- and three-lift materials handing construction procedures. In some cases, pipeline construction may actually reduce D_b. Naeth et al. (1987) found pipeline construction initially reduced surface D_b compared to blowouts on Solonetzic soils and improved D_b to 55 cm depth in the trench compared to the undisturbed prairie.

Soil handling and storage during surface mining activities may result in increased D_b, particularly with large earth moving equipment such as scrapers (Jansen and Dunker 1987). In mid-west USA, Albrecht and Thompson (1982) found pre-mined D_b of 1.2 to 1.4 and post-mined D_b of 1.7 to 1.8 Mg m^{-3}. In Northumberland premined soils with clay loam topsoil overlying clay loam and clay subsoil, D_b increased most (1.59 to 1.68 Mg m^{-3}) at depths of 0.2 to 0.5 m (King

1988). Pederson et al. (1980) reported surface (0 to 0.5 m) D_b of 1.76 Mg m^{-3} in Appalachian minespoils low in organic matter and high in coarse fragments due to blasting of overburden rock during mining operations. D_b first increased, then decreased with depth. In North Dakota fine silty and fine loamy soils, D_b increased from 1.03 Mg m^{-3} in undisturbed topsoils to 1.37 Mg m^{-3} in reconstructed soils (Potter et al. 1988). In south-west Indiana on silt loams, D_b increased after mining with an average D_b of 1.53 Mg m^{-3} in topsoil and 1.77 Mg m^{-3} in the overburden (Bussler et al. 1984). Anderson et al. (1989) found mining of Indiana fine silty and loamy soils increased D_b from 1.29 to 1.70 Mg m^{-3} in the undisturbed topsoil and subsoil compared to 1.53 Mg m^{-3} in the disturbed topsoil and 1.69 to 1.77 Mg m^{-3} in the overburden. In four to seven year old reclaimed North Dakota loam minespoils in the 0 to 50 cm depth, D_b was 50% to 60% greater for reclaimed than undisturbed areas (Schroeder 1989).

In some mining sites, D_b decreased after reclamation. In North Dakota, Gee et al. (1978) reported decreases in D_b as volume increased 20% to 25%. Harrison (1974) found D_b in the Crowsnest Pass and Elk Valley of Alberta and British Columbia was affected by both material composition and compaction history. D_b of weathered bedrock and spoil was 1.38 to 1.62 Mg m^{-3} at the dump platform. D_b of carbonaceous shales and sandstone at the free face were 0.97 to 1.13 Mg m^{-3} whereas it ranged from 1.13 to 1.46 Mg m^{-3} at the dump platform. D_b of bituminous coal in situ was 0.97 Mg m^{-3}, but where soil was wheel-compacted, D_b was 1.22 to 1.30 Mg m^{-3} .

Scraper and bulldozer traffic used in topsoil replacement and regrading can create a layer of higher bulk density directly below the replaced topsoil layer (Albrecht and Thompson 1982). When soil is replaced with scrapers, a higher density layer is formed every time a lift is replaced causing a wave of compacted layers. Problems are more prevalent in sandy soils and soils with low organic matter than in clay soils. These layers may require up to 15 years to return to predisturbed D_b levels naturally. Often affected soils must be subsoiled to shatter these layers.

Vegetative treatment also has an impact on bulk density. At Grande Cache, Alberta, coal mine spoil D_b ranged from 1.07 Mg m^{-3} on plots established for five years with minimum compaction and high organic matter to 1.81 Mg m^{-3} on unrevegetated disturbed sites.

In lignite strip mines on fine silts and fine loams, differences between reclaimed topsoil and subsoil and undisturbed A and B horizons existed four and eleven years after reclamation (Potter et al. 1988). D_b on non-topsoiled reclaimed mine land in southwestern Illinois (1.5 Mg m^{-3}) was 15% higher than that on topsoiled land (Chong et al. 1986). In minesoil reclaimed to forest in southwestern Indiana (pre-mine fine silty loams) topsoil D_b was 1.53 Mg m^{-3} and graded cast overburden was 1.69 to 1.77 Mg m^{-3} (Bussler et al. 1984). Chong et al. (1986) found Indiana silt loams reclaimed without topsoil had D_b of 1.5 Mg m^{-3}, 15% greater than topsoil treatments.

Several researchers concluded physical properties of minespoil were less favourable than those of unmined reference soils. Although the theoretical limiting value was 1.80 Mg m^{-3}, minesoil D_b of 1.70 Mg m^{-3} restricted corn root penetration in western Illinois (Fehrenbacher et al. 1982). Heilman (1990) found D_b of spoils reclaimed from open pit mines in western Washington were significantly higher (to 1.87 Mg m^{-3}) than unmined soils. Although the upper limit for root growth of Douglas fir and red alder in loams and sandy loams was 1.45 to 1.60 Mg m^{-3}, D_b associated with root limitations in finer textured soils was as low as 1.32 to 1.35 Mg m^{-3}. On reclaimed Solonetzic and Dark Brown Chernozems, subsoil densities on all treatments were very high averaging 1.7 Mg m^{-3} but there was a trend with time to natural amelioration over five years detected with radiation measurements (Leskiw 1989). Densities were still high at 1.34 Mg m^{-3} in the topsoil, 1.80 Mg m^{-3} at 15 to 30 cm, and 1.77 Mg m^{-3} at 30 to 45 cm. Macyk et al. (1988) found bulk density varied during the growing season on the Paintearth mine. Overall D_b decreased with time. D_b varied from 1.16 to 1.76 Mg m^{-3} at the surface and from 0.99 to 1.80 Mg m^{-3} at a 90 cm depth. In research plots at the Battle River mine, topsoil D_b was normal for agricultural soils but subsoil densities were excessive at 1.70 Mg m^{-3} (Leskiw 1989). Bulk density on well drained reclaimed sandy soils at Syncrude was 0.84 to 1.29 Mg m^{-3} at 18 cm and 1.43 to 1.49 Mg m^{-3} at 36 cm (Fedkenheuer 1980).

Byrnes et al. (1981) reviewed the literature on transmission r-o-w construction. Increases in D_b were reported from heavy construction equipment on access roads, and near structures, wire pulling sites, and graded areas. D_b increased 10% to 20% in access road areas and yield reductions were measured for two to three years after construction. On peatland in northwestern Minnesota, surface D_b increased significantly after construction. On oil and gas wellsites in east-central Alberta, Thacker (in preparation) found on-lease D_b of 1.53, 1.39, 1.62 Mg m^{-3} compared to off-lease D_b of 1.42, 1.32, 1.42 Mg m^{-3} for loams, sandy loams, and silty loams, respectively.

Agricultural practices, through pressure applied by tires on the surface, pressure beneath the surface by tillage implements, and shear deformation at the time of operations all contributed to D_b increases (Byrnes et al. 1981). The first pass with any type of equipment reportedly caused the greatest increase with wheel slippage and equipment storage causing further increases. Common axle loads of agricultural equipment (9 to 18 Mg) can compact soil deeper than normal tillage depths (20 to 30 cm), particularly under wet conditions. In three upper Bavaria soils, Becker and Martin (1988) found D_b increased to 50 cm due to tillage and harvesting with heavy machinery. In studies on Maryland silt loam to assess effects of continuous long-term conventional and no-tillage management, the largest differences in D_b occurred at 3.8 cm depth and were equalized by 30 cm.

Chang and Lindwall (1989) found no significant differences in D_b between long-term conventional, minimum, and no-tillage on Chernozemic clay loams in southern Alberta. Chanasyk and Nyborg (unpublished) found higher surface (0 to 7.5 cm) D_b under no-tillage for both Chernozemic and Luvisolic soils. In a no-tillage corn production system, D_b was unaffected by cover crop, but significant differences occurred between row, untrafficked, and trafficked areas, with trafficked areas having higher D_b (1.70 to 1.76 Mg m^{-3}) to 17.5 cm (Wagner and Denton 1989). Hill and Meza-Montalvo (1990) found bulk density increased from wheel traffic in silt loams under both no-till and conventional tillage. There were 50% increases in D_b in wheeled versus non-wheeled areas, although this was less under no-till than conventional till. The effects decreased with depth and were largely dissipated by 30 cm.

Use of small scale farm equipment (axle load < 4.5 Mg) does not alter soil physical properties to an extent detrimental to plant growth. Although D_b is used to determine effects of agricultural management practices, it may not be the most sensitive parameter. D_b increased with wheel traffic and depth, but soil strength was considered a more sensitive indicator of effects (Hill and Meza-Montalvo 1990). Voorhees et al. (1986) also concluded that measures of hydraulic conductivity and penetrometer resistance were better indices of compaction than D_b.

Grazing has an impact on soil D_b. In mixed prairie and fescue grassland ecosystems of Alberta, Naeth et al. (1990) found heavy intensity and early season grazing had a greater effect on D_b than did light intensity and late season grazing, increasing D_b by at least 0.10 Mg m^{-3}. D_b changes due to grazing were to a greater extent and depth on Chernozemic than Solonetzic soils. Warren et al. (1986) found similar results near Sonora, Texas; D_b increased significantly with increased trampling rate and soil water.

Forestry activities, particularly ground-based timber harvesting, increased D_b resulting in long-term reduction in tree growth rates (Wert and Thomas 1981). Allbrook (1986) found traffic during log harvesting using ground based-skidders (axle load 3 to 7 Mg) on Oregon volcanic soils increased D_b up to 25%, with maximum effects found 15 to 20 cm below the surface. Natural recovery of D_b on skid trails was slow and varied with soil type and depth. Froehlich et al. (1985) found D_b on volcanic soils and below 5 cm on granitic soils had not returned to predisturbed values in 23 years. Ruark et al. (1982) reviewed influences of compaction on tree root growth and tree vigour and Froehlich and McNabb (1984) discussed D_b and tree root growth relationships. Both emphasized the use of D_b as an index of change related to texture, water, soil strength, and aeration of a particular soil at a particular site. Childs and King (1990) examined forest soils with rock fragments, demonstrating that in skeletal soils, high total soil D_b does not necessarily indicate a poor root growth environment. On coarse textured granitic soils in south-western Idaho, Clayton (1990) found caterpillar tractors and rubber tired skidders increased bulk density 15% on main and secondary skid trails. In western Canada, skidder traffic on roads and tracks increased D_b by more than 65% of the undisturbed soil (Senyk 1990). Surface D_b increased from 0.85 to 1.44 Mg m^{-3}. On the total road, not just the track, D_b increased 12% from 1.63 to 1.82 Mg m^{-3}. The number of passes contributed the most to the severity, regardless of running gear or vehicle weight. This was particularly true after 15 to 20 passes, after which surface debris, root mats, etc. no longer provided flotation even for wide tires. A 26 tonne forwarder increased D_b in sandy loam forest soils up to 34% to 780 cm, with the greatest increase in the first pass (Jakobsen 1985).

Forest disturbances are different from agricultural ones in that tree roots persist and apply mechanical forces for long periods of time; felling and snigging of large trees impose unique loads on soils (Graecen and Sands 1980). After logging spruce forests, it takes five to seven years for D_b to return to normal in well drained soils and 15 years for semi-hydromorphic soils (Graecen and Sands 1980). Forest disturbances such as tree skidding increase bulk density, with skid trail D_b 10% to 12% greater than undisturbed soils (Standish et al. 1988). Traffic increases D_b at 7.6 to 15.2 cm depths off primary skid trails and 22.9 to 30.5 cm on skid trails. Some increases are attributed to soil displacement and exposure of naturally denser soils. Most serious degradation from severe soil disturbances (scalping, compaction, puddling) are associated with landings and skid roads or landslides triggered by harvesting operations.

3.9 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

Development/management activities alter D_b. In most situations, due to required use of heavy equipment, some compaction, and thus increases in D_b, are not completely preventable. There are, however, various ameliorative and remedial procedures that successfully alleviate this increased D_b. From the agronomically related compaction literature, it becomes evident that the primary method for reducing compaction is to avoid the application of compaction forces. This can be best accomplished by not working soils under wet conditions, particularly those soils low in organic matter. These same recommendations are summarized in the forestry compaction literature. Monitoring to ensure proper topsoil conservation and replacement of spoil materials was recommended for pipeline r-o-w (Culley et al. 1982; Landsburg 1989).

Increases in D_b from pipeline construction activities can be minimized by construction during optimum weather conditions (hot and dry). Landsburg (1989) found that if construction in a cultivated Chernozem and a Solonetzic pasture occurred during optimum weather conditions with no rutting or mixing of topsoil and subsoil, D_b did not increase in the Ap horizon of the workside or trench. It increased on the spoil side, but values did not limit crop growth. Winter versus summer pipeline construction is recommended but few data are available for analysis.

McSweeney and Jansen (1984) recommended soil construction operations need to be carefully evaluated to determine their influence on the physical condition of resultant minesoils. Resultant bulk density is closely related to machinery used in deposition of soil, with little change in D_b from side dumping haul trucks, bulldozers, and draglines but significant compaction with scrapers (Schafer et al. 1979). Using bulldozers to spread material will create fewer D_b problems than scrapers because of their lower ground pressure (Albrecht and Thompson 1982). Compaction can be avoided if disturbance is avoided when the soil is wet, if light equipment is used, if wide tracks and low pressure tires are used, if tillage and subsoiling are carried out, and if traffic patterns on the mine are controlled (Asplundh Environmental Services 1981).

Operations using a mining wheel or bucket wheel excavator in combination with belt transportation favour the formation of more desirable fritted structure, whereas operations using scrapers exclusively favour formation of less desirable massive physical conditions. Combination bucket wheel excavator/conveyor systems are successfully being used in Illinois (Smout 1989). Hauling by base-level, rear, or bottom dumping trucks avoids traffic on soil being replaced and can thus reduce compaction (Smout 1989). Since the compactive effort applied by reclamation equipment is not uniformly applied over the mine site, but is concentrated under tire paths, average D_b may not be an adequate measure of soil compaction on reclaimed land (Sweigard et al. 1989). Even areas of high D_b may have sufficient interconnected voids for root penetration and water infiltration to minimize normal detrimental effects. Because machinery is only as good as the operator, there is a need for skilled operators and inspectors.

Hardy Associates (1983) recommended reducing surface D_b by cultivation and subsurface D_b by deep cultivation. Schroeder (1988) found that chiselling, grader ripping, deep ripping, and subsoiling after or during subsoil respreading, but prior to topsoil respreading, did not lower D_b and recommended that methodologies be developed to reduce D_b after reclamation and reseeding. D_b has been reduced in compacted minesoils using a vibrating chisel capable of operating to 120 cm depths (McCormack 1989). However, its operation is expensive and perched water tables at the contact between the loosened upper profile and the compacted soil below were reported. Mutrie and Wishart (1989) found topsoil D_b on the work side of pipelines increased with no stripping, ditch line stripping, blade width stripping, and ditch with spoil side stripping, but was minimized with full r-o-w stripping and stripping frozen soils. Ripping was, however, often required to reduce increased subsoil D_b. Chiselling of reworked spoil after land forming and before topsoil application reduced bulk density and facilitated infiltration and percolation (Omodt et al. 1975). These researchers also discussed the bulk density related problem of large spoil voids caused by large overburden blocks, which, after grading or levelling can cause surface channels and hollows. They suggested the problem could be minimized by spreading overburden over a wider area during stripping and avoiding grading and levelling frozen spoil. After compaction on primary and secondary logging skid trails, bulk density was reduced with ripping, but ripping had no effect on increased bulk density on landings to a 10 cm depth (Clayton 1990).

Surficial organic amendments, particularly in combination with deep ripping have reduced high bulk densities due to surface mining (Chanasyk and Naeth 1989). At the Highvale mine, surface D_b was significantly higher in unripped and ripped treatments (1.01 to 1.15 Mg m^{-3}) compared to ripped+peat and ripped+manure treatments (0.84 to 0.97 Mg m^{-3}). From depths of 15 to 35 cm, D_b was highest in the unripped treatment. After several years of massive sewage sludge additions to the soil, Glauser et al. (1988) found a dramatic decrease in soil bulk density on treated plots, from 1.27 to 0.88 Mg m^{-3}. Leskiw (1989) suggested amendments more effectively increased crop yields when placed on the surface than above the spoil. Bottom ash was more effective than gypsum in reducing D_b although gypsum was initially used to reduce SAR.

Natural systems such as freeze-thaw regimes, wet-dry cycles, earthworm and other burrowing animals, and plant roots reduce postmining D_b, but are very slow. Since handling soil when it is dry minimizes compaction, mine operators can plan to handle topsoil and subsoil materials during seasons in which soil has the lowest water content (McCormack 1989). Kay et al. (1985) found freeze-thaw cycles in Ontario did not reduce D_b of soils compacted under zero-till despite the formation of extensive ice lenses in the soils. Moran et al. (1987) found in plains coal mines of Alberta that D_b was greatest for any depth in April then declined in May through August, increasing again in September and October, with a gradual decrease in the overall D_b over two years. Ashby (1989) tested plants with a large number of deep roots per unit area for their usefulness in mitigating compaction problems of graded minesoils. Bald cypress, hybrid poplar, sycamore, and silver maple roots were the most successful in penetrating the compacted reclaimed minesoils. Culley et al. (1982) recommended that the r-o-w be seeded with legumes rather than with row crops.

With time, many disturbances will revert back to near predisturbed levels. Leskiw (1989) found bulk density in the topsoil did not change on the Vesta Mine over one year (1.33 in 1988 and 1.30 Mg m^{-3} in 1987), or in the subsoil (1.67 Mg m^{-3} both years). However, it decreased in the spoil material from 1.58 in 1987 to 1.46 Mg m^{-3} in 1988.

3.10 PERSPECTIVE

Bulk density remains the soil physical property most easily understood and widely used by researchers, field extension people, and government regulators. It is often used as an interpretive guide to problem soils, in spite of the paucity of limiting values to plant growth for a variety of soil textures. Although its sensitivity as a parameter to indicate changes in soil physical status is questionable for this reason, many researchers consider bulk density to be a good predictor of root system performance, especially root extension, in newly constructed soils. It has the distinct advantage of being relatively easily measured.

When measurements are to be repeated at a site, bulk density is best measured by radioactive methods, which have the advantages of being non-destructive, rapid, and relatively accurate. If radioactive instruments are not readily available, the core method is most appropriate. Whatever method is chosen, sampling with the same method should be continued throughout the duration of study.

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A sheep in sheep's clothing.
Edmund Gosse 1849-1928
Under the Bridge

4. POROSITY, VOID RATIO, AIR FILLED POROSITY, AND PORE SIZE DISTRIBUTION

4.1 INTRODUCTION

Knowledge of the number, size, configuration, or distribution of soil pores is essential for a meaningful evaluation of structure. However, classification of pore size lacks standardization. Bevin (1981), Bouma (1981), Luxmoore (1981), and Skopp (1981) presented and discussed different classification schemes and approaches to describing pore size. Pores are generally classified as macropores >100 μm, mesopores 30 μm to 100 μm, and micropores <30 μm. Pore space is often more useful in characterizing the soil medium for plant growth or other uses than soil texture or density (Danielsen and Sutherland 1986; Doll 1987).

Porosity (S_t) is defined as the ratio of the volume of the pores to the soil bulk volume (the volume of solids plus pores). Void ratio is the ratio of the volume of pores to volume of solids. Air filled porosity is the ratio of air filled void space to the soil bulk volume. Pore size distribution refers to the relative proportions by volume of different-sized pores (Danielson and Sutherland 1986; McIntyre and Loveday 1974).

Porosity is calculated from D_b and particle density (D_p) according to $1 - (D_b/D_p)$. It can be expressed as a decimal (less than 1.0) or a percentage. Porosity of mineral soils generally ranges from 28% to 75% and that of organic soils from 55% to 94%. Particle density is calculated from a measured soil mass and volume as determined from the density of a fluid (usually water) displaced by the quantity of disturbed sample analyzed. Particle density is generally constant over time and estimates may be satisfactory where highly accurate determinations are not required. The particle density of many mineral soils is approximately 2.65 Mg m^{-3}. Estimates should be avoided when an accurate weighted mean density of all sample particles is required. Particle density of an Alberta clay loam (39% clay, 41% silt, and 20% sand) ranged from 2.45 Mg m^{-3} to 2.50 Mg m^{-3} (Singh 1991). In mine spoils, assumption of a constant particle density may lead to erroneous values for clay and fine silt (Shetron and Trettin 1984).

Void ratio, a common term in engineering, is calculated from the particle density and bulk density [(particle density/bulk density) - 1]. It is also related to porosity; for example if porosity is equal to 50%, void ratio equals 1.00. Void ratio is useful when measuring soils undergoing changes in total volume due to compaction, swelling, or shrinking and ranges from 0.39 to 1.37 (Glinski and Lipiec 1990). The relationship between void ratio and total porosity is illustrated in McIntyre and Loveday (1974).

Air filled porosity can be calculated from measured bulk density, water content, and particle density. It can also be evaluated in the field using variable (Russell 1949) or constant (Page 1948) volume air pycnometers. Pore size distribution is determined in the laboratory after measurement of the pressure difference across an air-liquid meniscus associated with incremental desorption or intrusion of a liquid of known surface tension from or into a soil sample. Pore size distribution can also be estimated from water retention curves.

4.2 METHODS

Soil samples for laboratory determination can be obtained by core or clod methods (Section 2.1.2). If a gas pycnometer is used to measure total porosity, a core sampler compatible with the pycnometer is required. Soil samples for pore size distribution determination should be contained in a metal or plastic cylinder approximately 1 cm high and 6 cm in diameter, with the exact size determined by the specific laboratory equipment used (Danielsen and Sutherland 1986).

The air pycnometer for field determination of air filled porosity consists of a cylindrical sample chamber with a siphon bellows (variable volume) or reservoir (constant volume) and a manometer attached. The core sample of known volume is placed in the chamber and the pressure recorded from the manometer. The siphon bellows is used to change the volume of the system by a known constant amount or until equilibrium is established between the reservoir and the sample chamber. The resultant change in pressure is measured and the percentage sample volume filled with air can be calculated from Boyle's law. Calibration is required. Temperature and barometric pressure are generally not considered significant in field measurements.

Standard laboratory methods of determining porosity include calculation from density measurements and direct evaluation by gas pycnometer. Samples for analyses in gas pycnometers are oven dried, and barometric pressure and temperature are considered. Pore size distribution is determined in the laboratory by water desorption, mercury intrusion, and nitrogen sorption. Pore size distribution is usually measured from the curve relating water content to matric potential and directly with the use of a mercury porosimeter (Glinski and Lipiec 1990). Laboratory methods for analyses of samples are provided by Danielson and Sutherland (1986), McIntyre and Loveday (1974), and McKeague (1978). The chosen laboratory method, desired level of accuracy, and spatial variability of the soil are important considerations.

4.2.1 Accuracy And Efficiency

The accuracy and efficiency of core and clod methods are reviewed in Section 3. Stone (1989) examined the effect on total porosity of using a hand held hammer double cylinder core sampler using the required number of blows (Hammer), extra force (HammerEx), and a double cylinder hydraulic sampler (Hydraulic). The difference in effect was significant between techniques and S_t decreased in the order Hammer>Hydraulic>HammerEx. Higher S_t was reported using a hydraulic sampler on a well structured soil and as related to fracturing caused by constant pressure as opposed to plastic deformation caused by hammering. Use of clods (aggregates) for measuring total porosity will provide only the aggregate and not the inter-aggregate pore volume. Air pycnometers give higher values of porosity than gas pycnometers with the difference attributed to gas-adsorption phenomenon when air is used as the gas phase (Bielders et al. 1990).

Inaccuracies in sampling and measurement of D_b and particle density will directly influence porosity and void ratio determinations. Similarly, pore size distribution as determined by water desorption and mercury intrusion of cores will be adversely affected. Shrinkage in fine to medium textured soils renders pore size distributions obtained from relationships between water content and suction unreliable (Lawrence 1977; Wires et al. 1987). Water content measurements at sampling time and appropriate laboratory techniques are essential. Mercury intrusion is the most convenient and rapid method for pores of the size 10^5 nm to 10 nm, and nitrogen sorption is most satisfactory for pores <10 nm; for pores >10^5 nm micrometric techniques are used (Lawrence 1977).

Comments on accuracy and efficiency of laboratory methods are provided in Danielson and Sutherland (1986). A review of existing techniques for pore size measurements in fine-textured soil is provided in Lawrence (1977). Jury (1986) reported CVs for porosity ranging from 7% to 11%. Estimates of sample numbers required to estimate porosity to within 10%, 20%, and 50% of the mean at the 95% confidence level, assuming a CV of 10% were 4, 1, and 1, respectively.

4.3 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Soil pores differ in size and shape as a result of textural and structural arrangement. Coarse textured soils tend to have lower porosity than fine textured ones, although the mean size of pores is greater in the former than in the latter. In clayey soils, porosity is highly variable as the soil alternately swells, shrinks, aggregates, disperses, compacts, and cracks. Increasing soil bulk density results in decreased total pore volume and a change in pore size distribution with a decreased proportion of larger pores. Wires et al. (1987) clearly showed the dependence of soil porosity on water potential and reinforced the contention that for comparisons, porosity must be expressed at a reference water content or potential. Air permeability at relatively high soil water contents is governed by air-filled porosity; at lower soil water contents, in addition to air-filled porosity, pore size distribution of air-filled pores also plays an important role (Gupta and Bhatia 1975). The moisture content range of 22 to 35% is the range of maximum volume change of the solid phase in soil causing a fast reduction in the air permeability with moisture content.

Plants, microorganisms, and soil animals depend on pore space for storage and movement. Optimal porosity for plants is 50% (Glinski and Lipiec 1990). Quantity of pores between 0.2 μm and 60 μm determines the reserves of water available to plants since these pores hold water against gravity. Root growth necessitates continuous pores which roots can enter freely (> 60 µm diameter). Aeration porosity for optimum plant growth should be at least 0.10 to 0.12 m^3 m^{-3} within two to three days after a heavy rainfall. Storage availability and transport of soil solution and soil air are more dependent on pore size distribution than on porosity. Roots represent a small fraction of total soil volume (often < 5%); thus, influence of pore size distribution on water and air movement is more important for root growth than for possible area restriction to growth. Plant growth will in turn have an effect on porosity. Root penetration leaves macropores which contribute to a system of continuous pores in the soil that improve water and gas movement.

4.4 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

Effects of development/management on porosity have been directly reported in the literature in only a few studies, and of these there is a noted trend for activities to decrease porosity.

In south-western Indiana, total porosity decreased with mining averaging 33.5% to 36.2% in the overburden and 42.4% in the topsoil (Bussler et al. 1984). In North Dakota, macropore volume was lower after mining but increased with time (Potter et al. 1988). Micropore volume was similar in undisturbed and disturbed topsoils but greater in reclaimed subsoils. In Saskatchewan, de Jong and Button (1973) found air filled pore space decreased with pipeline trenching from 24.5% on the undisturbed area to 18.3% in the trench. In a silt loam, pore volume was reduced in the upper 18 cm under conventional till but not under no-till (Hill and Meza-Montalvo 1990). Tillage implements such as mouldboard ploughs create macropores in the topsoil but reduce the number of pores continuous into the subsoil.

After compaction of a flinty clay loam in Rothamsted with a Landrover at 200 kPa, macroporosity in a flinty silty clay loam overlying flinty clay on permeable chalk decreased 50%. Structure regenerated after 18 months but the void arrangement was different than that prior to disturbance, being mostly planar (Bullock et al. 1985). Voids < 6 µm were not affected. Thacker (in preparation) reported oil and gas wellsite porosity values of 40.3, 49.8, and 36.3% on-lease and 43.0, 47.1, and 41.8% off-lease, for loams, sandy loams, and silty loams, respectively.

4.5 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

As with bulk density, some change in porosity associated with reclamation activities is inevitable. Due to the reciprocal relationship between bulk density and porosity, any measure to minimize increases in bulk density will also improve soil porosity. In sandy loam forest soils, a 26 tonne forwarder decreased porosity (Jakobsen 1985). Not working in sandy soils in wet weather is not sufficient precaution since Jakobsen (1985) found compression at water suction of 30 kPa resulted in 1% to 2% higher porosity than compaction at 3 kPa. Since both are very wet conditions, compression of the 30 kPa soil could quickly result in saturation as porosity decreased;

further compression would be ineffective as all pores would be filled with water (assuming 30 kPa suction was not re-established). This would result in little differences between the two soils.

4.6 PERSPECTIVE

Most researchers have measured bulk density or penetration resistance and inferred porosity characteristics from those data. Porosity is often calculated from D_b, and if water content is known, air filled porosity is easily calculated. Although instructive, such techniques reveal nothing about pore size distribution. In actuality pore size distribution is more important than total porosity, yet is much more difficult to quantify. Thus, rather than trying to measure porosity, it may be a better use of field time to concentrate on quantifying bulk density and soil water. In this manner, possible limitations to plant growth can be assessed.

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Alas, all the castles I have, are built
with air, though know'st
Ben Jonson 1573-1637
Eastward Ho

5. AIR PERMEABILITY

5.1 INTRODUCTION

Air permeability is a measure of the convective transmission of air through the soil in response to a total pressure gradient (Hillel 1980). Used as a parameter to indicate the ability of the soil to transmit gases when a difference in pressure exists, the coefficient of air permeability k_a in the air-flux equation (Darcy equation) is a function of soil water content and the continuity and/or tortuosity of the pore space (Corey 1986; Gupta and Bhatia 1975). Air permeability is a measure of mass flow and is less significant in the consideration of gas exchange between soil and atmosphere than the concentration diffusion established by respiration of microorganisms and plant roots, gas production associated with biological reactions, and the incorporation of fumigants and fertilizers (Corey 1986; Glinski and Lipiec 1990).

Air permeability measurement can provide valuable information regarding the influence of pore size, continuity, tortuousity, and pore size distribution on structure and transport processes within the soil (Roseberg and McCoy 1990). Air permeability is commonly expressed as μm^2 with average values from 0.01 to 500 x 10^{-12} μm^2 (Glinski and Lipiec 1990).

5.2 METHODS

Soil air permeability is measured by steady-state methods that measure the coefficient of air permeability at constant and uniform water content and unsteady-state methods used to determine the coefficient during a controlled change in water content (Corey 1986). These are laboratory techniques suitable for disturbed repacked soils. Air permeameters measure a pressure reduction in a known time interval or the volume flux of air per unit area through a linear sample under a known pressure gradient by use of a descending float chamber, a diaphragm type pressure regulator, an automatic pressure control valve, or by using the falling head principle (Glinski and Stepniewski 1985). To preserve the validity of the Darcy equation in the measurement of air permeability, high pressure gradients must be avoided. Reported pressure gradients vary from 0.5 to 8 kPa cm^{-1} (Glinski and Stepniewski 1985; Roseberg and McCoy 1990).

The air permeameter for laboratory measurement of undisturbed soil samples utilized by Roseberg and McCoy (1990) was comprised of a sample chamber, compressed air supply, air-pressure regulator, manometer, humidifier and dew-point hygrometers, and rotometers (air-flow measurement device). Undisturbed soil cores were obtained using a hydraulic core sampling device (inside diameter of 70 mm).

Grover (1955) and Kirkham (1947) described falling-pressure and constant-pressure devices for field use. Tanner and Wengel (1957) modified the Grover (1955) permeameter for use in pasture soils. Van Groenewoud (1966) described a permeameter for use on forest soils in Saskatchewan. Roseberg and McCoy (1990) modified the air permeameter described by Corey (1986) to measure macropore air permeability on undisturbed soil cores. Barden and Pavlakis (1971) measured air and water permeabilities using a modified triaxial cell permeameter, maintaining separate continuity of air and water phases during permeation. Sabatier et al. (1990) obtained qualitative indications of the relative air permeability of silt loams and silty clay loams using acoustic reflection and transmission methods. Ball (1987) used air permeability, relative diffusivity, and air-filled porosity measurements to describe pore structure variation with water content as related to the compaction process.

5.2.1 Accuracy And Efficiency

Air permeability of disturbed, repacked samples is of limited value as an indication of the pore structure of the soil. Although characterization of pore structure by air permeability measurement has been impeded by the inability to control matric potential, in situ measurement (Sabatier 1990) and measurements of undisturbed samples using techniques to control matric potential (Roseberg and McCoy 1990) may provide useful information on pore geometry. However, use of these methods has been limited. In situ techniques provide only qualitative information and the measurement values obtained from the method of Roseberg and McCoy (1990) are limited by sensitivity to air-flow paths, rotometer and exhaust locations, sleeve and chamber design, soil cohesive strength, a limited range at negative matric potentials, and a limited utility on soils with high rock or root content. Early methods to measure air permeability were slow and cumbersome. However, recent advances in flow sensor technology and computer data acquisition and control systems have overcome these limitations (Morgan 1988).

Air permeability measurements for quantifying soil compaction have the advantage of being fast, reproducible, and very sensitive to soil porosity and bulk density (Holmes et al. 1988). Over a depth interval of 13 to 18 cm, bulk density increased from 1.28 to 1.47 Mg m^{-3}, porosity decreased from 51% to 47%, and air permeability decreased from 50 to 0.08 x 10^{-8} μm^2. Nau (1987) found air permeability was 20 times more sensitive than bulk density in reflecting changes in compaction in a Verango silt loam. Tanner and Wengel (1957) found air permeability the most sensitive measure of compaction compared to bulk density, porosity, pore size distribution, aggregate stability, and penetrability.

5.3 SPATIAL AND TEMPORAL VARIABILITY

Ahuja et al. (1984) found that with n equal to 4 to 5 in their equation (section 5.4), they could successfully characterize the spatial distribution of K_s (saturated hydraulic conductivity) from measurements of effective porosity in two widely different soils with different horizons. If Ball's extension is correct, his equation could likewise be used to determine the spatial distribution of air permeability. Air permeability is a sensitive parameter in compaction studies, however, its usefulness in comparisons of treatment effects may be limited by high variability.

5.4 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Air flow within the soil is affected by soil temperature, atmospheric pressure, soil water, wind, soil porosity, and the continuity and tortuosity of air-filled pore space. Reduced internal drainage of compacted soils reduces the flow of gases and prolongs the duration of anaerobic stress (Smucker and Erickson 1989). Ahuja et al. (1984) related saturated hydraulic conductivity to effective porosity (ϕ_e) as $K_s = B\phi_e^n$ where B and n are empirical constants. Ball (1987) used this equation, substituting air permeability for K_s and porosity for effective porosity, and found a strong relationship. At constant soil water tensions, air permeability of various soils is curvilinearly related to bulk density (Smucker and Erickson 1989).

Pressure gradients in soil air have little effect on fluid displacement but are important for plant growth. However, resistance to air flow may be significant during infiltration. Relationships between water content and air permeability may have indirect significance in relation to transport of soil gases by molecular diffusion. Diffusion of gases is affected by several of the factors that affect air permeability. Thus measurement of air permeability as a function of water content may be a useful tool for analyzing the problems of aeration as well as infiltration and drainage.

5.5 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

Consolidation of the soil matrix by tillage and/or traffic operations theoretically reduces mass flow and diffusion of soil gases. However, few studies to date have measured values under development/management activities.

5.6 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

In compaction, the largest pores always disappear first. Unfortunately they are the most conductive ones. Therefore, even small changes in bulk density can cause large changes in air permeability. Thus any practice that minimizes changes in bulk density is desirable. Remedial practices, like deep ripping, that restore macroporosity will likely be effective in increasing air permeability.

5.7 PERSPECTIVE

Measurement of air permeability is not common, although its sensitivity in discerning changes in soil physical properties due to compaction makes it an attractive parameter. However, the effort required to determine air permeability is not commensurate with the information gained.

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More matter with less art.
William Shakespeare 1564-1616
Hamlet

6. AGGREGATE SIZE DISTRIBUTION, STABILITY, AND STRENGTH

6.1 INTRODUCTION

Aggregation is an indication of soil tilth, with good aggregation reflecting good tilth, which in turn is indicative of soil properties such as good infiltration, seedbed, etc. Its importance is further translated into desirable plant growth.

An aggregate is a group of primary soil particles bound or cemented together more coherently than surrounding soil particles. Organic substances, iron oxides, carbonates, clays, and silica contribute to the coherence of the particles. Aggregate size distribution is a measure of the amount of aggregates in various size ranges. The measure of resistance of aggregates to slaking and dispersion, reflecting the externally applied forces of wetting and drying, rainfall impact, and wind, is known as aggregate stability. Aggregate strength is the measure of energy required to disrupt surface aggregates by physical forces that reflect the force associated with tillage, compression, and compaction.

6.2 METHODS

Field sampling for laboratory analysis of aggregate size distribution, stability, and strength is best accomplished using a square-ended spade to sample at the same depth for all comparable samples (Kemper and Rosenau 1986). Pre-treatment procedures vary. For dry aggregate analysis, air drying at field humidity is recommended. Samples for wet aggregate stability analysis can be air dried, wet under vacuum, or wet slowly under vapour (Kemper and Rosenau 1986).

Aggregate size distribution is measured in the laboratory by multiple or single wet or dry sieving techniques and by elutriation and sedimentation (Kemper and Rosenau 1986). Elutriation and sedimentation are generally used to separate aggregates <1 mm in diameter (Baver et al. 1972). A single measure is necessary to rank and evaluate treatments and soils and therefore mathematical techniques are used to express aggregate size distribution data as a single parameter (Kemper and Rosenau 1986). Aggregate size distribution indices are most commonly calculated as mean weight diameter (MWD) and geometric mean diameter (GMD). The MWD assigns a weighting factor to groups of aggregates proportional to size. GMD calculations assume aggregate size distribution is log normally distributed and the aggregate size distribution of soils can be described using geometric mean diameter and log of standard deviation (Kemper and Rosenau 1986).

Aggregate stability is measured by dry and wet sieving techniques, the water drop impact method, turbimetry, and ultrasonic procedures. Rotary sieving of dry aggregates can provide information on resistance to abrasion (Fryrear 1985; Lyles et al. 1970). Wet sieving and water drop impact methods measure aggregate resistance to deformation (Chanasyk and Goddard 1988; Kemper et al. 1985). Aggregate stability can also be measured by turbimetry, photometric or pipette techniques of soil dispersion in water after agitation, ultrasonic dispersion, energy absorbed during disruption into micro-aggregates, or the concentration in suspension or weight percentage of screened aggregates after ultrasonic dispersion (Imeson and Vis 1984; North 1976).

Differences in aggregate stability between soils necessitates selection of pretreatment and analysis methods. Wetting of air dry stable soil aggregates, typical of humid areas with high free iron oxide, by immersion at atmospheric pressure provides disruption necessary to detect treatment differences (Kemper and Rosenau 1986). Wetting under vacuum or by vapour provides limited disruption and is suitable for unstable soils (Purson and Mulla 1989). Unstable soils are most suitably analysed using the water drop impact test, whereas stable soils are better analyzed using wet sieving and ultrasonic methods (Imeson and Vis 1984; Kemper and Rosenau 1986). A single or double screen to separate aggregates was successful as a less laborious method of determining aggregate size distribution and stability (Kemper and Rosenau 1986; Hagen et al. 1987).

Drop-shatter and crushing tests of aggregate strength are methods based on the calculation of the energy required to create new aggregate surface areas and are more closely related to resistance to soil surface changes caused by tillage, compression, and compaction (Dexter 1988; Dexter and Kroesbergen 1985; Skidmore and Powers 1982).

Aggregate size distribution is commonly expressed numerically as a single parameter: percent aggregate distribution, mean weight diameter (MWD), and/or geometric mean diameter (GMD) in mm. Aggregate stability can be expressed as a stable weight fraction calculated after sieving, a median number of water drop impacts required to disrupt an aggregate, the concentration of sediment in suspension, weight percentage of selectively screened aggregates, energy absorbed in disruption after ultrasonic dispersion, or a measure of turbidity from pipette or photometric analysis after mechanical agitation. Aggregate strength can be expressed as the tensile strength calculated from crushing forces ($J\ m^{-2}$) required to disrupt the aggregate (Boyd et al. 1983; Skidmore and Powers 1982), or the height from which a sample must be dropped onto a hard surface to cause disruption (Farrell et al. 1967). Aggregate size distribution and aggregate stability values have been reported for a number of cultivated soils in Alberta (Goddard 1988; Singh 1991).

6.2.1 Accuracy And Efficiency

Stability measurements are only meaningful in the context of the method employed. Selection of a method for evaluating aggregation is largely dependent upon forces in the studied field. Dry aggregate methods are used to assess forces associated with wind erosion, while wet aggregate methods more adequately reflect the forces associated with water erosion. Wet and dry methods are correlated to changes occurring as a result of tillage, compression, and compaction. Field methods require attention to accuracy of sampling depth, prevention of compression during sampling, and prevention of crushing or agitation of collected samples.

Pre-treatment methods produce varied results and effects. Drying aggregates at room temperature is recommended to limit irreversible dehydration of bonding materials and clay particles that can occur at high temperatures. Age hardening of aggregates can occur if sampling to analysis time is extended. Water temperature, salt content, and use of solutes to assess biological activity, can influence wet aggregate techniques (Kemper and Rosenau 1986; Molope et al. 1985).

Water drop impact and wet sieving methods failed to differentiate a variety of cultivated soils in Alberta on the basis of erosion, texture or soil series classes (Goddard 1988). Wet sieving of a Black Chernozem in central Alberta resulted in the reliable separation of cultivation techniques on the basis of aggregate size distribution and wet aggregate stability (Singh 1991).

The production of reliable aggregate strength indices is closely associated with the approximation of the diameter of the aggregates (Dexter and Kroesbergen 1985). Orientation of the aggregate in the plane of maximum projection reduces the measurement error (Dexter 1985).

6.3 SPATIAL AND TEMPORAL VARIABILITY

Information on the variability of aggregate stability indices is limited. However, Shouse et al. (1990) observed that the spatial variability of an aggregate stability index increased in cultivated fields. CVs for cultivated clay soils in Texas ranged from 10.3% to 11.5%, while an aggregate stability index of the same soil under native prairie had a CV of 6.2%. In cultivated silt loam and loam soils of Utah, Idaho, and Oregon, seasonal variation of an aggregate stability index was much larger than the differences between soils or residue treatments (Bullock et al. 1988). Aggregate stability decreased during fall and winter (September to April) due to frost action as a function of water content, and increased in association with microbial activity and plant growth during spring and summer (May to August).

6.4 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Formation and degradation of water stable aggregates comprise complex interrelationships of physical, chemical, and biological reactions. Wetting and drying, rainfall impact, freeze-thaw cycles, heavy machinery traffic, animal trampling, abrasion by windblown particles, tillage, and biological activity all contribute to changes in aggregation (Angers and Mehuys 1989; Baldock and Kay 1987; Bullock et al. 1988; Chaney and Swift 1984; Hadas 1987; Haynes and Swift 1990). Measures of physical, biological, and chemical factors contributing to soil aggregation provide the basis for empirical relationships between field factors and forces applied in the laboratory.

Wetter soils tend to have lower aggregate strength, with porosity and tensile strength of the dry soil strongly dependent on the water content at which it was previously molded (Dexter 1988). Aggregate strength and stability is more influenced by wetting than by drying. Rapid wetting causes slaking and crack formation. Friability measured via decreases in aggregate tensile strength is associated with increases in aggregate size. Age hardening of aggregates is an effect caused by redistribution of soil water and the formation of menisci. Particle rearrangements lead to new configurations of minimum free energy (flocculation process) and reformation of cementing bonds. While freezing and thawing and/or wetting and drying cause soil particle reorientation, it appears the stability of aggregates formed by these processes is highly dependent on soil type (Chaney and Swift 1986). Bullock et al. (1988), studying silt loam and loam soils in Utah and Idaho, found freezing disintegrated soil aggregates when water contents were >0.2 kg kg^{-1}. Aggregate stability increased in spring and summer with major reductions in cohesion when minimum air temperatures were below 0^oC attributed to pressures and associated shearing forces caused by freezing at high water contents. Disruption increased with water content at freezing. Cohesion was also decreased by rototilling and compaction. Harris et al. (1966) also found the effect of freezing on aggregate stability was a function of soil water content. Pawluk (1988) cited the formation of granic and metafragmic microfabrics due to repeated freezing and thawing in clay loam glacial till cores.

Aggregate stability is generally strongly correlated with organic matter content (Chaney and Swift 1984; Tisdale and Oades 1982). Harris et al. (1966) found aggregation in surface horizons predominantly a function of microbial populations and decomposition of soil binding materials, with microbial polysacharides and fungal mycelia playing major roles in soil binding. Organic materials are involved in two stages in the formation of stable soil aggregates: the aggregation phase involving exocellular microbial polysaccharide mucigels and the stabilizing phase which involves humic materials. The production of mucigels by large microbial populations associated with pasture grass rhizospheres will promote aggregation while in the longer term, the build up of soil humic material will stabilize the aggregates. Earthworms also affect the formation of water stable aggregates through their burrowing activity and production of casts. Arable aggregates, because of low organic matter, are weakly bound and drying causes incipient fracture faults to develop (Haynes and Swift 1990). Upon contact with water, aggregates quickly rewet due to rapid rehydration of particle surfaces and the rapid release of energy causes considerable aggregate breakdown. Pasture aggregates, more strongly bound by organic compounds, fine plant roots, and associated fungal hyphae, rewet more slowly because organic material imparts partial hydrophobic characteristics, making aggregates considerably more stable upon rewetting. Upon drying and contraction, intermolecular associations may form between organic macromolecules (humic substances and polysacharides) which are acting as binding agents and between organic molecules and mineral surfaces, thereby increasing aggregate stability. Oades (1984) found vesicular-arbuscular mychorrhiza fungal hyphae were involved in binding of soil aggregates. Stone and Buttery (1989) found the amount of fungal hyphae varied and was not associated with improvements in aggregation of a clay loam, but rather forages with the greatest root mass showed the greatest aggregation improvement. Molope and Page (1986) found an increase in aggregate stability parallelled fungal growth. Kemper et al. (1985), however, finding the rate of cohesion recovery faster at 90°C than at 23°C, said the processes were physical-chemical not biological.

The relationship between carbohydrate content and aggregate stability has been studied by many researchers, with indications that it may be more important in soils low in organic matter. Haynes and Swift (1990) found extractable carbohydrates were higher in the stable than in the unstable fraction of aggregates from regrassed soils and higher for pastures than for arable soils. Under mixed cropping rotations, where rotations were too short for the build-up and break-down of soil organic matter, changes in aggregate stability were more closely related to extractable carbohydrates than to total organic matter content. Angers and Mehuys (1989) found the 50% increase in MWD of clay soil after two seasons of barley and alfalfa compared to fallow or corn was at least partly due to carbohydrates (correlation of $r=0.63$ between MWD and carbohydrate content). In a greenhouse study on sandy loam and silt loam, Reid and Goss (1981) found increases in aggregate stability were associated with perennial ryegrass and lucerne and were attributed to materials produced in the rhizosphere, possibly polysacharides. Molope and Page (1986) found polysaccharides were independent of fungal effects and that the greater part of the constant component of aggregate stability was probably attributable to polysaccharide material. Thus the hot water extractable fraction of soil carbohydrates may be useful in indexing the stability of soils under short-term mixed rotations.

Higher clay contents are associated with increased aggregate stability (Kemper et al. 1987). Stability and strength of soil aggregates influences infiltration, aeration, soil water retention, water transmission, crust formation, and plant germination and growth (Bohne and Lessing 1988).

Measurement of aggregate size distribution, stability, and strength provides an index of soil structure and tilth and resistance to wind and water erosion. Chepil (1958) reported that aggregates between 0.05 mm and 0.50 mm in diameter were the most easily wind transported, whereas aggregates > 0.84 mm in diameter were resistant to wind erosion. Young (1980) found that for sandy soils, aggregates between 0.05 mm and 0.25 mm diameter were highly erodible, while for high silt and clay soils, aggregates with a diameter of 0.02 mm to 0.25 mm were the most erodible.

Water stable aggregates at the soil surface have a direct effect on the potential for sheet erosion, crust formation, and excessive runoff. Water stable aggregates >0.5 mm were strongly negatively correlated with gravimetric soil water content for a sandy loam in Ontario (Coote et al. 1980). Aggregate stability increased in loamy sand and clays of eastern Ontario following springmelt, with index values 15 times those for July. This would indicate that springmelt time was one of high erosion susceptibility.

Bulk density decreased with decreased aggregate size in some studies (Tabatabi and Hanway 1968) and increased with decreased aggregate size in others (Gumbs and Warkentin 1976). Aggregate strength influences the load soils can bear without undue structural damage from vehicles and also affects the detachment of particles under raindrop impact and hence surface crusting (Braunach and Dexter 1989). Resistance to compaction of aggregate beds increases with increased tensile strength of the individual aggregates. Crust formation and the entrainment of soil during erosion depends on the stability of aggregates against raindrop impact or against abrasion from wind-driven particles. There is also a positive correlation between aggregate breakdown and organic matter (Wustamidin and Douglas 1985). The amount of water retained by aggregates increases with increasing aggregate size.

6.5 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

Reclaimed systems exert pronounced effects on aggregation but interpretation of controlling mechanisms in any system is complicated by the diversity of factors through which the effects are manifested. Important variables are the potentialities of plant roots to form and destroy aggregates, the effect of the particular system on soil microbial and earthworm activity, the extent of coverage relative to soil protection against wind and rain, the type of disturbance, and the type of reclamation and revegetation methods practiced. Management will affect aggregate stability mainly through its effect on organic matter content.

When arable land is sown to pasture, there is a concommitant increase in aggregate stability (Clement 1961). Soil organic matter decreases under arable cropping are associated with corresponding deterioration in soil structure as related to aggregate stability (Low 1972). In an Ontario silt loam, Baldock and Kay (1987) found that size and stability of aggregates increased with increased domination of bromegrass in the cropping history; after 15 years of conventional tillage and corn cropping, size and water stability of aggregates decreased. These changes in aggregate stability can occur in response to changes in soil management before significant changes in total soil organic matter are observed (Baldock and Kay 1987; Monroe and Kladivko 1987). Haynes and Swift (1990), studying the top 15 cm of silt loams, found aggregate stability in long-term pastures increased 15% to 20% compared to arable lands which increased 10% to 18% over several years; the MWD of the aggregates was 261 to 266 mm in pastures and 130 to 176 mm in arable fields. Angers and Mehuys (1989) found MWD of clay soil increased 50% after two seasons of barley and alfalfa compared to fallow or corn.

Cropping and amendments exert significant effects on soil aggregation and aggregate strength (Thacker 1989). In a pot experiment with soils from sodic minespoils of clay loam and sandy clay loam treated with manure, gypsum, bottom ash, brome, or quackgrass, all treatments, especially the cropped treatments promoted development of fine rather than large aggregates.

Dexter (1985), studying shapes of soil aggregates oriented in their planes of maximum projection, found aggregates were less rounded with increasing clay content and decreasing organic matter. He suggested aggregates of Dutch soils may become less round with increasing age from reclamation. A large component of increases in aggregate stability of remoulded soils is physical (Molope and Page 1985). Thixotropic changes, whereby plate-like clay particles orient into uniform parallel arrangements by external shearing forces, become randomly oriented due to thermal oscillations during aging. The rigidity imparted by random orientation increases stability.

Glauser et al. (1988) found that after years of massive sewage sludge additions, treated soil had an increase in proportion of soil in the 0.65 to 2.00 mm aggregate size fraction and a decrease in fine fractions. Water stability of treated soil was 85% but 45% in untreated soils. Aggregates originating from sludge itself and newly formed soil aggregates contributed to increased stability.

Shouse et al. (1990) found no significant correlations between aggregate stability and textural components under conventional tillage; clay was negatively correlated under native prairie; and silt content was significantly correlated under conventional tillage. Readily metabolizable sources of carbon can produce stable aggregation even when indigenous carbon levels are low, emphasizing the importance of residue retention on arable rotations (Chaney and Swift 1986).

6.6 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

Most traffic and tillage operations associated with reclamation activities reduce aggregate size, increasing wind and water erosion potential. Although prevention is not likely, minimization of traffic will reduce negative impacts. Remedial measures include chemical and organic amendments like manure to promote re-development of aggregates and increase stability. Planting and maintaining grass and legume crops rather than annual crops is beneficial. Due to their role in aggregate size and stability, pastures may be a predisturbance management tool to build up soil.

6.7 PERSPECTIVE

Measurement of aggregate size can be useful in determining positive or negative effects of a treatment on soil physical status (e.g., crop rotations). They are only valuable in a comparative sense; knowing MWD for a single soil state is not useful. Much interpretation of results is required and controversy on the validity of the tests continues. The physical representativeness of dunking a dry soil in water and sorting on sieves is questionable. The lack of correlation among tests is disconcerting, but suggestive that each measures some different aspect of aggregation. The seasonal nature of aggregation and stability is evidence of their dynamic nature. Wet sieving remains the most commonly accepted method of assessing aggregate stability.

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A foolish consistency is the hobgoblin of
little minds.
Ralph Waldo Emerson 1803-1882
Self-Reliance

7. CONSISTENCE

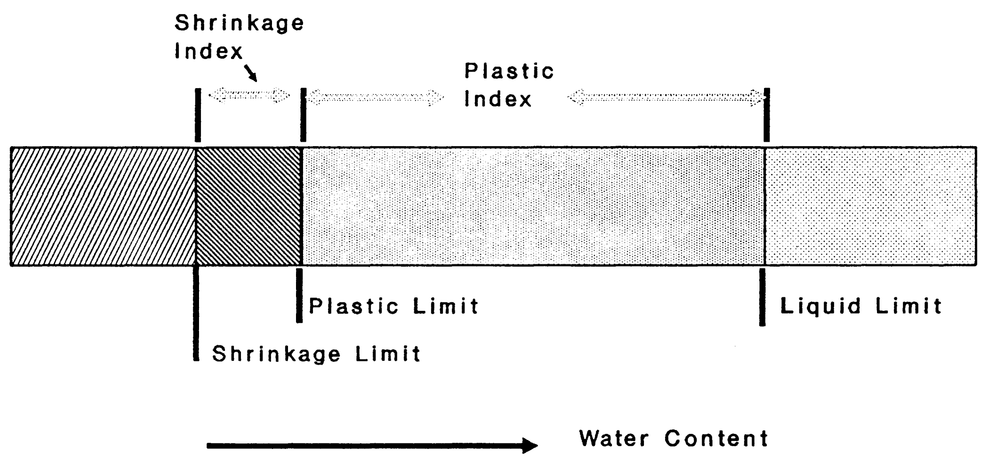
7.1 INTRODUCTION

Consistency can be defined as the relative ease with which a soil can be deformed (ASTM 1984). Consistence is used to characterize degree of cohesion and adhesion of a soil under wet, moist, dry, and cemented conditions. Plasticity is a measure of the ability of a soil to change shape continuously under an applied stress and to retain the impressed shape upon removal of the stress. Soil scientists and engineers use Atterberg limits to describe soil consistence at different moisture states. These include plastic, liquid, and shrinkage limits. Water content of a soil corresponding to the point between plastic and semisolid states is the plastic limit. The liquid limit is the water content corresponding to the point between liquid and plastic states. The maximum water content at which a reduction in water content will not cause a decrease in the soil mass volume is the shrinkage limit. The minimum water content at which soil will adhere to a metal spatula is termed the sticky point and closely approximates the liquid limit in most soils. The plasticity index is the difference between liquid limit and plastic limit (Baver et al. 1972) and represents the range of water contents over which a soil behaves plastically (ASTM 1984). The difference between the plastic and shrinkage limits is the shrinkage index. It separates the friable consistency of moist soil from the hard consistency of dry soil. A liquidity or consistency index is calculated as the ratio, expressed as a percent, of the difference between the natural water content and the liquid limit, and the plastic index (ASTM 1984; Revut and Rode 1981). See Figure 7.1 for details.

Plastic, liquid, and shrinkage limits are generally expressed as percentage moisture content values on a mass basis. Indices are reported as the nearest whole number, a percentage, or a whole number ratio. Liquid limits of sandy loams (0.15 cm depth) near Vegreville, ranged from 36% to 66%. Plastic limits of the same soils ranged from 30% to 38% (Sichinga 1989).

Liquid and plastic limits and plastic indices are used as guides to the water content at which a soil can be handled. Consistency limits provide a clearer indication of the probable mechanical behaviour of soils in the field than particle size distribution alone (Campbell et al. 1980). Manipulation of soil in the plastic range increases compaction and strength; a favourable outcome for most engineering purposes but undesirable in reclamation and agriculture. While consistency limits are merely indices of soil workability or firmness, the concept underlying Atterberg limits is extremely useful. In conjunction with other soil physical parameters, consistence limits and

Figure 7.1. Soil consistence classification.



indices correlate with other processes and properties, such as compressibility, permeability, compactibility, shrink swell characteristics, and shear strength (ASTM 1984; Hillel 1980).

The Unified Soil Classification System (USCS) based on the Atterberg limits (liquid limit and plasticity index) is a simple yet useful technique for grouping soils for engineering purposes (Wu 1976). In the USCS, the general range in values for the plasticity index is 0% to 60% and for the liquidity limit is 0% to 100%. Clay soils, predominantly illite and kaolinite, have limits in the above ranges. Predominantly montmorillonitic clays have much higher liquid limits (usually several hundred %) and much higher plasticity indices with attendant management problems.

7.2 METHODS

Simple laboratory tests to determine water content at upper and lower limits of plasticity of a soil containing sufficient fine material to exhibit plastic behavior, were first described by Albert Atterberg in 1911. The plastic limit is the water content at which a soil can be rolled into 3.2 mm (1/8 in) diameter thread without crumbling (ASTM 1984). The liquid limit is the measured water content at which a soil sample in a standard cup, cut by a groove of standard dimensions, flows together at the base of the groove for a distance of 13 mm (1/2 in) when subjected to 25 shocks from the cup being dropped 10 mm in a standard liquid limit apparatus operated at 2 shocks sec^{-1} (ASTM 1984; McKeague 1978). The standard method for determining liquid limits in British laboratories is to measure the water content at which a drop-cone penetrometer enters the soil to a standard depth (British Standards Institute 1377 1975). Campbell et al. (1980) and Wires (1984) tested both the Casagrande (modified Atterberg) method and the drop-cone penetrometer method for determination of liquid and plastic limits of loams and heavy clays and found similar values with both methods. Cone penetrometer determined plastic limits were lower than ASTM standard determinations. McBride and Bober (1989) used a static uniaxial compression test to obtain comparative indices of upper and lower plastic limits. McBride (1989) also used a soil water retention model to simulate a desorption procedure for Atterberg consistency limit determinations. Reasonable estimates of Atterberg consistency limits for soil survey purposes were obtained.

7.2.1 Accuracy And Efficiency

Accuracy of determination is affected by initial water content and the time taken for the test. ASTM standard procedures for determining limit values are inherently subjective and difficult to reproduce (Campbell et al. 1980; McBride and Bober 1989; Wires 1984). If the liquid or plastic limit cannot be determined, or the plastic limit is equal to or greater than the liquid limit, soils are considered non-plastic. In sandy soils, the plastic limit should be taken before the liquid limit to facilitate use of the same sample for both tests (McKeague 1978).

Laboratory techniques for determinations of consistency limits are standardized and well documented (ASTM 1984; McKeague 1978). Penetrometer methods of determining liquid and plastic limits required 60% less time to perform and were less variable than ASTM standard techniques (Wires 1984). Uniaxial compression tests distinguished plastic from nonplastic soils more clearly than did current ASTM procedures and were better suited to soils with high organic matter (McBride and Bober 1989).

7.3 SPATIAL AND TEMPORAL VARIABILITY

Variability in consistency limits is expected to approximate that of texture and organic matter content, with medium to high CVs. There is often wide variability in different samples of the same soil due to mineral structure, substitutions within that structure, effects of larger particles, and exchangeable cations. Variability was less with liquid and plastic limit determinations from penetrometer methods and uniaxial compression tests than with ASTM standard methods (McBride and Bober 1989; Wires 1984).

7.4 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Texture, organic matter content, amorphous inorganic materials, clay mineralogy, and chemical properties affect liquid and plastic limits (Baver et al. 1972). The major determinant of soil consistency is the soil's degree of wetness (Hillel 1980).

7.5 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

Haynes and Swift (1990) found pasture sites had higher plastic and liquid limits than samples from arable sites.

7.6 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

In general, development and management activities that do not alter texture significantly will not affect consistence. Other activities that affect organic matter content or chemical properties might affect consistence. Deliberate measures to alter consistence are not commonly initiated because consistence limits are often accepted as static soil physical properties.

7.7 PERSPECTIVE

Consistency limits are underutilized in the non-engineering literature. Research efforts investigating compressibility or compactibility often reference field moisture contents to field capacity and/or wilting point. These latter parameters are an indicator of the availability of water for use by plants and do not relate to the mechanical behaviour of soils. Thus, their usage in the latter context should be discontinued. If Atterberg limits are unavailable, then expressing field soil moisture contents as a degree of saturation is likely more meaningful than referencing them to field capacity and/or wilting point.

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And may not doubt that, somehow, good
Shall come of water and of mud;
And, sure, the reverent eye must see
A purpose in liquidity.
Rupert Brooke, 1887-1915
Heaven

8. SOIL WATER

8.1 INTRODUCTION

Soil water may be expressed in two ways: soil wetness as in water content, or energy level as in water potential. Soil water retention is the relationship between soil matric potential and soil water content. The matric potential or pressure potential component of total soil water potential is the measured energy attributable to capillary and adsorptive forces within the soil matrix. Soil water content is the amount of water within the soil matrix as free water contained in the pores or as water bound to soil particles by chemical or physical forces per mass or volume fraction. The relationship between matric potential and soil water is represented graphically as the soil moisture characteristic curve or the soil water retention curve (Bruce and Luxmoore 1986; Hillel 1980; Klute 1986). These curves are flatter and higher in magnitude for fine textured soils than coarse textured soils. Also curves for coarse textured soils are steep at high potentials, and remain flat at lower potentials (Figure 8.1). Pore geometry and absorption effects, as determined by texture and structure, influence the shape of the soil moisture characteristic curve.

The differential or specific water capacity is the change of water content per unit change of matric potential (the slope of the soil moisture characteristic curve) and is important in soil water storage and availability of water to plants. Unfortunately, the soil moisture characteristic curve is not a unique function; it exhibits hysteresis with higher water contents at a given suction for desorption than sorption. This phenomenon is often ignored in field studies.

Total soil water potential includes gravitational potential, osmotic (solute) potential, and pressure (matric) potential. Matric or pressure potential can be termed capillary potential, capillary pressure head, matric pressure, head, tension, or matric suction. Hillel (1980) discusses matric potential and matric suction which are equivalent in magnitude but opposite in sign. Hydraulic head or potential is the sum of matric and gravitational potentials and is an indication of water flow direction if hydraulic head is known at two points. Matric potential and hydraulic head for water retention determination are measured in the laboratory using tension plates and air pressure extraction cells and in the field using tensiometers. In assessing plant water relationships, the sum of matric and osmotic potentials is more useful (Hillel 1980). Field and laboratory measurements using thermocouple psychrometers combine the values of matric and osmotic potential. However, where semi-permeable membranes do not exist, osmotic potential is often ignored.

Soil water potential can be expressed as energy per unit mass, energy per unit volume, and energy per unit weight. Units of energy per unit mass are joules per kilogram. Energy per unit volume is equivalent to force per unit area or pressure and is expressed as Newtons per square meter, bars, or atmospheres. Energy per unit weight or hydraulic head is most often expressed as the length of a fluid column of known density.

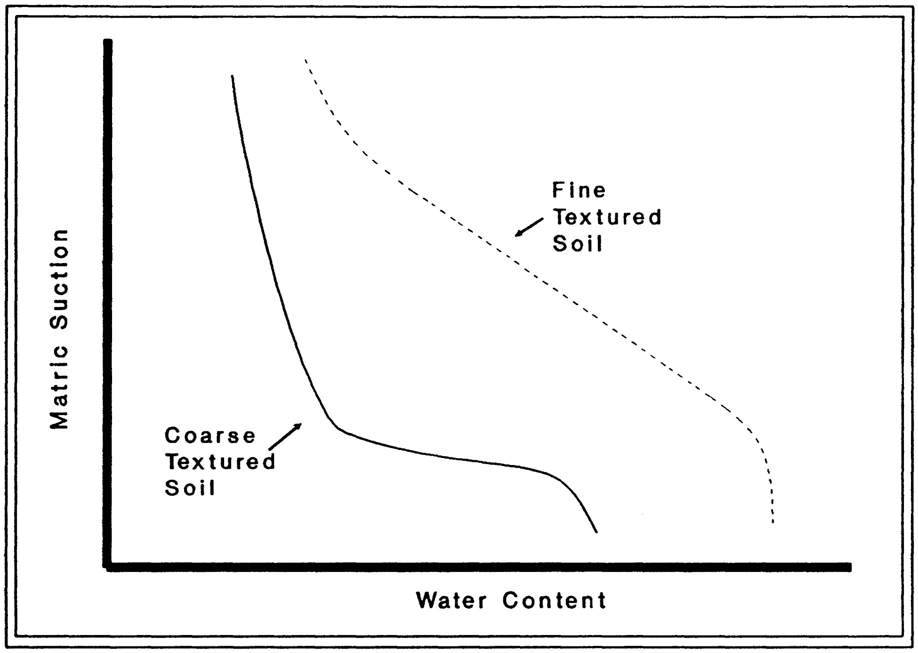
Soil water is generally considered within the soil profile (1 to 2 m depth) and interacts with the atmosphere and plant roots, fluctuating in response to precipitation, evapotranspiration, ground water levels, and plant cover (Schmugge et al. 1980). Soil water within a unit mass or volume of soil contains a wide range of solutes and when compared to pure water, has a lower vapour pressure, freezing point, and chemical potential, but a higher boiling point and osmotic potential (Glinski and Lipiec 1990; Stafford 1988). Saturation is defined as that condition of the soil in which all the soil pores are filled with water (matric potential = 0). Air dry or oven-dry in the field or in the laboratory, respectively, are the lowest moisture contents possible (Hillel 1980).

Water content is expressed on a mass (gravimetric) or volume (volumetric) basis. Water content, as gravimetric water content, is the ratio of water mass to dry soil mass. Volumetric water content is the ratio of water volume to total bulk soil volume. The dimensionless ratios are often reported as percentages. Mass and volume water content are related by bulk density and the density of water that are used to convert mass soil water measures to volume measures. Water content can also be expressed as a depth of water in a specific depth of soil.

Methods of measuring soil water potential include piezometry, tensiometry, thermocouple psychrometry, electrical resistance and heat dissipation sensing, and tension and pressure plate devices. Campbell and Gee (1986), Cassel and Klute (1986), Rawlins and Campbell (1986), and Reeve (1986) reviewed laboratory and field methods of measuring soil water potential. Erbach (1987), Schmugge et al. (1980) and Stafford (1988) reviewed measurement of soil water content. Soil water content measurement methods are categorized as sampled, in situ, and remote. Sampled methods include gravimetric, immersion, and sulfuric acid techniques. Tensiometer, radiation, electrical and thermal resistance, thermocouple psychrometers, nuclear magnetic resonance, and time domain reflectrometry are in situ methods. Remote sensing approaches include thermal infrared, and passive and active microwave methods. Klute (1986) and Bruce and Luxmoore (1986) reviewed these methods for determination of water retention characteristic curves. Water retention is measured with combinations soil water potential and content methods.

Hysteretic phenomenon in the field, soil heterogeneity, operator performance, instrument performance, calibration and data manipulation are the principle sources of inaccuracy of measurement in the field. While data manipulation can cause arbitrary or systematic error, it is generally less significant than the preceding sources (Bruce and Luxmoore 1986).

Figure 8.1. Affect of texture on soil water retention.



8.2 GRAVIMETRIC METHOD

Representative samples for laboratory analysis are obtained with an auger or core sampler and stored in moisture-proof containers prior to laboratory analysis. The gravimetric (mass) technique of water content determination involves measurement of the (wet) mass of soil sampled, removal of water, and reweighing of the sample (Stafford 1988). Water is generally removed by evaporation (oven drying), although leaching or chemical reaction are also used. The amount of water removed is determined by: measuring the sample weight loss after drying, collection by distillation or adsorption in a desiccant, replacement of water with substances and measurement of a physical or chemical property of the extracting material that is quantitatively affected by water content, or quantitatively measuring reaction products displaced from a sample (Gardner 1986). In the ASTM (1980) standard method for laboratory determination of water content, air drying at a temperature of 110°C ± 5°C is employed to remove water from the sample. Utilization of the microwave oven for removal of soil water is described in ASTM (1987) standards and provides a rapid alternative to oven drying. Aggarwal and Tripathi (1975 as cited by Erbach 1987) described an improved immersion method for water measurement based on the principle that dry weight of a moist sample can be obtained by weighing the sample in water. The sulphuric acid method, as evaluated by Gupta and Gupta (1981), involves use of a linear correlation between water content and the temperature reached when the sample is in a solution of concentrated sulphuric acid.

8.2.1 Accuracy And Efficiency

While the gravimetric method with oven-drying for water removal is used as the standard for calibration of other soil water determination techniques, it has disadvantages (Gardner 1986; Schmugge 1980). Water contained within mineral lattices or adsorbed to protected lattice positions will be released only at elevated temperatures. Thus, at standard drying temperatures of 105°C to 115°C, significant amounts of water remain. Segments of the organic fraction of soil are subject to oxidation and decomposition during drying with resultant sample weight changes. Soil water with high solute concentrations can result in errors in weight determination. Thus method of water removal and quantity of dissolved substances influences dry weight of the soil (Gardner 1986).

Sample acquisition is labour intensive and site destructive; laboratory analysis is time consuming. To obtain accurate results, oven temperature must be controlled and monitored. Drying times require standardization (Gardner 1986: Schmugge et al. 1980). Microwave oven drying is a more rapid than oven-drying. However, standard drying temperature is difficult to assess because of measurement rapidity and the resulting absence of a plateau in the water loss vs time curve. This may not yield unacceptable variation, but drying time and temperature depend on sample size, water content, and chemical composition, reducing probability of standardization (Gardner 1986).

8.3 NUCLEAR METHODS

The neutron scattering method determines the water content of the soil by measuring thermal or slow neutron density. Neutrons with high energy that are emitted by a fast neutron source (usually Am-241/Be) collide with hydrogen atoms to produce thermal or slow neutrons that are counted per unit time as they return to a slow neutron detector. Water is assumed to be the major source of hydrogen in the soil and water content is determined from a previously obtained calibration curve (Schmugge et al. 1980). Greacen et al. (1981) provided detailed theory, methodology, and applications for the use of the neutron probe method.

Neutron probes measure water content at depth via their insertion in pre-installed access tubes or within the top 13 to 35 cm using a surface probe (Gardner 1986). Sources of high energy neutrons and the source strength are dependent upon type of probe and manufacturer (Schmugge et al. 1980). Neutron depth probes, neutron moisture meters, and combined gamma density probes are the basic equipment types available (Bell 1969; Culley and McGovern 1990; Gardner 1986).

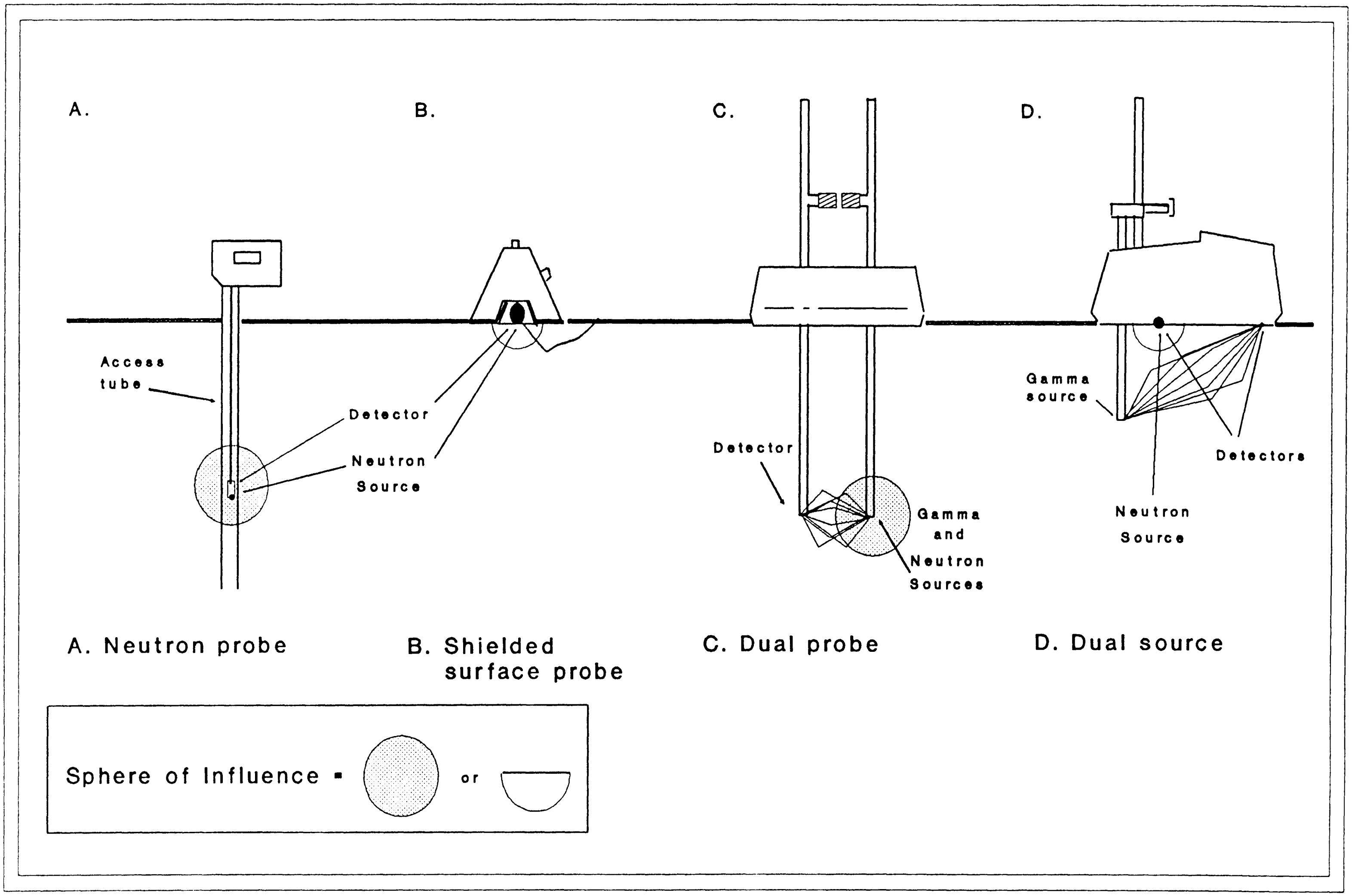
The sphere of influence of the probe measurement or soil volume over which the average moisture content is calculated (Figure 8.2) is dependent upon the soil water content, soil texture, and organic matter (Schmugge et al. 1980; Stafford 1988). Thien (1983 as cited by Erbach 1987) found that water content was measured in a spherical volume of soil 15 cm in diameter for wet soils and 50 cm in diameter for dry soils. Near-surface moisture measurement (0 to 7.5 cm) can be accomplished using a hydrogenously shielded neutron probe placed horizontally on the soil surface (Chanasyk and Naeth 1988). Combined nuclear moisture/density gauges can also be used to measure soil water, either at depth or at the surface.

8.3.1 Accuracy And Efficiency

Neutron probe determination of water content is rapid, non-destructive, and repeatable at the same sampling point. Water content can be determined regardless of its physical state, and the temporal changes and spatial variability are easily monitored. Automatic recording options allow direct transfer of data to a processing system. Probes can be calibrated to give volumetric water contents facilitating hydrologic studies. Neutron probes can be used to study soil water storage, soil water deficits, available water, plant water use, water balance, soil-plant-water relationships, soil hydraulic properties, water flow, and ground water hydrology (Williams et al. 1981).

High capital cost, inaccurate near surface water measurements when using the probe downhole, poor depth resolution due to large spheres of influence, the dependency of water measurement on difficult to assess soil physical and chemical properties, and the need to minimize potential health risks constitute disadvantages of the method's use. Errors inherent in the method are discussed by Parkes and Siam (1979) and Williams et al. (1981). The relatively large spheres of influence are an advantage because the sensing volume is high and minimizes errors due to point

Figure 8.2. Spheres of influence for measurement of soil water using nuclear methods.



measurements but also a disadvantage in that near-surface or soil horizon interface measurements are hindered. Furthermore the sphere of influence is dependent upon water content.

To determine water content accurately, calibration of neutron probes for specific soil types is required. Different soils and neutron probes have widely varying calibration curves (Greacen et al. 1981). Errors in calibration arising from soil composition and density effects are caused by constitutional hydrogen effects on neutron response, bulk density variations, and absorption of neutrons by strong absorbers such as boron, chlorine, iron, and organic hydrogen sources. While field calibration of the neutron probe is more difficult than laboratory calibration, field determined calibration curves may be more representative (Stafford 1988). Greacen et al. (1981), Sinclair and Williams (1979), and Vachaud et al. (1985) examined procedures for calibrating neutron probes.

Prebble et al. (1981) reviewed methods of installation of access tubes to minimize errors caused by air gaps between loose fitting tubes and the soil. They also discussed compaction, failure and/or plastic flow of the soil caused by soil removal and driving of the tube. Table 8.1 is a summary of the recommended installation methods for different soil types.

Insertion methods to avoid include the use of screw augers (except with tube sheath), jack hammer into undersized holes, sharpened rods or outside sharpened tubes, core samplers or back filling of air gaps. Access tubes require a removable top cap to exclude precipitation and may require a permanent bottom seal in cases where a water table may enter the zone of measurement.

8.4 TENSION PLATE AND PRESSURE PLATE APPARATUS

Soil water retention curves are most commonly determined in the laboratory using tension plate and pressure plate or membrane devices, using repacked (dried and sieved) or soil core samples. If laboratory analysis is the chosen method, then the use of soil cores of 5 to 15 cm in diameter and 1 to 5 cm height is preferred.

Matric suction in the low range (< 1 bar) can be measured using a tension plate apparatus, with pressure controlled by either vacuum or hanging water column. Higher range matric suction can be measured in a pressure plate apparatus (porous plate placed in a pressure chamber), and extreme values can be assessed in systems by increasing the bubbling pressure of the ceramic plate and the gas pressure application system. Water content is determined gravimetrically. Detailed methodology for determination of both drying and wetting curves is reviewed by Klute (1986).

8.4.1 <u>Accuracy And Efficiency</u>

Unsuitable wetting agents, inappropriate wetting methods, temperature effects during measurement, and sample loss during wetting and transfer, are all sources of error. Pressure fluctuations in the apparatus, inaccurate bulk density, entrapped air, poor contact between soil and the porous plates, and water loss due to vapour transfer in the cell can introduce error into the

Table 8.1. Recommended methods for installation of neutron probe access tubes.

Soil Type	Soil Condition	Method
Sandy soil	Moist cohesive	1. Augering by hand ahead of a driven tube 2. Augering ahead of a tube with drill rig and hydraulic ram 3. Augering ahead of a polythene liner using a drill rig
Loams and non-swelling clay soils	Dry	1 to 3 above and 4. Augering and reaming an undersized hole
Swelling clays	Dry	5. Access tubes encased in a kalinite/cement slurry 6. Horizontal access tubes
Stony soil		1 to 5 above and 7. Impact hammer, pilot rod, driving pile for large gravels
Soils with water tables	Lowest table	1 to 3 above
Soils with potential perched water tables	Absent table	7. Composite holes

Modified from Prebble et al. 1981

determinations. Several days may be needed for equilibrium depending on soil texture and sample size. If available samples are limited, water content at more than one matric pressure head can be determined by removal, weighing, and replacing the core for equalization at a series of pressure heads. This procedure is recommended when additional samples can not be obtained.

8.5 TENSIOMETERS

Tensiometers measure changes in matric suction values and consist of a porous cup connected through a tube or barrel to a vacuum gauge, mercury manometer or electric pressure transducer. The tensiometer is filled with de-aired water and equilibrium is established between water inside the device and the soil water across the permeable cup. Changes in soil water surrounding the cup result in fluctuations in the measured pressure within the tensiometer. Cassel and Klute (1986) and Hillel (1980) reviewed theory and methodology for use of tensiometers in the field and laboratory.

8.5.1 Accuracy And Efficiency

Tensiometer design varies, and matching tensiometer cup size to structural inhomogeneity of the soil needs to be considered (Cassel and Klute 1986). Flow lags can occur as a result of the hydraulic resistance of the cup and soil or of the contact area between the device and the soil. Use of a transducer type manometer with rigid tubing will reduce this effect.

While tensiometers typically only measure effectively in the 0 to 0.8 bar range of matric suction, this is not a limiting factor in coarse to medium textured soils soils (Hillel 1980). In clay soils (> 42% montmorillonite), matric suction can fluctuate between 200 to 800 cm of water with a 1% change in volumetric water content (Abele et al. 1979 as cited by Schmugge et al. 1980).

Air temperature and air pressure fluctuations affect tensiometers, particularly at shallow depths, by altering the fluid surface tension and density within the tensiometer. The construction material of the tensiometer can also result in altered heat conduction characteristics (Cassel and Klute 1986). Temperatures below freezing can damage the device and present hazards to its use in spring, winter, and fall. Ethyl glycol solutions have been used to determine water potential in soils below 0^{o}C. Shielding from direct sunlight to prevent establishment of temperature gradients between components of the device may also be required.

8.6 THERMOCOUPLE PSYCHROMETERS AND DEW-POINT HYGROMETERS

Thermocouple psychrometers and dew-point hygrometers measure the vapour phase in equilibrium with the liquid phase of soil. Vapour potential is the sum of matric and osmotic potential. Thermocouple psychrometers measure wet bulb temperature depression and the dew-point hygrometer measures dew-point temperature. Theory governing use of thermocouple psychrometers and dew-point hygrometers is discussed by Hillel (1980) and Rawlins and Campbell (1986).

The psychrometer apparatus consists of a fine wire thermocouple with one junction equilibrated with the soil atmosphere inside a hollow porous cup and the other maintained in an insulated medium to provide a temperature lag. The thermocouple junction within the porous cup can be cooled by the Peltier effect to condense water on it and the voltmeter to which it is connected measures the temperature depression as the water evaporates. Details of these two procedures can be found in Rawlins and Campbell (1986).

8.6.1 Accuracy And Efficiency

Thermocouple psychrometers and dew-point hygrometers for field and laboratory use require calibration. It is important that calibration be made in the same axis of symmetry as will exist during in situ measurements. Temperature differences between the reference junction and the liquid phase within the sample must be controlled to within $\pm 10^{-3}$°C if an accuracy in water potential of ± 10 J kg^{-1} is to be achieved. Thermocouple length and reference junction temperature drift introduce errors but can be overcome with design modification (Rawlins and Campbell 1986).

8.7 ELECTRICAL AND THERMAL CONDUCTIVITY AND CAPACITANCE

Conduction or resistance measurements, made using a variety of implantable sensors, measure soil water content indirectly through its influence on the dielectric properties of the soil. Sensors of varying types are implanted directly or within porous blocks in the soil profile and measure resistance or polarization (capacitance). Porous blocks can be constructed of gypsum, fibre glass matt and open pore ceramics (Stafford 1988). Gardner (1986) and Schmugge et al. (1980) reviewed the principles and methodology of the technique.

8.7.1 Accuracy And Efficiency

The equilibrium established between the soil and porous block is a measure of water potential as opposed to a water content, and as such is more useful to indicate optimum plant growth condition. However, Carlson and Salem (1987) reported good correlation with soil water content. Implantation of electrodes in porous blocks prior to installation is preferred to the direct use of sensors within the soil because of problems associated with attaining uniform soil electrode contact. Frequent site specific calibrations are required to deal with changes in ion concentrations. Gypsum blocks can partially overcome this, where the saturated gypsum solution around the electrode provides a fairly stable ion concentration. Use of an implanted resistor or capacitor type sensors at successive depths can provide accurate determinations of water content. Variation in sensor size and type will provide some control over the sphere of influence. Capacitor type devices provide the most direct indication of water content. However, ease of installation, long term reliability, calibration considerations, and the cost of readout and collection equipment need to be assessed prior to selection of the technique (Schmugge et al. 1980).

8.8 SPATIAL AND TEMPORAL VARIABILITY

The dynamic nature of the measured components of water retention suggest both spatial and temporal variability will be in the medium to high range. The CV of water content varies more at high suction values, ranging from 15% to 45% at 15 bar and 4% to 20% at 0.1 bar (Jury 1986). Soil water content at the Highvale Mine in Alberta had CVs of 10% to 15% when high in May and 10% to 20% when low in August (D.S. Chanasyk, 1991 unpublished data).

8.9 INTERRELATIONSHIPS WITH OTHER PARAMETERS

The functional relationships between sizes and volumes of water-filled pores as indicated by matric pressure measurements and the amount of water remaining in the soil at equilibrium (water content) is primarily affected by soil texture and structure. Organic matter and soil water solute concentration also affect water retention. The relationship between soil water content and potential is essential to the understanding of soil water capacity, retention, and flow.

Both matric potential and soil water content are needed to answer all questions related to plant water use. For example, in irrigation, matric potential is needed to answer the question "when to irrigate" and soil water content is used to determine "how much water to apply". Other physical properties such as penetration resistance are correlated to matric potential or soil water.

Rooting is directly affected by soil water. This influence is closely related to plant species and depth in the soil profile. With decreasing soil water potential from -50 kPa, root growth decreases (Glinski and Lipiec 1990). Prolonged wet soil conditions result in slower root growth and favour the development of root diseases. Water use efficiency depends on soil conditions that affect water infiltration, distribution, and storage in the soil.

Water content fluctuations tend to be greater in tilled than in untilled soils (Dexter 1988). Soil water potential and hydraulic conductivity vary widely and nonlinearly with water content for different soil textures (Saxton et al. 1986).

The upward movement of water may be enhanced by capillary rise along the fibrous remnants of roots inside biopore channels (Blackwell et al. 1990). The importance of biopore channels to fluid movement and root exploration is particularly noticeable in swelling clay soils where fissures, which provide similar advantages, close at high water contents, while channels should remain open. Biopores greater than 4 mm are particularly important because they remain stable under vertical stresses up to 200 kPa.

Saxton et al. (1986) estimated the relationship of soil water content to potentials and hydraulic conductivity from texture. The potential relationship is continuous and nonlinear from 10 to 1500 kPa, linear from 10 kPa to air entry potential, and constant below air entry potential. The hydraulic conductivity relationship is continuous and nonlinear from saturation to near air dry.

8.10 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

In Pennsylvania, Thompson and Hutnik (1972) reported soil water content 2.5 cm below the surface of steep slopes of mine and coal processing wastes was below the permanent wilting point, although water was sufficient for plant growth at a 23 cm depth. Schumacher (1978) found available water holding capacities of 0.1 to 0.2 cm^3 cm^{-3} at Keephills, Alberta. In Pennsylvania, minesoils at 75 cm retained 35 mm of water at 10 to 1500 kPa compared to 136 mm in undisturbed soils (Pedersen et al. 1980). In south-western Indiana, mining decreased water-holding capacity with averages of 16.5% in topsoil and 10.8% to 11.7% in overburden (Bussler et al. 1984). Soil water above the subsoil-minespoil contact decreased with time under forage but accumulated under cereals when the subsoil was 1.85 m or less (Graveland et al. 1988). Sparse vegetation on young minespoils does not use much available water, leading to drainage below the root zone (Schafer et al. 1979). Vegetation type may dramatically affect soil water if a heavier cover exists. Water use patterns in minesoils with four to six year old reclaimed plant communities were similar to natural soils. Macyk et al. (1988) found no evidence of a perched water table at the subsoil-spoil interface at the Paintearth Mine, except where perching reflected the major pathway for lateral movement of water out of one profile. Water content and distribution pattern were similar in undisturbed and mined soils. Leskiw (1989) found no perched water tables in plots at the Battle River mine.

Mutrie and Wishart (1989), evaluating topsoil stripping methods on pipeline r-o-w, found full r-o-w stripping may dry soils to greater depths than other methods. Chang and Lindwall (1989) found no significant effects of tillage treatments on water holding capacity comparing conventional, minimum, and no-till in Alberta Chernozemic clay loams.

8.11 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

Soil water is a reflection of hydrologic regime which is generally difficult to control. However, infiltration, the major process affecting soil water, can be greatly manipulated through anthropogenic activities. Any activity that increases D_b and decreases porosity will likely reduce infiltration and soil water, and affect soil water retention characteristics. Remediation measures such as ripping and organic amendments which enhance infiltration will increase soil water.

Mulches may affect soil water through soil temperatures changes and evaporation. In Wyoming, Schuman et al. (1980) found decreased water storage in crimped straw versus small grain stubble on reclaimed land, with stubble improving infiltration by producing a more porous soil, decreasing evaporation, and increasing snowcatch. Fedkenheuer (1980) found peat amendments improved water holding capacity of Syncrude sandy soils, increasing available water from 2.7% to 9% to 20%. Chanasyk and Naeth (1990) found surficially amended soils (peat or manure) at the Highvale Mine had higher near surface soil water than unamended treatments.

Landsburg (1989) found soil water decreased in the top 45 cm with increasing amounts of ash. Blanket application yielded highest soil water (33.7%) and disc application lowest (30.2%).

8.12 PERSPECTIVE

Water content measurement is important in research on effects of equipment use, water run-off and infiltration, trafficability, compaction, and compression. Soil water affects soil mechanical properties such as compression and compactibility, and air content and gas exchange states that influence plant growth. Knowledge of soil water potential is essential in studies of water transport and flow in soils, soil-plant-water relationships, microbial activity, and when to use machinery and heavy equipment. Knowledge of antecedent air temperature and precipitation is vital to proper interpretation of soil water data.

Numerous techniques, from simple to complex, exist to determine soil water, with new instrumentation constantly being developed. The literature on the subject is voluminous. In situ determination of the soil water retention curve is preferable to laboratory determinations using disturbed or intact soil cores. Core samples retain more water at a given matric potential than is measured in situ. However, field determinations are costly and laborious.

Gravimetric determination is still the old stand-by and even in difficult soils or locations, measurement is possible. However, soil water is dynamic, making single measurements of limited value. Neutron probes have gained wide acceptance as a measurement technique.

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Please do not shoot the pianist.
He is doing his best.
Oscar Wilde
Impressions of America

9. INFILTRATION

9.1 INTRODUCTION

Infiltration is the process of water entry into the soil. The infiltration rate, water entry rate, or intake rate involves the measurement of water movement across the air-soil interface into the soil. Infiltration rate is defined as the volume flux of water flowing into the profile per unit of soil surface area and is usually expressed in units of mm h^{-1} or derived units of cm h^{-1} (Hillel 1982). Infiltration capacity denotes the maximum rate at which water can enter the soil under a given set of conditions (Horton 1933). The rate of infiltration declines exponentially with time, reaching a constant or steady state that is considered equal to the saturated hydraulic conductivity.

Empirical and theoretical formulations are used to express infiltration rate or total quantity of water entering the soil as a function of time. Three basic types of formulations include: the empirical equations of Holton (1961), Horton (1940), and Kostiakov (1932); the Green and Ampt (1911) model based on water movement through a capilliary tube; and the more mathematical diffusion equation of Philip (1969) based on water potential gradients. Modifications have been made to these formulations, and models developed to address flux and dimensionality within the infiltration process (Morel Seytoux and Khanji 1974; Smith and Parlange 1978). Each approach has limitations and advantages associated with the variables and assumptions of the model.

Infiltration rates can be determined in several ways; those obtained using flooding systems are generally higher than those from sprinkler systems. While the actual rates measured by cylinders and rainfall simulators differ, comparative indices do not. The sprinkling method is more applicable to measurement of pre-ponding infiltration, or infiltration under conditions where macropores are only partially utilized. Cylinder infiltrometers may more accurately assess underlying soil physical properties and are more efficient for indexing soils or cultural practices (Aboulabbes et al. 1985; Amerman 1983). Drop forming rainfall simulators and cylinder infiltrometers under site specific conditions (vegetative cover, fine grained poorly structured soil with low permeability), showed similar final infiltration rates. Where vegetative cover or mulch reduce rainfall impact, cylinder devices are preferred (Julander and Jackson 1983).

Infiltration measurements may be made on wet or dry soils. The soil can be pre-wet to obtain uniform antecedent conditions or measurements can be made of the "natural" condition with accompanying soil water measurements adjacent to the cylinder. Infiltration rates determined under wet conditions are lower than "natural" measurements. Cylinder-measured wet rates are generally lower than rainfall simulator rates except at low rates (< 1 cm h^{-1}). Method of measurement and land type are both important variables in the magnitude of the difference, with rangelands having the largest difference between methods (Aboulabbes et al. 1985).

9.2 FLOODING INFILTROMETERS

Cylinder flooding type infiltrometers are used primarily to determine infiltration rates on flooded soils associated with: surface or flood-type irrigation systems; infiltration basins for ground water recharge; seepage from streams, canals, reservoirs, or waste water lagoons; or clay lining and compaction treatments used to reduce infiltration or seepage. Cylinder infiltrometers are also used on reclaimed lands and rangelands, and under a variety of agronomic conditions. Flooding border and furrow-flow methods that measure surface storage and inflow and outflow volumes are used to determine water volume balance in surface irrigation systems.

The double ring cylinder infiltrometer consists of two concentric metal rings that are pushed or driven into the soil surface to depths of 5 to 30 cm. Diameters vary from 30 to 70 cm for the outer ring. The American Society for Testing Material Standards (1981) recommends 30 to 60 cm inner cylinder diameters, a ring height of 50 cm, and a 190 liter water supply. Haise et al. (1956 as cited by Upadhyaya et al. 1988) recommended the outer ring should be at least 305 mm larger in diameter than the inner ring. The double cap infiltrometer is a smaller portable alternative to the ASTM standard device and is suitable for field areas where access and water supply are limited. Cylinder diameters are less than the ASTM device (18 cm inner and 75 cm outer ring diameters) and the cylinders are closed by a plate welded to the top of the cylinder. The cylinder height totals 11 cm. Water is supplied via ports in the surface plate and the pressure head is monitored with manometers (Constantz 1983). In both devices, constant water levels are maintained in both inner and outer cylinders and intake rate of the inner ring is taken as the infiltration rate for that point in the sample site. The volume infiltrated during timed intervals is converted to an infiltration rate expressed in cm h^{-1}. Equal and constant water depths are maintained manually by adjusting a valve in a supply line, or automatically with a float valve or syphon arrangement (Bouwer 1986). The single ring cylinder infiltrometer consists of one ring which is installed and used in a similar manner to the double ring infiltrometer. See Table 9.1 for details.

9.2.1 Accuracy And Efficiency

Cylinder infiltrometers are simple to install, easy to use, inexpensive, and provide rapid results. However, inherent in the method are systematic errors of time and depth effects, restrictive surface layers, lateral divergence of flow, and installation and measurement techniques. The cylinder infiltrometer is most useful for predictive or comparative analysis among treatments.

The characteristics of the soil system for which infiltration rates are desired must be assessed and the conditions of that system duplicated as closely as possible. While relationships

Table 9.1. Cylinder infiltrometers.

Type	Size	Water Supply	Reference
Single cylinder	30.0 cm to 1.6 cm	Valve regulator or syphon	Bouwer 1986
Double cylinder	Outer ring - 60 cm Inner ring - 30 cm Height - 5 cm	Valve regulator or syphon	ASTM 1981
Double cap cylinder	Outer ring - 18 cm Inner ring - 7.5 cm Height - 11 cm	Mariotte reservoir	Constantz 1983
Automatic reading cylinder	Outer ring - 60 cm Inner ring - 30 cm Height 5 cm	Float control	Garman 1984

between infiltration rates from rainfall simulators and cylinder methods exist, cylinder infiltrometers do not duplicate raindrop impact energy , and water quality information for runoff cannot be collected during the measurement (Aboulabbes et al. 1985; Bouwer 1986).

Chemical composition and water supply temperature influence clay flocculation and air movement from soil into the water, thus influencing measured rates. Careless, rapid water application in the cylinder can result in erosion and puddling on the soil surface. Bacteria and algae can restrict water entry and decrease infiltration while holes remaining after worms evacuate can increase infiltration rates. Large diameter, thin walled cylinders with bevelled edges minimize errors due to compaction, disruption of surface crusts or restricting layers caused during insertion.

Lateral flow effects can cause errors in infiltration rates measured with the cylinder method. The hydraulic gradient created between the wetted zone directly below the infiltrometer and the underlying unsaturated soil, layers of reduced permeability, and water depth in the cylinder are principal causes of lateral flow. Bouwer (1961) showed that where lateral flow exists, measuring infiltration in the smaller ring does not eliminate edge effects. Bouwer's analysis demonstrated that because measurement of actual infiltration rate can only be achieved when the ratio of critical pressure head to cylinder diameter is equal to zero, small inside cylinder diameters do not give true values of infiltration rate. (Critical pressure head = middle of the pressure head range where most of the changes in hydraulic conductivity occur.) While cylinder diameters greater than 1.2 m produce a zero ratio (Swartzendruber and Olson (1961) as cited by Bouwer 1986), cylinders with diameters less than 15 cm have high percentage errors (Tricker 1978).

Soils with restrictive surface layers (normally < 5 cm in depth) caused by crusting and/or compaction reduce infiltration rates. If infiltration rates rapidly become constant, and vary significantly with water depth above the soil, a restrictive surface layer likely exists. Measurement of infiltration rate prior to removal of the surface layer, followed by infiltration rate measurement of the underlying layers, will confirm the presence of a layer of low permeability (Bouwer 1986). However, where restrictive surface layers exist, the use of small diameter cylinders (< 1.2 m) will result in values that more closely approximate actual infiltration rates, due to the limiting of lateral flow caused by the restricted surface infiltration rate. Restrictive subsurface layers can result in a mounded, perched water table above the restrictive layer. Soil horizons of differing permeabilities produce irregularities in the wetted shapes under cylinders. The wetted shape flattens and a greater proportion of water applied contributes to lateral flow (Tricker 1978). Water infiltrates through a more dispersed area above the restrictive layer and infiltration rates are higher. Errors of several hundred percent are common. Large cylinder diameters and low water levels in the cylinder during measurements limit lateral divergence of flow (Bouwer 1986). Equations are used to correct measured infiltration capacities for lateral flow (Tricker 1978).

Air encapsulated during ponded infiltration significantly reduces water intake into the soil during a given time period. Soils with large interconnected pore structures (e.g., sands and well-aggregated soils) are characterized by larger amounts of encapsulated air (Constantz et al. 1988). Infiltration times of ≤ 1 hour are inadequate to accurately determine saturated hydraulic conductivity, but useful for assessing treatment effects on cumulative infiltration (Starr 1990).

9.3 SPRINKLER INFILTROMETERS

Sprinkler infiltrometers or rainfall simulators are designed to simulate the impact velocity, drop-size distribution, and intensity level of rainfall under natural conditions and are principally used in the study of erosion and runoff. The sprinkler infiltrometer is an indirect method of infiltration determination designed to measure the difference between application rate and runoff. The measurement system consists of a water supply sufficient to allow water application for the time required, a pumping unit or constant flow device, a drop forming or spray nozzle system, a runoff collection system, and protective covering from wind and rain. Rainfall simulators are divided into two groups of devices by type of drop forming apparatus which include wire or capillary tubes and spray nozzles. Sprinkler infiltrometers using nozzles are most prevalent.

The selection of a simulator for research should be based on reasonable reproduction of the natural rainfall of the study area including impact velocity, drop-size distribution, and intensity level. The area measured by the simulator must be representative of the area to be evaluated. Continuous application and vertical angle of impact are preferable. Consideration should also be given to prevalent field weather and the ability of the simulator to function in the environment.

Numerous rainfall simulators are currently available. Peterson and Bubenzer (1986) provided a brief review of nozzle type rainfall simulators and Table 9.2 is an adaptation from that review providing a representative summary of rainfall simulators.

9.3.1 Accuracy and Efficiency

Rainfall simulators are typically difficult to design, and expensive and cumbersome to operate. However, sprinkling infiltrometer systems more accurately reflect the rainfall-runoff process than flooding infiltrometers. The degree to which rainfall simulator design approximates natural precipitation conditions, and the operator's technical expertise, are primary determinants of the accuracy of the system. The lack of detailed information on the characteristics of the various types and designs makes comparison and selection of simulators difficult. The range of intensities and expected spatial uniformity are not commonly reported. Information on drop size distribution, drop velocity distribution momentum, and kinetic energy provides a more complete basis for comparison but is seldom reported (Tossell et al. 1990a, b).

Table 9.2. Rainfall simulators.

Analyses	Type And Nozzle	Pressure (kPa) And Intensity (mm h^{-1})	Drop Size (mm)	Plot Size (m)	Reference
Erosion Infiltration	Rainulator Spraying system 80100 Veejet	41.4 64 to 127	1.0 to 3.0	4.0 x 11.5	Hermsmeier et al. 1963
Erosion Infiltration	Rainulator Spraying system 80100 Veejet	41.4 30 to 200	1.0 to 3.0	4.0 x 22.5	McKay and Loch 1978
Erosion Infiltration	Rotating boom Spraying system 80100 Veejet	41.4 64 to 127	1.0 to 3.0	4.0 x 11.0	Swamson 1985
Infiltration Nutrient transport	RAINS Beta Fog SRN303	 5 to 27	0.4 to 1.2	1.0 x 1.0	Shriner et al. 1977
Erosion Infiltration	Rocky Mountain Infiltrometer Type F	138 to 206 127		0.5 x 0.7	Meeuwig 1969
Infiltration	Palouse Infiltrometer Spraying system 14WSQ Fulljet	41.4 1 to 50	0.8 to 2.6	2.0 x 2.0	Bubenzer et al. 1979
Infiltration	Purdue sprinkling Infiltrometer Spray Engineering Co. 7LA 5B 5D	41.4 119 64 82	 0.1 to 2.4 0.1 to 1.5 0.1 to 1.5	1.2 x 1.2	Bertrand and Parr 1961

Adapted from Peterson and Bubenzer 1986

Table 9.2. Rainfall simulators (continued).

Analyses	Type And Nozzle	Pressure (kPa) And Intensity (mm h^{-1})	Drop Size (mm)	Plot Size (m)	Reference
Erosion Infiltration Soil management	Modified Purdue Spray Engineering Co. 7LA	41.4 119	0.1 to 2.4	1.0 x 1.0	Dixon and Peterson 1968
Erosion Infiltration	Sprinkler head grid Rainjet 78C	193 36 to 58	0.7 to 2.8	13.0 x 26.0	Holland 1969
Erosion Infiltration Runoff	USGS Rainjet 78C	193 50	0.6 to 2.8	4.0 x 11.0	Lusby 1977
Erosion	Inter-rill simulator Spraying system 80100 Veejet 80150 Veejet	41.4	 0.7 to 3.2 1.1 to 4.2	0.7 x 0.9	Meyer and Harmon 1979
Erosion Infiltration	Rotadisk Rainulator Spraying system 1.5 H30 Fulljet	 17 to 1520		1.5 x 1.5	Cluff 1971
Erosion Infiltration Nutrient movement	Portable simulator Rose sprayhead	 80		2.0 x 3.3	Costin and Gilmour 1970
Erosion Infiltration	Guelph simulator Fulljet 1.5 H30 1HH12	30.4 to 101.3		1.2 x 1.2	Pall et al. 1983

Adapted from Peterson and Bubenzer 1986

Table 9.2. Rainfall simulators (continued).

Analyses	Type And Nozzle	Pressure (kPa) And Intensity (mm h^{-1})	Drop Size (mm)	Plot Size (m)	Reference
Infiltration Erosion	Field sprinkler Fulljet 1/4 GG10W 3/8 GG17W	70 1 to 40		3.0 x 3.0	Zegelin and White 1982
Erosion	Guelph simulator II Fulljet 6 nozzle sizes	48.3 to 96.5 20 to 191		1.0 x 1.0	Tossell et al. 1987

Analyses	Drop Formers	Fall Distance (m)	Drop Size (mm)	Intensity (mm h^{-1})	Plot Size (m)	Reference
Erosion Infiltration Runoff	Portable simulator Capillary tubes	1	5.6	101	21 cm diam.	Adams et al. 1957
Erosion Infiltration	Tahoe Basin simulator Polyethylene tubes		3.2	230	61 x 61 cm	Munn and Huntington 1976
Infiltration	Drip infiltrometer Hypodermic needles	2.6	Variable	5 to 102	1 x 2	Brakensiek 1979

Adapted from Peterson and Bubenzer 1986

Basic design criteria for simulators include impact velocity near terminal velocity, drop size distribution similar to natural rainfall, and intensity near natural conditions. Impact velocity is affected by wind speed, turbulence, and drop size. Wind speed and turbulence are usually not included in simulator design. Equations have been developed to relate median drop size, mean fall velocity, intensity, and drop size distribution (Laws 1941; Laws and Parsons 1943). However, in erosion and infiltration processes where drop impact is an important factor, similarity between the simulator drop size distribution and natural rainfall events is preferable. Characterizing drop diameter and fall velocity in the design and assessment of rainfall simulator performance can be achieved by photographic and laser-based systems (Beals et al. 1983; Tossell et al. 1990a, b). Rainfall intensity-frequency-duration curves for the geographical area studied are needed to determine realistic rainfall intensities and durations for simulations.

Nozzle systems require calibration due to spray cone shape and plot dimensions, i.e., flow valve regulation does not directly correspond to application uniformity. Larger nozzle sizes provide wider drop size distribution. Higher pressures with high intensities, narrow drop size distribution, with drop applicators directly controlled by flow valve regulation (Amerman 1983).

Despite providing raindrop impacts on the soil surface, no rainfall simulator perfectly matches the kinetic energy and momentum of a natural rainstorm. Usually a compromise (e.g., accepting 80% of terminal velocity) is required. Drop forming infiltrometers can simulate up to 83% of natural kinetic energy, and intensity can be controlled during application. Nozzle type infiltrometers can provide 100% of kinetic energy but varying the intensity during any one event requires changing nozzles or frequency of intermittent application. Kinetic energy is considered more important in characterizing the effects of cultural practices on infiltration than in studying infiltration phenomenon and theory (Amerman 1983).

9.4 SPATIAL AND TEMPORAL VARIABILITY

The methodology for determining and describing infiltration rate is varied and frequently depends on either the use of a model form for the coefficients, or an approximate model for the process. Infiltration processes are influenced by pore size distribution, bulk density, structure, water content, chemical concentrations, topography, and the presence and activity of plant roots and vegetative cover. Thus, the coefficients of variation (CV) for infiltration rates are in the medium to high range and vary from 23% to 94%. CVs are lower than those for other water transport processes possibly due to the time-averaging process involved in calculating a cumulative infiltration value and the influence of matric potential on early stage infiltration (Jury 1985). The frequency distribution for infiltration rate is considered to be log-normal (Bouwer 1986; Wilson and Luxmoore 1988). Most of the indicators of infiltration variability are inferred from hydraulic conductivity variation because the final infiltration rate theoretically is equal to the vertical saturated hydraulic conductivity. However for heavy clay soils steady state infiltration may be only 0.25 saturated hydraulic conductivity (Bouwer 1986).

Variations in infiltration rates due to mesoporosity and macroporosity were found to be equal on forested watersheds. Ponded infiltration is largely controlled by macroporosity (> 1 mm diameter), whereas infiltration during rainfall events is controlled by mesopores (Luxmoore et al. 1990; Wilson and Luxmoore 1988).

In studies to assess the spatial and temporal variation of ponded infiltration, as affected by plow and conservation tillage in corn systems, strong differences in infiltration rate were observed during the early season. Plowing resulted in early season decreases in saturated hydraulic conductivity (final infiltration rate) and was attributed to reduction in mean soil-pore diameter due to soil reconsolidation after plowing, subsequent early-season rainfall events, destruction of soil aggregates, and surface puddling (Starr 1990).

Daily heating and cooling of the water supply used for infiltration measurement can produce a marked diurnal variation in infiltration rates (Jaynes 1990).

9.5 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Good ground cover, medium to coarse textured soils, good soil structure, high organic matter content, and gentle slopes are associated with high infiltration rates. Where a coarse textured material such as sand overlies a fine textured material such as clay, infiltration rate will be dependent on the clay layer and water will accumulate in the sand. Where clay overlies sand, infiltration rate will be decreased when the wetting front encounters large sand pores. Water will not enter larger pores until accumulation in the clay layer is sufficient to overcome adhesive and cohesive forces of the finer pores in the clay layer. Excess sodium in soil can cause deflocculation of aggregates leading to surface sealing and reduced infiltration. For most soils, ESP of > 15% will decrease infiltration because of clay dispersion; as ESP and clay content increase, saturated hydraulic conductivity will decrease. Smectite clays have slower saturated hydraulic conductivities than kaolinite clays with the same ESP levels, because of higher adsorption capabilities.

Structure affects infiltration as water seeps between soil peds, with the rate of seepage dependent on type of structure, size, and orientation in the profile. Compaction loads as small as that equivalent to a man walking (0.43 kg cm^{-2}) can significantly decrease infiltration rates (Akram and Kemper 1979). Compaction from trucks on sandy loam after a rainstorm decreased infiltration from 15 cm h^{-1} to 0.3 cm h^{-1}. At the Highvale mine, infiltration rates at 1 minute had CVs 25% to 40% (n=10) and approximately 50% at 60 minutes (Chanasyk and Naeth, unpublished data).

Foliage intercepts rainfall and decreases raindrop impact and resulting surface sealing. Litter and organic matter increase aggregation and promote activity by soil organisms and decrease raindrop impact, thereby increasing infiltration. High biotic activity in and below the humus loosens soils, leading to high entrance capacities. Root development loosens soil and provides channels for water to seep down.

Raindrop impact leads to appreciable reductions in infiltration by dislodging silt and clay particles. This process of surface crust development can be aggravated by high sodium levels.

9.6 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

After several years of massive sewage sludge additions to the soil, Glauser et al. (1988) found a decrease in infiltration due to the hydrophobic nature of the sludge.

In the surface horizons of reconstructed mine spoils and soils of western Kentucky, laboratory measured rainfall simulator infiltration rates were > 0.50 cm h^{-1} after several minutes (Ward et al. 1983). In Alberta, double cylinder measured infiltration rate on Highvale minespoil was 35.6 cm h^{-1} after five minutes. Undisturbed Solonetzic soils at the same site had a 5 minute infiltration rate of 8.3 cm h^{-1} and a non-Solonetzic soil measured value was 11.2 cm h^{-1} (Doram et al. 1983). Gilley et al. (1976) used a rainulator to simulate 6.4 cm h^{-1} of rain on rangeland, spoil, and topsoil of sandy loam textures in western North Dakota. There was relatively unrestricted vertical water movement in the rangeland, and a limited change in water content of the spoil due to dispersed soil conditions. In south-western Illinois silt loams, topsoil did not affect infiltration rate and sorptivity on mined soils (Chong et al. 1986).

In New Mexico, low rates were attributed to poor spoil wettability, with shiny coal fragments in spoils being water repellent (Miyamoto et al. 1977). Curtis (1973) found infiltration rates on graded coal mine spoils were lower than on ungraded spoils due to puddling, crusting, and compaction. On a North Dakota mine spoil of SAR 30, Gilley et al. (1976) found rototilling altered infiltration and percolation only on sandy clay to a 15 cm depth and not on clay loam or silty clay loam. Discing had no effect on infiltration.

Infiltration rates on tailings pond coal spoils in Crowsnest Pass, Alberta were equal to those in grasslands over glacial materials and exceeded precipitation for most summer storms (Harrison 1974). He also found compacted pit roadways and finer grained spoil from weathered surface rock had markedly lower infiltration rates and high erosion.

On sandy loam and loamy sand soils in Montana, the average infiltration rate from eight reclaimed sites was 10.2 cm h^{-1}, ranging from 1 to 53.2 cm h^{-1}; from 10 undisturbed sites the average rate was 8.9 cm h^{-1}, ranging from 0.9 to 30.4 cm h^{-1} (Stearns et al. 1983). Schafer et al. (1979) found no significant differences in infiltration on mined and unmined soils, with infiltration rate averaging 6 to 15 cm h^{-1}. New minesoils ranged from 6 to 15 cm h^{-1}, natural areas from 8 to 15 cm h^{-1}, and old mine soils from 9 to 12 cm h^{-1}.

Infiltration rates increase and erosion rates diminish as plant communities are established, soils are better held in place and nutrient cycling begins (Sanchez and Wood 1989). Mechanical treatments to increase surface roughness on recently seeded areas increase infiltration and suppress sediment discharge. Established reclaimed areas in clay loam soils had higher infiltration rates and and lower soil erosion than the undisturbed prairie. Average initial rates were 8.42 to 6.67 cm h^{-1} and 24 hour infiltration rates were 6.58 to 3.31 cm h^{-1}. On adjacent rangelands, initial rates averaged 5.48 and final rates averaged 3.66 cm h^{-1}.

Sodicity is considered a prime cause of low infiltration rates on Alberta mine spoils (Sims et al. 1984). Sodic silt loam to clay soils on Lake Wabamun minespoils capped with 18 to 33 cm of topsoil had lower final infiltration rates than non-Solonetzic soils but higher than Solonetzic soils (Doram et al. 1983). Double ring infiltration rates in minesoils were 35.6 cm h^{-1} at 5 minutes and 0.8 cm h^{-1} after 3 hours. Cumulative infiltration in 5 hours was 12.9 cm. On nontopsoiled plots infiltration rates were 12.7 and 1.3 cm h^{-1} for initial and 3 hour rates, respectively with a cumulative infiltration of 9.7 cm. Undisturbed non-Solonetzic soils had rates of 11.2 cm h^{-1} initially, 3.0 cm h^{-1} after 3 hours, and cumulative values of 4.4 cm. Undisturbed Solonetzic soils had rates of 8.3 cm h^{-1} initially, 0.66 cm h^{-1} after 3 hours, and cumulative values of 3 cm.

Steady state infiltration values, measured by cylinder infiltrometers on mixed prairie and fescue grassland ecoystems in Alberta, varied from 5 to 125 cm h^{-1} (Naeth et al. 1990). Under grazing in mixed prairie initial and steady state rates were 1.5 to 1.7 times higher in the control than in early season grazed sites (Naeth et al. 1990). In Parkland fescue, lowest infiltration rates occurred under June grazing with final rates greatest in the light autumn and control treatments. In foothills fescue, initial infiltration rates were 1.5 to 2.3 times higher in the control and light treatments than in the heavy and very heavy grazed ones. Steady state infiltration rates were 1.5 to 2.0 times greater in light and control treatments than in heavy and very heavy treatments. Warren et al. (1986) found infiltration rates decreased as stocking rate increased in Texas silt clays.

Infiltration rates, as measured by rainfall simulation in a mixed evergreen forest zone of southwest Oregon, exceeded 11.4 cm h^{-1} (McNabb et al. 1989).

9.7 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

Since infiltration is a soil surface phenomenon, any alterations to that surface in terms of increased bulk density, reduced organic matter, etc. will affect infiltration. Thus changes in infiltration capacity may be unavoidable with many reclamation related activities. Remedial measures include organic amendments, ripping, and effective vegetation establishment and cover.

Landsburg (1989), Leskiw (1989), Lutwick et al. (1981), and Shaneman and Logan (1978) found bottom ash amendments improved infiltration in reclaimed sodic minesoils. Landsburg (1989) concluded 30 cm of ash was best and subsoiling the best incorporation method.

Rototilling did not affect water movement into spoil on sandy clay loam but it did on clay loam and silty clay loam soils in western North Dakota (Gilley et al. 1976). They concluded water movement was limited to the topsoil material. Disking topsoil-spoil interfaces had no effect on water movement into the spoil medium.

At the Highvale Mine, addition of peat or manure increased 1 minute infiltration rate by 25% and 60 minute infiltration rate by almost 30% (Chanasyk et al. 1989). The benefits of topsoil over subsoil to increase infiltration were well documented by the early 1980s.

9.8 PERSPECTIVE

Infiltration is a critical factor in water resources management affecting surface-water runoff, soil erosion, soil water storage, and deep percolation. However, infiltration characteristics are difficult to assess efficiently and accurately because of their spatial variability. Measurements of infiltration can readily be used to differentiate treatment effects, although use of them for predictive purposes requires careful thought. It is often difficult to compare results among researchers at different locations because of the methodological differences, and especially in the manner of how antecedent conditions are handled. Infiltration rates can be used to rank soils as to runoff potential, if a similar methodology is used for all soils.

Although sprinkler infiltrometers may be more representative of infiltration under rainfall conditions, ponded infiltration tests are usually simpler, less costly, provide direct measures of infiltration capacity, and provide good comparisons among treatments. Only in cases where vegetation is completely denuded might infiltrometers provide more reliable comparisons since they incorporate puddling and slaking due to raindrop impact on the bare soil surface.

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Everything flows and nothing stays
Heraclitus 513 B.C.
Plato, Cratylus

10. HYDRAULIC CONDUCTIVITY

10.1 INTRODUCTION

Hydraulic conductivity is a measure of a soil's ability to transmit water. It is the ratio of volume flux density to hydraulic head gradient. Hydraulic head gradient is the ratio of hydraulic head drop (between the inflow and outflow boundaries) to the vertical column length. Flux is the volume of water passing through a unit cross-sectional area (perpendicular to the flow direction) per unit time (Hillel 1980). Hydraulic conductivity can also be separated into two factors; intrinsic permeability of the soil and fluidity of the liquid or gas. Intrinsic permeability is a measure of the pore geometry attributes of the soil. Fluidity is function of liquid density and viscosity. Hydraulic diffusivity is the ratio of hydraulic conductivity to the water content-suction gradient.

Hydraulic conductivity can be assessed both in the laboratory and in the field. Laboratory and in situ methods are designed to assess hydraulic conductivity at the surface, under saturated or unsaturated conditions, or with shallow or deep water tables. Although in situ characterization is preferred, numerous laboratory methods are used including: steady state (constant head) and falling head permeameter methods for saturated and unsaturated soils, sorptivity method, instantaneous profile method, porous plate method, unit-gradient drainage method, and the parameter ID method (Klute and Dirksen 1986). In situ methods for saturated soils include methods for areas with a shallow water table, auger hole and piezometer, and areas with deep water tables including double tube methods, the shallow well pump-in method, permeameter (cylindrical permeameter) method, the infiltration-gradient method, and the air-entry permeameter method (Amoozegar and Warrick 1986). Field determinations of hydraulic conductivity in unsaturated soils are made using the unsteady drainage-flux, the crust-imposed steady flux, and the sprinkler imposed steady flux methods. Sorptivity by ponded infiltration or at negative matric pressure method can also be used to calculate unsaturated conductivity (Clothier and White 1981; Green et al. 1986). Due to the difficulty obtaining representative data for soil hydraulic properties, hydraulic conductivity, water content, and water potential relationships are computed using either empirical, semi-empirical, or theoretical models. Mualem (1986) reviewed approaches for estimating soil hydraulic properties.

The units of expression of hydraulic conductivity are dependent upon the expression of hydraulic gradient. If the hydraulic head gradient is expressed in the simple form of a dimensionless ratio, the dimensions of hydraulic conductivity are equal to those of flux, i.e., LT^{-1} and are the most common form of expression.

Figure 10.1 is a summary of saturated hydraulic conductivity values for various materials. Reliable prediction of hydraulic conductivity in unsaturated soils from basic soil properties such as texture has yet to be achieved.

While the measurement of hydraulic conductivity of unsaturated soils in the field can be costly and time-consuming, these measurements provide the most relevant information regarding soil-plant-water interactions (Green et al. 1986; Hillel 1980). However, due to the difficulty in obtaining data for unsaturated soils, saturated values are often obtained for semi-disturbed cores brought to the laboratory. Constant head permeameters are used for coarse textured soils and the falling head permeameter is utilized for medium and fine textured soils. The techniques for measuring hydraulic conductivity on unsaturated soils will be considered in this review because of the need for data that are more representative of field conditions.

10.2 SPRINKLING-IMPOSED STEADY FLUX METHOD

Water application to a soil at a constant rate lower than the effective hydraulic conductivity results in the establishment of a steady water distribution in the soil profile over time. Hydraulic conductivity is obtained as a function of water content and/or soil water pressure by conducting a series of tests on the same plot, starting with a low application intensity on relatively dry soil until steady flow is achieved, and increasing the intensity for successive measurements. Tensiometers and a neutron moisture probe are used to monitor soil water pressure and water content response at various depths in the soil profile until steady flow is achieved at each incremental application. The hydraulic conductivity at each steady flow state is calculated from the flux divided by the gradient in hydraulic head over the depth interval of interest. Green et al. (1986) and Hillel (1980) reviewed the method for sprinkler infiltration measurement of hydraulic conductivity.

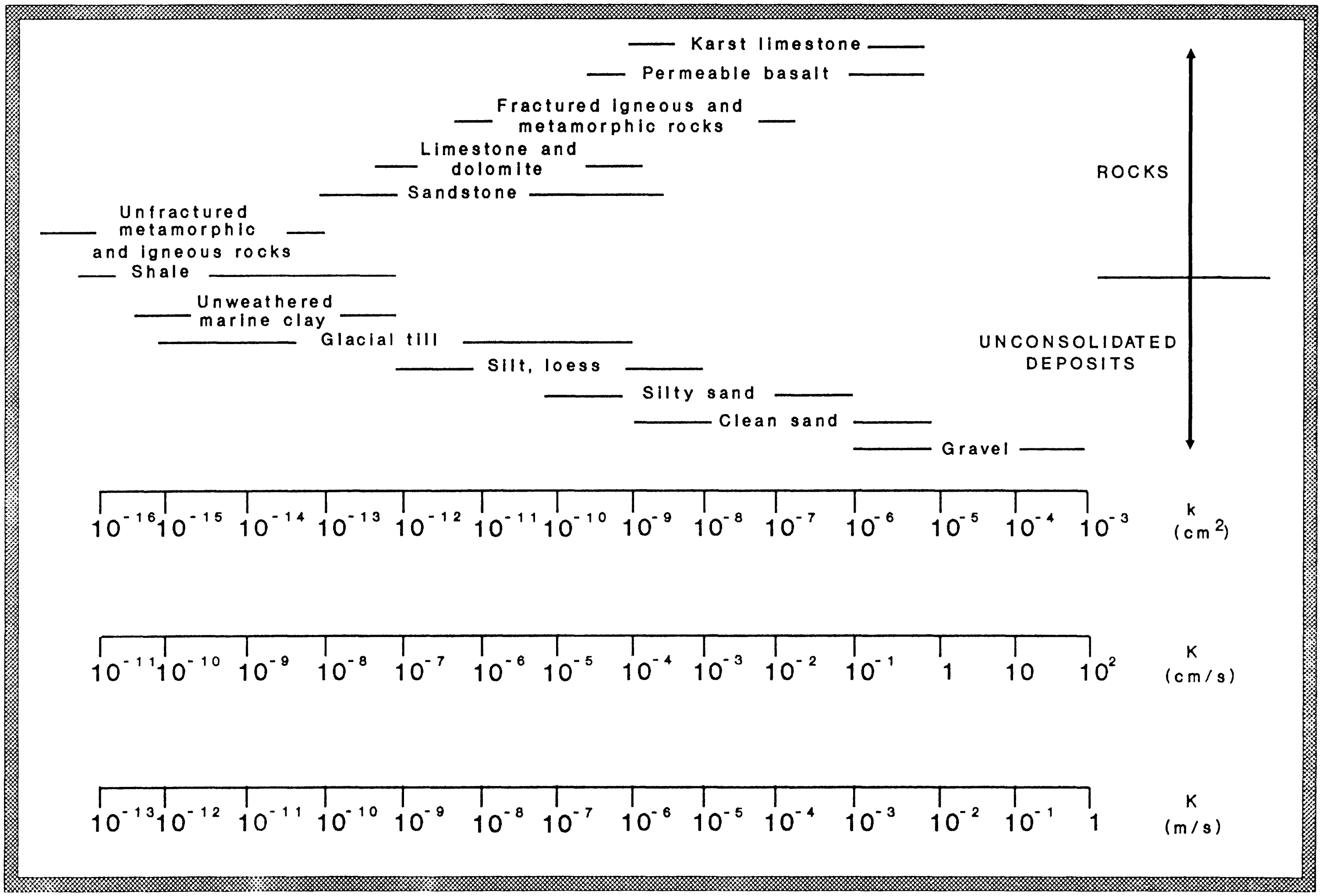
10.2.1 Accuracy And Efficiency

The sprinkler-imposed steady flux method is relatively uncomplicated, involving the establishment of steady water flux by sprinkler application of water and the measurement of water content and the average soil water pressure obtained with tensiometers during steady flow.

A sprinkling infiltrometer system should be selected that will provide uniform application, limit raindrop impact effects and cover an adequate plot size (1 m^2). This type of infiltrometer system minimizes the effects of lateral movement at the plot boundaries and the steady vertical flux adjacent to the neutron access tube and/or tensiometers.

The method is not suitable for soils with impervious layers as the development of temporary perched water tables will lead to subsurface lateral flow. Constant flux establishment at low sprinkler intensities is difficult and limits the use of the method to depths of 0 to 5 m.

Figure 10.1. Range of values of permeability (k) and hydraulic conductivity (K).



(Adapted from Freeze and Cherry, 1979)

10.3 CRUST-IMPOSED STEADY FLUX METHOD

This steady flux method involves the application of different impeding layers over the top of an isolated pedestal of soil and the establishment of a known flux of water. Hydraulic conductivity is equal to the imposed flux if the flux through the soil horizon is maintained at a value below the saturated conductivity under steady flow with unit hydraulic gradient.

A single tensiometer is located within a carved soil pedestal of recommended height/diameter ratio of 1.25 or greater. A sealed cylinder infiltrometer with a constant pressure water supply in which a gypsum-sand or hydraulic-cement and sand crust can be placed on the soil surface is placed as a cap on the soil pedestal. The crust conductivity is varied by varying the amount of gypsum-sand or hydraulic cement added.

10.3.1 Accuracy And Efficiency

While this method has good precision, site preparation and the time required to make the series measurement are considerations in selection of the method. Layering and tillage pans can cause the establishment of unit hydraulic gradients and necessitate the placement of an additional tensiometer to determine hydraulic gradient.

10.4 UNSTEADY DRAINAGE FLUX METHOD

The unsteady drainage-flux method involves the measurement of transient soil water content and hydraulic head profiles during vertical drainage (evapotranspiration prevented) after ponding of water on the surface and irrigation to wet the entire profile.

A neutron probe access tube is placed central to a series of tensiometers installed at different depths (< 30 cm difference in depth) in a field plot (> 3.6 x 3.6 m). Periodic measurements of water content and tension are made and hydraulic conductivity calculated. A simplified form of this method assumes a unit gradient and involves the use of tensiometers only at the limited depths of interest. The plot is replaced with a cylinder infiltrometer and soil water content is measured with a neutron probe or by sampling.

10.4.1 Accuracy And Efficiency

The use of the in situ unsteady drainage flux method avoids problems inherent in the structural disturbances of other methods and addresses the transient state nature of the processes under consideration. The method is not suitable for sloping or forested areas or in soils with horizons of widely differing hydraulic conductivity. The simplified form of this method is most useful to characterize the hydraulic properties of the upper horizons of homogeneous soils. Care must be observed in the assumption of unit hydraulic gradients in soils with natural horizon differences and variation due to tillage or other disturbances.

10.5 SPATIAL AND TEMPORAL VARIABILITY

Nielsen et al. (1983) indicated because of the limited observations from properly designed field research in soil water properties, an adequate assessment of the spatial variance structure and the development of efficient field technology to optimize measurements were lacking.

Jury (1986) reported that in thirteen studies of replicated measurements of saturated hydraulic conductivity, CVs ranged from 53% to 214%. There was no apparent relationship between the variability of hydraulic conductivity and soil type within surface soil textural classes. Nielson et al. (1973) reported that steady hydraulic conductivity and percentage of clay, percentage of sand, and bulk density were significantly correlated at the 91.4 to 121.9 cm depth. In addition, they found that the coefficient of variation of hydraulic conductivity increased with decreasing percentage of saturation; ranging from 85% at saturation to 450% at 54% saturation. The values of hydraulic conductivity and soil-water diffusivity were found to be log-normally distributed.

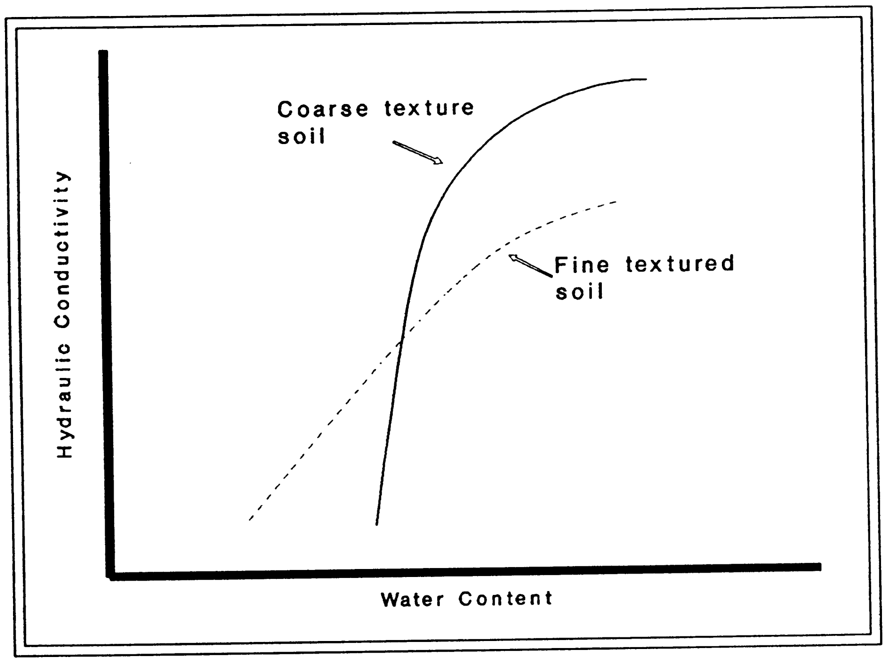
10.6 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Hydraulic conductivity is dependent upon soil texture, structure, and fluid density and viscosity. Structurally stable soils under saturated conditions exhibit characteristic hydraulic conductivities. Hydraulic conductivity is extremely sensitive to small changes in water content. Values decrease orders of magnitude for small decreases in water content and can range over a factor of five orders of magnitude for field measured water contents (Nielsen et al. 1973). Figure 10.2 illustrates the relationship between water content and hydraulic conductivity. Channels after root death can lead to increased saturated hydraulic conductivity (Glinski and Lipiec 1990).

10.7 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

Saturated hydraulic conductivity as measured by an air permeameter in North Dakota fine silty and fine loamy reconstructed soils was 25% that of the undisturbed A horizon and <10% that of undisturbed subsoil due to increased bulk density and disruption of soil structural units (Potter et al. 1988). Hydraulic conductivity did not differ between four and eleven year old sites. In southwestern Indiana silt loams, hydraulic conductivity decreased with mining from 1.6 cm h^{-1} in the topsoil and 0.2 to 5.4 cm h^{-1} in the overburden (Bussler et al. 1984). Also in Indiana, on fine silts and fine loams, Anderson et al. (1989) found saturated hydraulic conductivity decreased from 1.6 cm h^{-1} in the mine site topsoil to 0.3 cm h^{-1} in the overburden. Leskiw (1989) found saturated hydraulic conductivity under cereals at the Vesta Mine of 7.4×10^{-5} cm s^{-1} and 1.6×10^{-4} cm s^{-1} under forage. Moran et al. (1990) found hydraulic conductivities of mine spoil were generally low (>3.25×10^{-7} m s^{-1}). Mine spoil had a dual permeability system, with intergranular conductivity, represented by permeability tests, generally two orders of magnitude less than bulk conductivity,

Figure 10.2. Hydraulic conductivity as a function of water content.



represented by single well response tests. Except for zones of higher hydraulic conductivity at the spoil base in some places, and weakly developed trends of changing values with depth, variations in hydraulic conductivity were erratic and unpredictable. Spoil derived from till had values one to one and a half orders of magnitude greater than spoil derived from bedrock.

Hydraulic conductivity on pipeline r-o-w in Ontario decreased with disturbance with values in the undisturbed areas > trench > work area (Culley et al. 1982). Saturated hydraulic conductivity of the Bnt horizon in Saskatchewan Solonetzic soils also decreased with disturbance with values of 1.6 x 10^{-3} cm s^{-1} in the undisturbed area compared to 1.2 x 10^{-3} cm s^{-1} over the trench (de Jong and Button 1973).

There were no treatment effects on saturated hydraulic conductivity of Alberta Chernozemic clay loams under conventional, minimum, and no-till treatments (Chang and Lindwall 1989).

10.8 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

Any steps that minimize increases in bulk density would likely minimize decreases in hydraulic conductivity, although it is recognized that at midpoint values of soil water, hydraulic conductivity may actually be increased by increasing mesopores at the expense of macropores. Ripping and organic amendments are the most common and effective remedial measures.

10.9 PERSPECTIVE

Hydraulic conductivity is potentially a very valuable parameter to indicate changes in soil physical properties. Unfortunately the lack of ease of measurement and high degree of field variability have hindered its facility for that purpose. The technique is too time consuming for the amount of information gained in regular field assessment.

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This is too warm work, Hardy, to last long.
Horatio, Lord Nelson 1758-1805

11. HEAT CAPACITY, THERMAL CONDUCTIVITY, AND DIFFUSIVITY

11.1 INTRODUCTION

Soil thermal properties influence the rate and direction of changes in soil physical properties, atmospheric exchange, chemical reactions, plant growth, and microbial activity (Hillel 1980). The parameters used to describe the soil thermal regime include heat capacity, thermal conductivity, and thermal diffusivity.

Heat capacity is an indication of a soil's ability to store thermal energy. Volumetric heat capacity is the product of specific heat capacity and density and is expressed as J m^{-3} $^{o}K^{-1}$. Thermal conductivity is a measure of a soil's ability to transport heat and is measured as the quantity of heat flowing through a unit area in a unit time under a unit temperature gradient and is expressed as W m^{-1} $^{o}K^{-1}$.

Where an unsteady state exists, the thermal behaviour of a soil is governed not only by thermal conductivity but also heat capacity. The ratio of these two properties is the thermal diffusivity D_t, expressed as m^2 s^{-1}. A high value of D_t implies a capability for rapid and considerable changes in temperature.

Use of the term conductivity is justified because heat is transferred through soils mainly by conduction, with contacting solid grains providing the major conductive transfer (Farouki 1986). Different soil constituents have dramatically different thermal properties, and therefore proportions of the various soil components profoundly influence thermal properties. The thermal properties of soils depend mainly on the mineral composition of the soil, its porosity and water content.

Quartz has the greatest thermal conductivity of soil constituents and air the least, the ratio being 350:1. Water is approximately 23 times more conductive than air, but only 7% that of quartz. Volumetric heat capacity of quartz is 2000 times that of air, but only half that of water.

The understanding of thermal properties of soil is used in research on the energy balance at the soil surface, tree seedling establishment on reforestation sites, heat flow away from industrial installations in the ground (e.g., pipelines), and frost action on soil structure (Flint and Childs 1987; Sepaskhah and Boersma 1979; Wheeler et al. 1988).

11.2. METHODS

The volumetric heat capacity of a soil can be measured in the laboratory using calorimetric techniques or calculated by the addition of the heat capacities of the solid, water, and air constituents weighted according to their volume fractions (Hillel 1980; de Vries 1963).

Conductivity measurement necessarily results in the averaging of the thermal conductivity between two sections a finite distance apart. The actual conductivity will vary between these two sections because of soil composition and temperature differences (Farouki 1986). Methods for measuring thermal conductivity and diffusivity involve either steady state or transient heat flow. Steady state methods do not measure temperature as a function of time and resultant measurements include both temperature and moisture gradients. Thus transient heat flow methods that measure temperature changes with time are preferred (Mitchell et al. 1978). Transient in situ or laboratory determinations of thermal conductivity commonly involve either a single or multi-cylindrical probe method. In-situ measurements with proper evaluation of time dependent variables (e.g., water content) are preferred. Laboratory determinations can be used providing corrections are made for dependent variables and temperature differences between the laboratory and field. Attention must also be given to the use of representative, undisturbed samples.

The cylindrical probe method measures the increase in temperature over time generated by a power source within a heat-generating probe inserted into the soil. Rate of temperature increase is measured with a thermocouple or thermistor. In the single probe method, the thermistor is located in the heat-generating probe. The multi-probe method uses thermistors placed 0.06 to 0.20 m from the heat source. Thermal conductivity is determined by solving the equation for heat conduction in the radial direction from the line source (Hillel 1980). Thermal probe theory, including a solution developed by Blackwell (1954) and the integral solutions of Lindqvist (1983) and Kristiansen (1982), are reviewed by Sundberg (1988).

De Vries (1952) developed a model for calculating the thermal conductivity of soils from their volume fractions of constituents and the shape of their particles. This model has been tested on disturbed samples in the laboratory with reliable results for wet soils. A correction factor was needed for some dry soils but not others (Farouki 1986). Thermal conductivity can also be calculated from Fourier's heat flow law if data on soil heat flow (from the use of heat flow plates) and on soil temperature (thermistors or thermocouples at several depths) are available. Farouki (1986) reviewed methods for calculating the thermal conductivity of mineral soils and found that Johansen's method provided the best agreement with measured values and the de Vries (1963) method was preferred for coarse soils with degrees of saturation (S_r) of 0.1 to 0.2. Methods differ marginally on saturated frozen fine soil. Some problems associated with Johansen's method (the exclusion of vapour diffusion effects) have been addressed by Sundberg (1988) who achieved good results in calculating thermal conductivity of mineral soils by introducing a thermal grain contact resistance parameter to the self-consistent approximation of thermal conductivity.

Measurement of thermal diffusivity involves the use of soil discs of known size, temperature and water content taken from core samples. These soil discs are placed in a cylindrical apparatus with a heating plate and thermistor plate at opposite ends. The front face of the disc is exposed to a burst of radiant energy and the subsequent rise in temperature at the rear face is analyzed (Ross and Bridge 1987; Taylor and Jackson 1986).

Thermal properties of frozen and unfrozen soils are summarized in Table 11.1. Thermal conductivities of soil materials at different dry bulk density values are summarized in Table 11.2.

11.2.1 Accuracy And Efficiency

The determination of heat capacity using calorimetric methods can result in errors due to leakage of the calorimeter and/or energy created by stirring the soil suspension during the procedure. Graphical correction for heat loss can be used to approximate the value more accurately (Taylor and Jackson 1986). A given soil at a given water content does not have a unique value of thermal conductivity because of boundary conditions, which may cause moisture redistribution. Techniques to measure thermal conductivity can themselves cause such changes. Therefore these effects and the comparability of measurement conditions to field conditions must be considered before laboratory results can be applied with confidence.

Errors in cylindrical probe methods can be caused by thermistor drift, non-radial heat flow, probe radius and material effects, heat input variation, non-constant temperature, sample boundary effects, and compensatory thermal transport mechanisms (Mitchell et al. 1978; Sundberg 1988). Thermistors require regular calibration to prevent drift errors. With non-radial flow prevention, a probe length-diameter ratio of 30 is often recommended. However, Sundberg (1988) found probe length was more critical than probe diameter in preventing axial flow and developed a formula to estimate the required length-diameter ratio of the probe. Battery power can result in variation in power supply (1% to 2%) and errors in the value of conductivity. Even small variations (1%) can result in significant errors in the value of resistivity (Mitchell et al 1978). Mitchell et al. (1978) found that boundary conditions and probe composition effects were negligible. An evaluation of test duration effects indicated errors could be introduced when elapsed time exceeded 6.7 minutes in a laboratory sample of 101.6 mm diameter with a resistivity of 23^{o}-cm W^{-1}.

Laboratory measurement of thermal diffusivity using the pulse method was useful in the study of thermal properties of swelling clay soils (Ross and Bridge 1987). Thermal conductivity and diffusivity were several times higher than in non-swelling soils. In the suction range 10 kPa to 1.5 MPa, thermal conductivity and diffusivity decreased with increased water content, opposite to the behaviour of non-swelling soils. Although soils with increased porosity and decreased water content are generally associated with decreased thermal conductivity, vapour diffusion and radiation can combine with conductivity to produce misleading thermal conductivity and diffusivity values (Hopmans and Dane 1986).

Wierenga et al. (1969) found good agreement between in situ thermal conductivity (line heat source method) and calculated ones (using de Vries (1952) equation) for a Yolo silt loam over

Table 11.1. Thermal properties of frozen and unfrozen soils.

Type Of Soil	Thermal Conductivity ($W m^{-1} {}^{o}K$)		Heat Capacity ($J m^{-3} {}^{o}K \times 10^{6}$)	
	Unfrozen	Frozen	Unfrozen	Frozen
Clay with high clay content	0.85 to 1.1	2.0 to 2.2	3.0 to 3.6	2.0
Dry crust clay high clay	1.1 to 1.4	1.7 to 2.3	2.6 to 3.0	1.7 to 2.0
Silty clay silt layer	1.1 to 1.5	2.3 to 2.8	2.9 to 3.3	2.0
Silt	1.2 to 2.4	2.3 to 3.2	2.4 to 3.3	2.0
Sand, gravel below groundwater table	1.5 to 2.6 1.6 to 2.0	2.7 to 3.3 2.8 to 3.0	2.5 to 3.2 2.9	2.0 2.0
Sand, gravel above groundwater table	0.4 to 1.1 0.7 to 0.9	0.4 to 1.0 0.8 to 0.9	1.2 to 1.7 1.4	1.1 to 1.6 1.2
Till below groundwater table	1.5 to 2.5	2.3 to 2.7	2.2 to 3.0	2.0
Sandy till above groundwater table	0.6 to 1.8	0.5 to 1.6	1.3 to 1.9	1.2 to 1.5
Peat below groundwater table	0.6	1.7	4.0	2.0
Peat above groundwater table	0.2 to 0.5	0.4 to 1.5	0.7 to 3.2	0.5 to 1.7

Adapted from Sundberg 1988

Table 11.2. Thermal conductivites of soil at different bulk densities.

Soil Type	Dry Thermal Conductivity (WC)	Dry Thermal Conductivity (W m-1oK)	Wet Thermal Conductivity (WC)	Wet Thermal Conductivity (W m-1oK)	Bulk Density (Mg m-3)	Reference
Fairbanks sand	0.00	0.03	0.21	2.30	1.70	de Vries 1963
Sand	0.00	0.30	0.00	1.68	1.46	van Duin 1956
Sand	0.00	0.15	0.38	2.30	1.60	Riha et al. 1980
Pumice (Ac)	0.00	0.16	0.70	0.71	0.76	Cochran et al. 1967
Loamy sand	0.00	0.20	0.21	1.80	1.50	Hartmann et al. 1972
Loamy sand	0.01	0.03	0.35	1.50	1.69	Sepaskhah and Boersma 1979
Silt loam	0.16	0.75	0.40	1.18	1.35	Wieranga et al. 1969
Silty clay loam	0.04	0.30	0.31	0.90	1.25	Asrar and Kanemasu 1983
Clay	0.03	0.16	0.36	1.55	0.36-0.61*	de Vries 1963
Peat	0.02	0.05	0.80	0.45	0.84-0.79*	de Vries 1963
Forest litter	0.02	0.10	0.55	0.30	0.21	Riha et al. 1980

* Porosity
WC = water content
W $m^{-1o}K$ = thermal conductivity

Modified from Berge 1990

soil water from 0.14 to 0.40 $cm^3\ cm^{-3}$ in the top 50 cm. They recommended more measurements at low water contents (< 0.14 $cm^3\ cm^{-3}$) would be needed to assess correspondence between measured and calculated values.

11.3 SPATIAL AND TEMPORAL VARIABILITY

Heat capacity and conductivity are estimated from thermal conductivities of air, water, mineral particles, and organic matter. Thus thermal property variability is generally that of the specific components.

11.4 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Water has important and very complex effects on thermal properties of soils. It is the soil component most affected by temperature (Farouki 1986). A water content which varies from point to point implies a variable thermal conductivity which in turn affects the temperature distribution in the soil. Inversely, the temperature stratification in the soil affects water distribution. Freezing rate is greatly influenced by the moisture content, as is the depth of frost penetration.

Soil porosity, thus D_b, have a strong influence on soil thermal properties. An increase in porosity without a change in water content means more air is present and hence a lower thermal conductivity. A decrease in porosity (increase in D_b) increases thermal conductivity because of three factors: (1) more solid matter per unit soil volume, (2) less pore air or water per unit soil volume, and (3) more contacts to allow heat transfer. In general, experimenters found a linear trend between thermal conductivity of a soil (or its log) and D_b (Farouki 1986). Soil structure and packing are also important factors affecting a soil's thermal properties because they imply a certain arrangement of soil particles and therefore an orientation with respect to the direction of heat flow. Thermal properties of soils vary considerably with temperature. Temperature changes in soils mainly affect soil water. In frozen soils, the presence of unfrozen water is a major factor in the thermal behaviour of soil (Farouki 1986).

Optimum temperature for growth and function is related to plant species and stage of development, being higher in the early stages. When soil temperature decreases there is generally a decrease in absorption of nutrients and water by increasing viscosity of water and decreasing cell membrane permeability (Glinski and Lipiec 1990). Absorption of N as NH_4 is greater than that as NO_3 at low temperatures. Higher temperatures lead to reductions in mass action and breakdown of metabolic activity. Roots are much more sensitive to temperature fluctuations than are shoots.

11.5 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

Soil thermal properties are generally not measured. Rather, temperature, which is relatively easily measured, is used as the sole indicator of a soil's thermal regime.

Schramm (1966) found steep decreasing temperature gradients with depth in dry insulated sludge or refuse from anthracite coal mining in Pennsylvania. Surface temperatures in a fine dry refuse ranged from 63°C to 67°C with values at a 25 mm depth of 43.5°C to 49.5°C. These gradients were not present in moist soils. In coarse refuse with negligible capillary rise, surface drying was quick with resultant steep temperature gradients. In fine-textured sludge, with greater capillary uptake, surface dessication proceeded slowly and without temperature gradients. Similar results were reported by Thompson and Hutnik (1972) in Pennsylvania where temperatures greater than 60°C were common on refuse banks. Temperatures of 49°C were common at a depth of 1 cm with mean temperature differences between that depth and the surface of 1.6°C. Harrison (1974) completed a laboratory study and reported that fine coal spoil with 30% ash content had a thermal conductivity equivalent to loose snow, and specific heat close to that of iron. Schramm (1966) felt this rise in temperature was concentrated primarily in the first few mm of spoil where radiant energy is absorbed and converted to heat. The rise in temperature was due to the relatively low conductivities of the interstitial air in the dry layer which thus limited heat conduction down the profile. Any interference with heat transfer down the profile would increase the surface temperature in dry spoils. New minesoils were cooler than natural soils and old minesoils were warmer (Schafer et al. 1979).

Spoil grain size affects temperature, with a particle size increase from 80 to 10 mesh in the top 1.3 cm of spoil increasing temperature from 37°C to 41°C (Schramm 1966) due to increased volume of air in coarser spoils and decreased particle-to-particle contact. Schramm (1966) also found if the angle of incidence of the sunlight was between 70° and 90° then there was little temperature change but if the angle decreased, surface temperature dropped rapidly. At a 40° angle, spoil was 14.5°C lower than at a 70° to 90° angle. Spoil slope therefore affected temperature. Schramm (1966) found a moderate 20° northern slope 15°C cooler than a similar southern slope. In the Crowsnest area of Alberta, Harrison (1974) recorded temperatures of 73°C on south facing slopes.

11.6 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

Since soil thermal properties are so dependent on its constituents and their proportions, any measure that affects any soil constituent can affect thermal properties. Thus, some impact on soil thermal regime is not likely preventable, and remedial measures are not aimed at altering thermal properties. It is well known, that any measure that reduces soil water, will serve to increase soil temperature. In some instances, crop cover may be used to reduce incident light. Light colour amendments will reduce heating of black coal or spoil, and mulches will also reduce incident light, thus affecting soil temperature.

11.7 PERSPECTIVE

Measurement of a soil's thermal properties are difficult because these parameters are so dynamic. Thus these measurements are not routinely made. The interest in thermal regime is centered around temperature which can easily be measured directly.

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Vis consili expers mole ruit suar.
Force, if unassisted by judgement,
collapses through its own mass.
Horace 65-85 B.C.
Odes. iv 65

12. SOIL STRENGTH

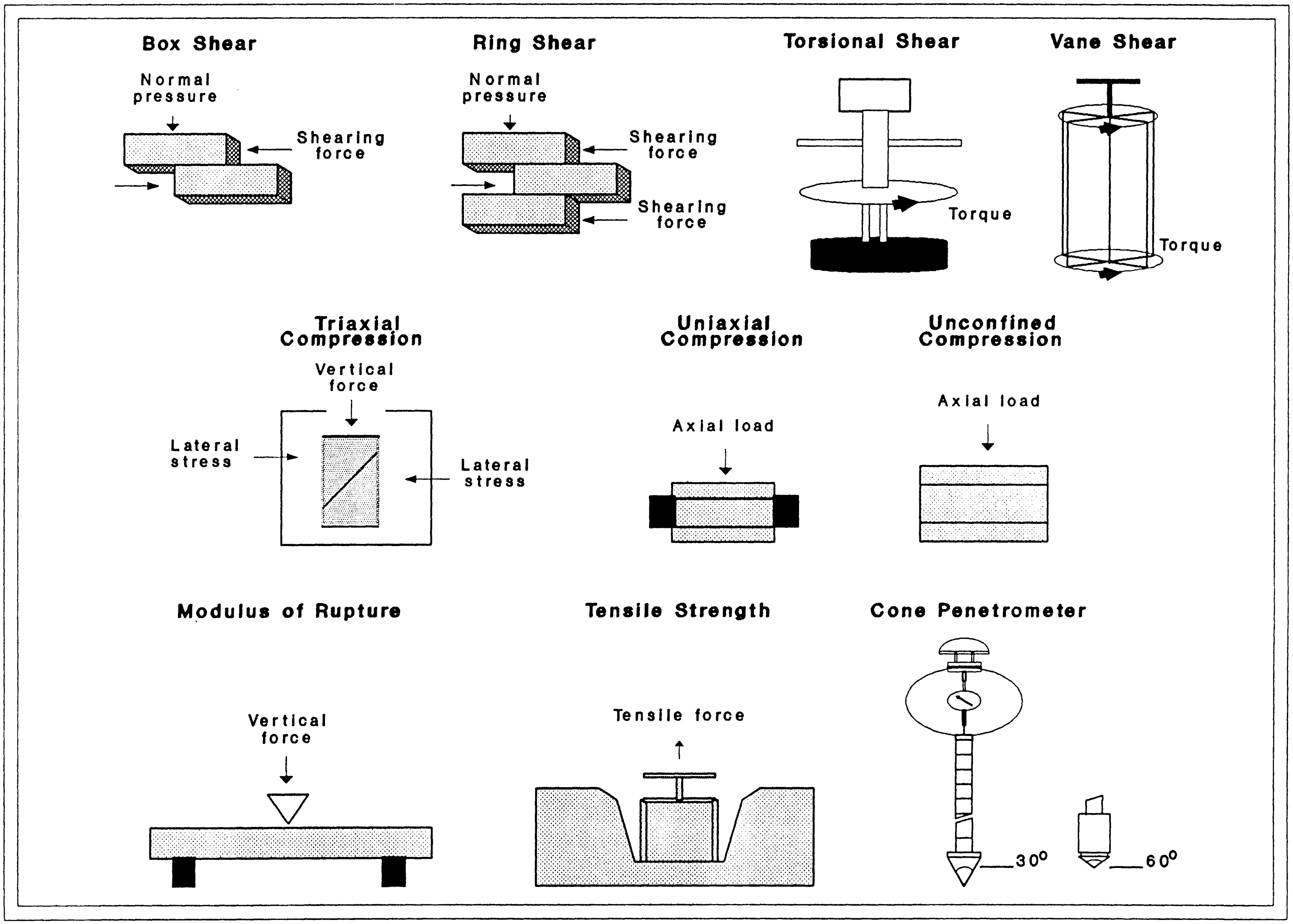
12.1 INTRODUCTION

Soil strength is the ability of the soil to bear or withstand stress without excessive deformation and failure by rupture, fragmentation, or flow (Hillel 1980). The resistance to collapse exhibited by a soil body is attributable to particle bonding (cohesiveness) and frictional resistance to deformation (angle of internal friction). Soil strength determination involves the measurement of shearing forces or combined shearing, tensile or compressive forces that produce failure or deformation. These forces are utilized to assess trafficability and impedance to root penetration. Composite parameters such as mechanical impedance, resistance to penetration, or cone index, provide integrated indications of moisture content, texture, type of clay minerals, and bulk density (Glinski and Lipiec 1990). Available testing methods are illustrated in Figure 12.1.

The measurement of soil strength by direct, triaxial and vane shearing tests, and unconfined compression tests involves two parameters: cohesiveness and angle of internal resistance. The shear failure at a single point within the soil mass is represented by the straight line envelope of the Mohr-Coulomb equation $Á_{max}$ = C + Âtanø where C=cohesion, ø=angle of internal friction, and Â and $Á_{max}$ are the normal and maximum shearing stress (Johnson et al. 1987). Tests of tensile strength measure the force per unit area required to separate one section of soil from another. Uniaxial compression tests of saturated soils determine the effective stress as the difference between the total applied axial load and pore water pressure. In unsaturated soil, a more complex relationship exists and the slope of the straight line portion of the curve relating the computed void ratio to effective stress is the compression index. The coefficient of compressibility is the slope of the linear portion of this curve expressed as kPa^{-1}. The coefficient of volume change (change per unit volume per unit increase in effective stress in kPa^{-1}) is also used to describe compressibility (Bradford 1986). Modulus of rupture involves determination of the centrally applied loading force needed to cause failure of a cylindrical or rectangular soil sample. Shear strength, compression, tensile strength, and modulus of rupture are generally expressed as kPa or as Nm in the case of torsional shear devices that measure a moment of force (torque).

Penetration resistance (mechanical impedance) is the measure of soil resistance to the penetration of a narrow cone-tipped probe in terms of force per unit base area, or cone index. The mechanical properties measured by cone penetrometers include the pressure for cylindrical

Figure 12.1. Soil strength determination methods.



(Adapted in part from Hillel, 1980; Payne and Fontaine, 1952; Barley et al., 1965; ASAE, 1985; Baver et al.,1972; Bradford and Gupta, 1986) expansion (cylindrical impedance) and the pressure for spherical expansion (spherical impedance) (Greacen 1986). Penetration resistance values can be reported in kg cm^{-2}, kPa or kN m^{-2}.

12.2 SHEAR, TENSILE STRENGTH, MODULUS OF RUPTURE, AND COMPRESSIBILITY METHODS

Direct shear methods involve measuring the force on a controlled shear plane of a small area of soil (Johnson et al. 1987). Direct shear measurement devices include the Grouser plate, the translational shear box or ring, and torsional and vane shear devices. Grouser plate devices measure the maximum shearing force required to shear the soil under a surface-placed grouser plate at various normal applied loads. Translational shear boxes measure the maximum shearing force required to move one part of a two-piece rectangular soil container relative to the other at different normal loads. Ring shear devices measure the maximum double shearing force to push a ring of soil from the center of a soil sample placed in a cylindrical metal container. Torsional shear devices measure the moment of force required to shear a solid cylindrical sample of soil on a plane perpendicular to the cylinder axis. Torsional devices include the British National Institute of Agricultural Engineering (NIAE) shear box, the sheargraph, and various annular torsional shear devices (Johnson et al. 1987). Vane shear devices measure the moment of force required to shear the soil along the surface of a cylinder created by rotating vanes driven into the soil (Hillel 1980).

Triaxial shear methods (also referred to as triaxial compression) measure the vertical force required to cause shear failure in a cylindrical soil sample contained within a rubber membrane. The membrane-enclosed sample is placed in a closed cell where lateral stress is controlled via regulated air or water pressure (Baver et al. 1972; Hillel 1980; Johnson et al. 1987). This type of cylindrical shearing test can also be performed without application of lateral pressure and is referred to as an unconfined compression test. Ploughing and traffic on wet dense soil can also result in deformation without volume change or nearly pure deformation that consumes energy and changes soil properties (Dawidowski et al. 1990). A distortion apparatus as developed by Lerink (1990) measures distortion beyond the principal strain capabilities (0.69) of the triaxial test.

Uniaxial compression tests measure the compressibility (volume strain) of a confined cylindrical soil sample prior to shear deformation. Undisturbed cores are placed within a ring between two porous stone plates. Loading of the cell is increased and the effective stress is plotted against the decrease in void ratio. The slope of the line is the compression index and values normally range between 0.2 and 2 (Bradford 1986).

Modulus of rupture devices measure the centrally applied force required to cause failure of a cylindrical or rectangular dried soil briquette that is supported at both ends. The procedure is designed to simulate soil crust formation under initially wet conditions followed by direct sun drying. The laboratory procedure involves the molding and drying of a rectangular block of ground soil. The formed soil briquette is supported as a plate on two parallel beams (5 cm apart) and loaded to failure at its center. The modulus of rupture is calculated from the load required to cause failure and the dimensions of the sample briquette (Reeves 1965). Buckland (1983) found the modulus of rupture of the Ap horizons of deep ploughed soils ranged from 0.035 to 0.276 MPa and was significantly higher than for Ap horizons under conventional tillage.

Direct tensile strength field measurement involves the isolation of a cylindrical sample of soil and measurement of the force required to separate that sample from the underlying soil layer. Laboratory measurements based on the use of centrifugation are also used (Perumpral 1987).

Equations that relate cohesiveness and angle of internal friction to the force required to cause failure can be found in Hillel (1980) and the review of shear measurement for agricultural soils by Johnson et al. (1987).

12.2.1 Accuracy And Efficiency

Johnson et al. (1987) concluded that the optimum method and apparatus for shear determination has yet to be defined. Convenience, practicality under a given soil condition, and access to equipment are the most important criteria for selecting a technique. Shear strength, compression, tensile strength, and modulus of rupture measurements are more frequently associated with soil-equipment interactions and trafficability. Use of shear strength measurements to assess mechanical impedance of root growth has been reported (Collis-George and Yoganathan 1985a, b). Values of spherical impedance closely approximated blunt penetrometer (60^{o} apex angle) measurements (Greacen 1986). However, as Collis-George and Yoganathan concluded, and Greacen (1986) emphasized, shear strength is not suitable for use as a single parameter to describe soil resistance to root growth. Shear strength measurement has been used to assess the susceptibility of trees to windthrow (Anderson et al. 1989).

Shear measurement as described by the Mohr-Coulomb theory does not characterize soil behaviour prior to shear failure or the effects of soil displacement caused by the applied load. The determination of shear strength in the laboratory using remoulded soils does not necessarily represent soil behaviour under applied stresses in the field.

In direct shear tests using grouser plates or translational shear boxes, the shear plane does not remain constant and the size and shape of the plate or container influences the final determination. Numerous measurements are required to define the shear failure envelope. However, the technique is simple and fast.

Use of torsional devices involves a number of assumptions that may be difficult to control (Johnson et al. 1987). Of the torsional devices, the sheargraph is the most efficient for field use and results can be plotted directly. Lloyd and Collis-George (1982) developed a hand-held shear box for both in-situ and laboratory measurement of shear strength of agricultural soils.

Vane shear device measurements have been shown to be better correlated to equipment draft than those from other devices (Yong and Youssef (1978) as cited by Johnson et al. 1987). While field measurement of soil strength has usually been made using torsional shear devices (Koolen and Kuipers (1983, as cited by Douglas 1986) and cone penetrometers (Anderson et al. (1980) as cited by Douglas 1986), Ball and O'Sullivan (1982, as cited by Douglas 1986) concluded a vane shear test might be more suitable than a penetrometer for assessing seedbed strength. Franti et al. (1985) were unable to predict soil erodibility from measurements of soil strength using drop cone and vane shear devices, but predicted differences in critical tractive force. The method also allows for testing of the complete profile without withdrawal of the apparatus.

Triaxial shear devices allow more precise measurement and control of the applied stress and are widely used to standardize other methods and measure shear strength. However, it is a laboratory device that applies relatively high stress and may not adequately reflect field conditions.

Modulus of rupture measurements of strength are used to describe the slaking and crusting behaviour of unstable soils in the assessment of seed germination problems (Hillel 1980). However, Awadhwal and Thierstein (1985) suggested that since there is no known way of equating the modulus of rupture of free samples with seedling force, it was easier to measure impedance directly than to seek the additional information needed to apply modulus of rupture.

12.3 PENETROMETER METHOD

Penetrometers consist of a probe, generally with conical tip, and a gauge or a spring device to measure the pressure applied as a function of depth. Penetrometer design and operational factors that influence penetration resistance include the cone angle, diameter, cone surface and rate of penetration. Standards for equipment and the performance of penetrometer tests to assess general mechanical conditions for comparative purposes are provided by the American Society of Agricultural Engineers (ASAE, 1985). A 30^{o} (apex angle) circular stainless steel cone with a base area 323 mm^2 or 129 mm^2 and a drive shaft diameter of 15.88 mm or 9.53 mm for soft and hard soils respectively is recommended. The standard uniform rate of penetration is 30 mm s^{-1}. Perumpral (1987) reviewed cone penetrometer applications and provided a summary of penetrometer types. Bradford (1986) reviewed principles and methods for use of penetrometer types for soil research.

The measurement of penetration resistance using penetrometer devices has been applied in the study of root impedance, traction and trafficability prediction, and stratification of soils (Greacen 1986; Hillel 1980). The use of penetrometers as a valid method to characterize mechanical impedance and structure has been controversial (Cassel 1982; Manor et al. 1989). Despite the differing physical properties of roots and penetrometers, their penetration behaviour has been shown to be similar (Dexter 1986; Misra et al. 1986). Thompson et al. (1987) concluded that penetrometer resistance was a useful predictor of root system performance in three Illinois mine soils representing different soil types and soil handling methods. Soils handled with a wheel-conveyer-spreader system had the lowest resistance with values ranging from 0.647 to 1.628 MPa. Scraper-hauled material had the highest penetrometer resistance with values ranging from 1.905 to 3.709 MPa. Gerard et al. (1982) reported critical strength values (probe pressure at which root elongation stopped) of 6.0 to 7.0 MPa in coarse textured soils and 0.647 to 1.628 MPa in clay soils. Critical strength varied with plant species, varieties, and soil types. Busscher et al. (1987) used the critical strength value of 2 MPa resistance for a 5 mm diameter flat tipped probe from Taylor and Bruce (1966) and Camp and Lund (1968). Regression equations that relate soil strength with bulk density and water potential were used to predict the bulk density at the critical rooting strength (2 MPa) in coarse textured soils equilibriated at -100 kPa soil water potential. Calculated critical rooting bulk densities were in close agreement with measured values.

Resistance to penetration can be indirectly estimated using regression equations for soils of known texture, bulk density, moisture content, and predetermined constants. Canarche (1990) developed a model estimating penetration resistance of mineral soils as related to texture, bulk density, and gravimetric water content. The model is not applicable to soils with high organic matter (>8% to 10%) or highly structured soils.

Elbanna and Witney (1987) developed an empirical equation relating cone index (CI) with particle size distribution, soil water content and density. This equation is based on the bearing capacity of a shallow profile and assumes an incompressible soil. Ninety-three percent of the variation in the plow layer CI was accounted for by the equation. They indicated the CI of sands varied with density but not with water content. Vepraska (1984) confirmed this by observing little or no change in CI with water content below relative saturation of 0.9. Farrell and Greacen's (1966) model was able to predict CI values within 10% of those measured.

Measurement of soil resistance to root elongation using penetrometers has not been standardized. Generally penetrometers used for this purpose are smaller than those for mechanical property analysis. Greacen (1986) discussed probe shape and size in the use of penetrometers for the study of root elongation. A 60^{o} (apex angle) cone with a base area of 14.14 mm^2 is commonly used. Rates of penetration range from 1 to 10 mm hr^1 (Perumpral 1987).

Of the two types of penetrometers, dynamic and static, static penetrometers that are pushed into the soil have been the most widely used in soil research (Bradford 1986). The three static types in common use are the cone penetrometer, the frictionless sleeve penetrometer, and the pocket penetrometer. Cone penetrometers measure resistance to the cone while frictionless sleeve cone penetrometers measure the separate resistance of a sleeve located above the cone and the cone resistance. Pocket penetrometers measure the total sleeve and cone resistance. Hand-operation of these devices can result in data with high variability, thus, various modifications for mechanical insertion, logging and integrating data, elimination of shaft friction, and measurement acquisition over larger cross-sectional areas have been developed (Armbruster et al. 1989; Perumpral 1987). Heslop and Tetrault (1989) and Larney et al. (1989) developed efficient portable, constant rate cone penetrometers with computer controlled data acquisition for tillage research. Hooks and Jansen (1986) constructed and modified a constant recording cone penetrometer, with graphical or digital recording for use in reclamation research.

Fall-cone, drop-cone, plummet or strike probes have been used to determine soil strength. These devices relate the potential energy of the falling instrument to the volume of the cavity created by the device in the soil (Baranowski 1983).

12.3.1 Accuracy And Efficiency

Cone penetrometers are portable and efficient devices for characterization of mechanical properties and root penetration behaviour. Cone index data provide useful relative comparisons and can be correlated with other field data for similar soil types and conditions. While the relationship between structural variation and probe penetration has not been quantitatively defined, comparative testing of similar soil profiles subject to different loading forces, to predict trafficability and locate hardpans, can be accomplished using penetrometers (Cassel 1982; Dexter 1986; Greacen 1986; Hartge et al. 1985; Manor et al. 1989; Misra et al. 1986).

The soil cone penetrometer standard (ASAE 1985) recommends the size of cone, base and shaft diameters, mode of insertion, surface reading initiation and rate of insertion. Irregular rates of insertion and failure of penetrometers to measure the depth at the cone base in relation to the soil surface are the two most important equipment related errors. Mechanical insertion (hydraulic or electric) provides constant speed measurement and adherence to the available standards will promote uniformity in characterizing the penetration resistance of soils. The advent of recording penetrometers that monitor insertion rate and permit computer downloading has revolutionized measurements, allowing many measurements to be made quickly and easily.

The displacement of soil by the penetrometer tip is influenced by the device type, technique, moisture, density, loading history, and soil type. Interpretation of cone index data is complicated by this soil-cone interaction. Busscher and Sojka (1990) reported that scaling of cone index data (subtracting each value from the mean and dividing by the range of cone indices for each date of measurement, yielding an equal mean but unique distribution for each date) reduced or eliminated some of the baffling treatment effects.

Tijink and Vaandrager (1983 as cited by Koolen and Vaandrager 1984) measured cone index values at a number of depths and cone angles for a variety of soils in the Netherlands. They produced a graph using the relationship of between-cone angles and CI/CI at 30^{o} to be used to translate cone measurements at unusual cone angles into 30^{o} cone measurements.

Penetrometers have been used as indicators of seedling emergence problems, wherein the penetrometer is pushed upward from below to penetrate the crust. This is useful in a laboratory only. Ball and O'Sullivan (1982) found that the vane shear test was more sensitive to differences in soil texture, and bias sensitive to water content differences, than the cone penetrometer.

12.4 SPATIAL AND TEMPORAL VARIABILITY

Soil strength variations are linearly related to water content and bulk density at depth (120 mm), and less distinctly related in the profile surface. Seasonal variations in factors affecting soil strength (e.g., water content) are common in surface layers of agricultural soils (Douglas 1986).

Manor et al. (1989) found that soil bin CVs for cone penetration resistance were 16.7% for loamy soil and 3% to 10% for sand. Field measured CV values ranged from 25% to 63% on the same soils. Cassel (1982) and Manor et al. (1989) reported that the variability in cone index values (8.3% to 38.4%) under field conditions was largely due to the random distribution of tillage and traffic patterns by different equipment rather than soil heterogeneity. The CV for the smaller blunt probe penetrometers on sandy loams in the field was 25% (Greacen 1986). Surface measurements and those at the interface between subsoil layers of increased strength exhibit higher variability because of extreme changes over small distances. At the Highvale mine in Alberta, CV for penetration resistance (5 measurements - 30^o cone) ranged from 10% to 25% (Chanasyk and Naeth, unpublished data).

Perfect et al. (1990) studied spatial variability of constant-load needle penetrometer and constant-rate micro-penetrometer measurements on undisturbed cores of silt loam soils under different tillage practices, and concluded that the sampling requirements for penetration resistance increase with decreasing moisture content and bulk density.

Singh (1991) found that penetration resistance of a Chernozemic soil at Ellerslie, Alberta was not normally distributed and that a log-transformation, as suggested by some researchers (e.g., Cassel and Nelson 1979), did not improve normality or homogeneity of variances to a desired level. Moolman and Van Huyssteen (1989) used a geostatistical analysis of penetrometer resistance obtained values for a deep ploughed red sandy clay using an automatic, recording, hydraulically driven, cone penetrometer (30^o with a 129 mm^2 base area). They found that penetrometer strength values were normally distributed and had an isotropic spatial structure with an average range of influence of approximately 9 m. Variation from isotropic behaviour was observed at the 35 cm depth and attributed to the working action of the deep plough.

12.5 INTERRELATIONSHIPS WITH OTHER PARAMETERS

Soil strength is dependent upon internal parameters and applied external forces. Internal parameters include grain size distribution, clay mineralogy, organic matter content and type, root stabilization, bulk density, pore size distribution, pore continuity, water content, and water suction (Hadas 1987; Horn 1990). There is usually an increase in soil strength following a manipulative process in which large forces are applied to the soil: the two most common being compaction and water loss (Camp and Gill 1969). The characteristics of the external factors that influence soil strength include the rate of loading, the load intensity, the number of loading events, and time (Horn 1990). Using a penetrometer and modulus of rupture to measure soil strength, Gerard et al. (1962) found that a slow rate of drying caused closer packing of soil particles and greater soil hardness on a fine sandy loam soil than did a fast rate of drying. Soil strength provides mechanical support for plant material and protection for the supply and transport system of the soil from stresses and loads applied by crops, forests, animals, or management activity. However, increased soil strength can be detrimental when associated with increased bulk density and stratification of the soil profile.

External factors include kind of loading, load intensity, and time dependence and number of compaction events. If maximum strength is exceeded there is a decrease in pore space induced because the mineral particles and liquid phase are incompressible. Less aggregated soil horizons are more compressible than those with prismatic or polyhedral structure. With increases in clay content, aggregates become weaker. Clay soils are stronger during short time loading than silty or well structured soils with the same bulk density, load, and water suction, because in the latter soils, the initial timeless settlement dominates while in the former soils, long lasting secondary settlement dominates due to soil creep. Ice lens formation during freezing will either increase soil strength due to water dependent volume expansion, or decrease it due to peeling off of soil material from strong aggregates during freezing.

Soil strength at all depths was influenced by bulk density, voids, and clay content (Gerard et al. 1982). Shear strength was strongly negatively correlated with with gravimetric soil water content for an Ontario sandy loam (Coote et al. 1980). Shear strength also increased in loamy sand to clay soils in Ontario following springmelt. It also increased in fine textured soils with increased degree days, but there was no such relationship in coarse textured soils. In loamy sand to loam soil in P.E.I., Carter (1990) found in undisturbed soil cores, 66% of the variation in vane shear strength was related to bulk density and macropore volume.

Root growth (elongation) can be reduced by increased mechanical resistance and soil water. These limiting conditions occur in strong soils simultaneously, making it difficult to distinguish unequivocally between their effects. The ability of roots to overcome mechanical resistance of soil varies with plant species due to diameter and/or anatomy of the roots. The influence of a layer with high mechanical impedance for root growth depends on its place and dimensions. A less harmful effect of such a layer appears when it is situated in the soil profile and the horizontal dimension is smaller than the lateral spread of the root system and when the thickness of the layer decreases

(Glinski and Lipiec 1990). The critical impedance of the soil for root growth differs as affected by soil water and stages of root development. General limiting values are 1.3 to 3.7 MPa for barley, 3.6 to 5.1 MPa for oats, and 8 MPa for ryegrass (Glinski and Lipiec 1990). Compared to metal probes, root tips may penetrate the soil more efficiently because of a more advantageous distribution of the stress applied to the soil. Displacement of soil particles by root tips is more nearly consistent with cylindrical than spherical expansion. Cylindrical expansion of the root tip weakens the soil in front of it. Roots have mucigel layers which decrease friction. Soil resistance to probe penetration is thus greater than its resistance to plant roots. The response of roots to mechanical impedance involves root elongation and increased radial growth and is hormonally modulated. Rigidity of metal probes prevents them seeking out planes of weakness, biopores, etc. Roots growing in mechanically impeded soils will have decreased size, diminished elongation rate, uneven distribution, thickening , greater lateral branching, increased amounts of assimilates and oxygen per unit area , decreased VAM fungi colonization, increased rot, reduced water, and less mobile nutrient uptake (Glinski and Lipiec 1990).

Root growth at all depths was significantly influenced by soil strength (Gerard et al. 1982). The critical strength at which root elongation stopped was a function of % clay. The critical strength was 60 to 70 bars in coarse textured soils and 25 bars in clay soils. Taylor and Gardner (1963) and Thompson et al. (1987) found soil strength as PR was related to the ease of root penetration of soil. Thompson et al. (1987) found a high correlation (r^2=0.73) between PR and root system development.

Cone resistance and vane shear stength decreased with increasing coarseness of texture but was also dependent on soil structure and organic matter content (Ball and O'Sullivan 1982). Organic matter may also decrease compactibility by increasing resistance to deformation and/or by increasing elasticity (rebound effects) (Soane 1990). At high moisture contents, density had little effect on penetration resistance, the reverse was true at low moisture contents (Perumpral 1987).

12.6 EFFECTS OF DEVELOPMENT/MANAGEMENT ACTIVITIES

Thacker (1989) did a pot experiment with soils from sodic minespoils of clay loam and sandy clay loam treated with manure, gypsum and bottom ash, brome and quackgrass. All treatments, especially the crops promoted development of fine rather than large aggregates due to the short time of the study. The drier aggregates had greater strength. In the quackgrass treatment, soil strength increased at all water contents, in the bottom ash and gypsum treatments it increased in moist aggregates and in manure and bottom ash aggregate strength decreased.

In Ontario, Culley et al. (1982) found PR increased significantly on pipeline r-o-w, being 67% and 50% greater on the trench and work areas, respectively, compared to the undisturbed area. On Saskatchewan Solonetzic soils, trenching increased PR of the Bnt horizons; there were no effects on Chernozems (de Jong and Button 1973).

Under heavy intensity early season versus light intensity late season grazing in southern and central Alberta PR increased to 2.5 cm depth in Solonetzic loams and 15 to 30 cm in Chernozemic sandy clay loams and clay loams (Naeth et al. 1990). Heavy trampling on pathways compared to regular grazed areas increased PR to 30 cm if heavily grazed and to 10 cm if lightly grazed. PR under cattle paths was as high as 1427 kPa compared to an exclosed area with 607 kPa. Warren et al. (1986) found PR increased with stocking rate on a Texas silty clay loam.

Thacker and Johnson (1989) found that texture, moisture, and salinity all exert significant effects on minespoil strength as measured by PR on pot experiments using Luscar minesoils. Strength values at 33% clay were 2.5 times higher than those at 8% clay. Strength at 15 bars moisture tension was 2.6 times that at 1/3 bar tension. Strength at high salinity (>7 dS m^{-1}) was 1.25 times that at low salinity (< 2 dS m^{-1}).

12.7 PREVENTION/AMELIORATION/REMEDIATION/ACCEPTANCE

Due to the direct relationship between bulk density and soil strength, and the inverse relationship between soil water and soil strength, any practices that affect these two parameters will dramatically affect strength. In general, undesirable effects on soil strength can be minimized by conducting operations and reclamation activities under dry soil conditions.

Landsburg (1989), Lutwick et al. (1981), and Shaneman and Logan (1978), found bottom ash amendments prevented crusting. In order of decreasing soil strength between 21 and 45.5 cm depths, methods of incorporation were disc and chisel plow (0.34 bars), blanket (0.29 bars), and subsoiler (0.20 bars) (Landsburg 1989). The best application was 30 cm of ash, and subsoiling the best incorporation method. Haynes and Swift (1990) found that pasture aggregates did not slake in comparison to arable aggregates.

12.8 PERSPECTIVE

Of the various shear tests, only the vane tests have been used in agricultural compaction studies. Modulus of rupture has had only modest use in agricultural applications. The former tests can be used in situ; the latter are limited in direct field applications by the some what artificial nature of the sample preparation. Only the vane shear method permits field measurement to consider the strong spatial and temporal variability of soil strength.

Laboratory techniques for determining soil strength are perhaps, like Atterberg Limits, underutilized. However, unlike Atterberg Limits, which are relatively static, soil strength is extremely dynamic and thus laboratory strength measurements are less attractive. Measurements can be made economically, quickly, and repetitively, and are thus extremely attractive. They can be most useful in a reconnaissance mode where an inexpensive determination of problem soils is required. As with most other data, problems arise if too much is inferred from the data.

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13. COMPOSITE PROPERTIES

Get used to thinking that there is nothing
Mother Nature loves as well
as to change exisiting forms
and to make new ones like them
Meditations II
Marcus Aurelius Antonius
121-180 C.E.

13.1 SOIL STRUCTURE

Soil structure can be described as the arrangement and organization of soil particles (Hillel 1980) or as the spatial heterogeneity of the different components or properties of soils (Dexter 1988). It is a qualitative concept described in terms of form, stability, and resiliency that cannot be quantitatively defined by a direct method. Structural form describes the heterogeneous arrangement of solid and void space represented as total porosity, pore size distribution, and continuity. This arrangement of primary particles into hierarchical structural states is separable on the basis of failure zones of different strengths. Structural stability is the ability of the soil to retain its arrangement of solid and void space when stressed, and is generally specific for a characteristic of structural form and applied stress. Structural resiliency is the ability of a soil to recover its structural form through natural processes after removal of the applied stress, and includes tilth mellowing, self mulching, and age hardening (Kay 1990).

Dexter (1988) reviewed recent advances in characterizing soil structure. Various soil structure indices include: numerical aggregation index after drying, numerical aggregation index after wet sieving, water stability index, water stability coefficient, soil structure index, coefficient of soil structure, index of soil dispersion, and index of optimum agricultural aggregation (Glinski and Lipiec 1990). Quantitative analysis of structural changes in the soil profile are essential in describing processes of compaction, compression, erosion, and the process of tilth development.

The more important soil structural characteristics that influence hydrologic properties and plant growth include macropore and strength characteristics, aggregate size, and aggregate size distribution. Macroporosity and macropore continuity are important in the conduction of water and air and in root development in compacted soils. Soil strength imparts resistance to deformation, but can reduce root growth where water and nutrients are limited. Aggregate size distribution and aggregate stability influence erosion, root growth, and crust formation. Rates of change of structural form parameters are determined by strength and resiliency. As soil structure becomes more massive and dispersed, infiltration and hydraulic conductivity decrease.

Extensive reviews of the effects of water content, loading, and cropping systems on soil structure exist (Drescher et al. 1988; Gupta et al. 1989; Kay 1990; Larson et al. 1988). Cropping system induced changes are highly variable, depending upon soils, plant species, equipment, and climate. Structural alterations on reclaimed land are further complicated by textural changes and the potential for textural and density stratification of the soil profile. Water retention characteristic curves, infiltration rates, hydraulic conductivity, and air permeability, all describe changes in pore related structural changes. Aggregate stability, strength, and size distribution characterize the soil matrix. Gross quantification of changes in soil structure in compaction research include measures of bulk density and void ratio or total porosity. However, macroporosity, air permeability, and strength appear to provide more sensitive indicators of changes in structure affecting water and air movement and root growth (Boone et al. 1984; Dexter 1986; Greacen 1986; Gupta et al. 1989). Koppi and Douglas (1991) concluded vane shear strength and textural analysis could be used to quantify aspects of soil structure influencing plant growth (soil/root contact, air and water availability, and low mechanical impedance). Kay (1990) reviewed the models of Boone et al. (1984) and Gibbs and Reid (1988) that summarized cropping system effects on soil structure, and provided a framework for the design and interpretation of soil structure experiments. Soil structure influences other soil physical properties such as aeration, heat and water economy, and soil mechanical impedance. It also has an effect on microbial activity, plant nutrient availability, and decomposition of organic matter.

Plant roots have an impact on structure. Roots and root hairs penetrating the soil produce lines of weakness along which the clod or soil mass may break into granules. The pressure of developing roots may also induce aggregation. Root secretions flocculate colloids and stabilize or cement aggregates. Water use dehydrates colloids leading to shrinkage and cementation of soil aggregates. Some plant roots improve soil structure in the plough layer, and some grow through compacted layers and improve the soil below the plow layer (Glinski and Lipiec 1990).

McSweeney and Jansen (1984) described fritted structure, which has round aggregates loosely compressed together. Fritted subsoils favour good rooting, due to extensive void spaces between aggregates. Generally in beds of large compared to small aggregates, roots are characterized by lower growth, greater diameter, greater deflection, and increased percent of forked roots. Larger aggregates greatly reduce the proportion of roots penetrating them. Nutrient uptake is lower from large aggregates. The response of roots to aggregate size is closely related to the types of roots. Main axes of seminal and nodal roots are longer in the coarser aggregate systems, while length of secondary laterals is lower. Root hairs explore greater soil volume in macrostructured soil, thus increasing nutrient absorption.

Schafer et al. (1979) reported that soil structure in Montana after mining developed within 10 to 50 years near the soil surface but after 50 to 200 years at depths below 10 cm. Processes which formed natural soils in the Colstrip area also occurred in the minesoils and were more rapid in clayey than sandy spoils (Schafer et al. 1979). Equilibrium is expected in 200 to 400 years.

Weak platy granular structure developed in the upper 50 cm of many older minesoils. Some old minesoils high in clay had vesicular structure in the upper 5 cm. This develops when slow infiltration saturates the surface layer of the soil, entrapping air as spherical voids that form a vesicular structure when the surface dries to a crust. If erosion is controlled after mining in western Illinois, normal pedological development under well managed grasses and legumes will produce a thin soil to give an A horizon-like character in 20 to 30 years (Caspal 1975). When tillage is included, mixing and aeration may accelerate the process to 10 to 15 years.

Our knowledge is fragmentary
And so is our prophesying
I Corinthians 13:9

13.2 TILTH

Hillel (1980) defined soil tilth as "a qualitative term used by agronomists to describe that highly desirable, yet unfortunately elusive, physical condition in which the soil is an optimally loose, friable, and porous assemblage of aggregates permitting free movement of water and air, easy cultivation and planting, and unobstructed germination and root growth." The Soil Science Society of America defines tilth as "the physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration." Karlen et al. (1990) modified that definition to "the physical condition of a soil described by its bulk density, porosity, structure, roughness, and aggregate characteristics as related to water, nutrient, heat and air transport; stimulation of microbial and microfauna populations and processes; and impedance to seedling emergence and root penetration". The authors went further to define tilth-forming processes as "the combined action of physical, chemical, and biological processes that bond primary soil particles into simple and complex aggregates and aggregate associations that create specific structural or tilth conditions".

Tilth is a qualitative description of those soil physical properties that best articulate relationships between management and plant growth, and primarily relates to the condition of the surface layers of the profile. The development of the quantitative analysis of soil tilth is directed towards an understanding of the productive status of a soil at a given time, and the means to influence that tilth status. As such, tilth assessment provides a meaningful integration of those parameters that influence crop productivity and soil degradation. However, quantitative evaluations of tilth are dependent on soil, site, crop, management, and time, requiring long-term monitoring to provide accurate assessments of soil condition.

Tilth is a descriptive agronomic term most closely associated with aggregate stability and aggregate size distribution parameters of structural form related to plant growth. An index was developed by Singh et al. (1990) to quantify soil tilth based on the quantitative assessment of texture, aggregate size distribution, consistence, strength, bulk density, and organic matter content. King and Evans (1989), in an assessment of spring barley growth as related to soil tilth on restored opencast and unmined land, used aggregate size distribution as an indicator of tilth. They concluded yield changes were largely influenced by changes in physical properties that resulted in compaction and impedance to root growth. Buckland and Pawluk (1985) found tilth was reduced in deep plowed soils in east central Alberta as indicated by lower plasticity and increased strength.

The challenge appears to be less in defining what the term tilth represents and more in the quantitative description of those soil physical properties that best articulate relationships between management and plant growth.

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14. PROCESSES

Dictum sapienti sat est.
What's been said is enough for anyone with sense.
Plautus d. c.184 B.C.
Persa

14.1 COMPRESSION AND COMPACTION

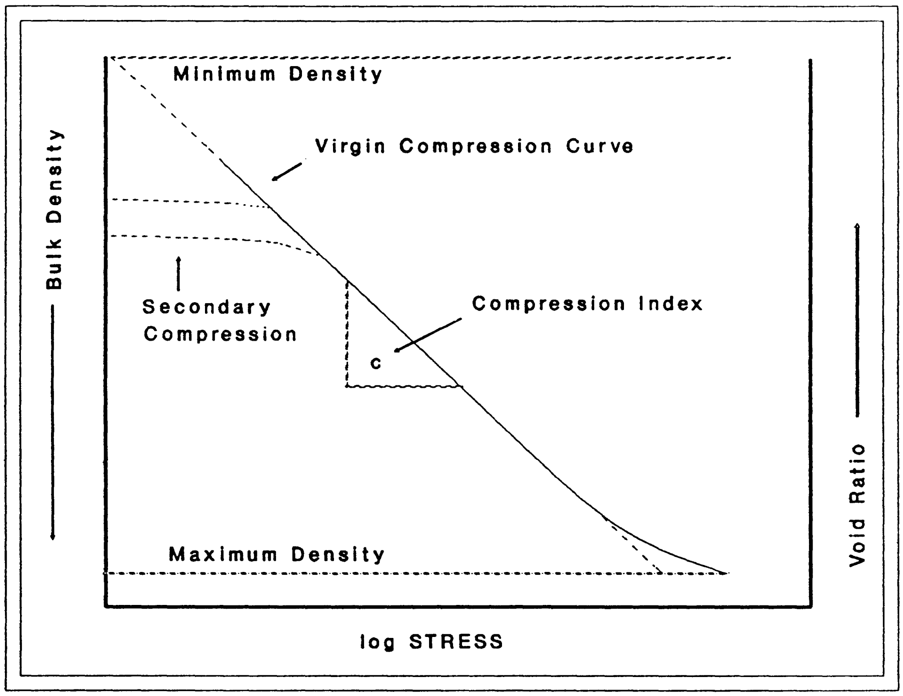
Compression is a process that describes the decrease in soil volume (increased density) under an externally applied load. Compression of saturated soils is called consolidation, while compression of unsaturated soil is called compaction (Gupta and Allmaras 1987). Under heavy traffic or moist soil conditions, density of the soil body increases and infiltration and air permeability are reduced. Root development is often restricted by mechanical resistance, reduced macropore space, and reduced oxygen availability. The hydrologic cycle is disrupted, resulting in susceptibility to drought stress and waterlogging (Gupta et al. 1989; Heinonen 1986).

Consolidation involves the exclusion of water from the voids of the soil matrix. It is tested under extreme conditions relating to engineering foundation design and has little applicability to unsaturated soils in reclaimed sites. Compressibility describes the ease with which a soil decreases in volume when subjected to a mechanical load. Compactibility is the maximum density to which a soil can be packed by a given amount of energy (Proctor test). While laboratory soil compaction consists of the compression of small homogeneous soil samples, field compaction can refer to the increase in density of several horizons within a soil profile. Compressibility adequately characterizes compaction in the laboratory, but soil compaction in the field cannot be described by a single property (Gupta and Allmaras 1987). Compression is a measure of the strength of a soil, or its resistance to a reduction in volume when subjected to an applied stress. Figure 14.1 is an illustration of the relationship between bulk density, applied stress and void ratio. Attempts have been made to predict the compressibility (influence of external forces on soil structure) of arable European soils, using combined measurements of water content, suction, saturated hydraulic conductivity, air permeability, bulk density, shearing resistance parameters, penetration resistance, and volumetric pressure transmission (Burger et al. 1988).

Compaction is often necessary to ensure good seed soil contact. However, excessive compaction is characterized by poor gaseous diffusion as pore size and porosity are reduced, large stresses that cause shearing of soil aggregates, and high soil strength impeding root growth. A comprehensive literature review on compaction was compiled by Byrnes et al. (1981)

Bulk density and total porosity are commonly used to assess the gross state of soil compactness but have limitations for characterizing compaction, and are poorly correlated with plant growth (Monier and Goss 1987). Applied force or applied stress parameters are used to

Figure 14.1. Soil compression curve.



determine strength characteristics and provide an indirect index of compaction. Differences in the adopted methodologies are research related. Pore size distribution and pore continuity are important in water, solute, and gas movement research. Information on soil pore geometry status can be obtained through determination of soil water retention characteristics, infiltration rate, and air permeability. Aspects of the soil matrix, such as strength and aggregate size distribution and stability, are generally studied in soil trafficability and erosion research. Establishment of a stable, continuous macropore system is considered the objective in the alleviation of soil compaction (Heinonen 1986). However, direct measurement of macropore volume and continuity is not possible. Bulk density and total porosity can provide measures of macropore characteristics.

The most widely used method of ameliorating compaction is subsoil disturbance or ripping. Research opinions vary as to the significant, persistent, benefits of ripping (Drescher et al. 1988).

But did thee feel the earth move?
Ernest Hemingway 1898-1961
For Whom the Bell Tolls

14.2 EROSION

Quantification of two factors, erosivity and erodibility, is the basis for understanding the erosion process. Erodibility is a measure of the soil's susceptibility to detachment and transport by an erosion agent. Erosivity is the ability of erosion agents to detach and transport soil particles. The facility with which particles are detached influences the degree of erosion (Lal 1988). Soil erodibility is influenced by particle size distribution, structural stability, organic matter content, clay mineralogy, chemical composition, and water transmission characteristics. Whereas erodibility is a function of detachment susceptibility of the soil, erosivity is determined by the force of the erosion agent. Rainfall erosivity is due to raindrop impact and runoff. The rate of rainfall and drop size distribution produce the kinetic energy or momentum responsible for detachment. The basic principles that describe water erosion processes apply to wind erosion, but the specific cause and effect relationships, the degree of the process within different landscapes, and the effectiveness of various control measures have not been widely studied (Lal 1988).

Soil erosion research methods are reviewed in Lal (1988). Erosion processes are assessed by measuring sediment yields from rainfall simulation on land, or suspended sediment and bed-load measurements in rivers. Wind erosion can be evaluated using wind tunnel devices. However, data from erosion research are often qualitative and extrapolated erroneously. Lal (1988) pointed out the dangers of applying generalized results of limited data over wide geographic areas, and called for increased standardization of methodology, improved data reliability, and increased duration and continuity of data collection. The capital and labour intensive nature of erosion research have largely precipitated these problems. However, there may be higher associated costs with using unreliable data or the lack of adequate data for predictions.

Control of erosion on disturbed lands has been subject to a number of misconceptions (Toy and Hadley 1987). While the areal extent of surface coal mining has long been touted as the principle component of environmental damage, Toy and Hadley (1987) argued that intensity and duration control the severity of disturbance.

Surface mining increases the erosion hazard by removing vegetative cover, altering land contours, and frequently leaving infertile materials on the surface (Robinson 1971). Severe erosion and sedimentation associated with decreased vegetative cover and the erosive nature of the soils in Swan Hills, Alberta, by oil industry activity affected 12% to 18% of some townships (Wyldman 1971). Downing (1972) reported that erosion control on colliery shale in England required gradient control to minimize sheet and gully erosion, but that cut-off drains lined with erosion resistant materials could control it. Lusby and Toy (1976) used rainfall simulators to determine erosion on Wyoming recontoured mine spoil. The reclaimed sites were more easily eroded than the undisturbed, with runoff of 1.52 cm and 1.98 cm, respectively under dry conditions. Under wet conditions, values were 3.12 cm and 2.16 cm, respectively. They concluded loam versus clay, dense root networks, and surface mulching were all effective in reducing erosion. Associated surface disturbances such as haul roads can cause erosion. In eastern Kentucky, abandoned sandy and clayey silt haul roads lost 6.6 and 12.7 cm of soil, respectively (Weigle 1965). In southwest Virginia, where rainfalls average 114 to 140 cm, sediment and runoff were effectively controlled with valley fills and sediment basins along with re-established vegetation (White and Plass 1974).

For revegetation, slides and slumping must be minimized by keeping bank slopes less than the critical angle of repose (Weigle 1965). The biological angle of repose, at which plants can colonize, is generally between 25^o and 30^o (Harrison 1974). However, steep 30^o to 35^o spoil slopes had significant vegetative cover (50%) from natural colonization 30 years after mining.

In four to seven year old reclaimed loam spoils in North Dakota, soil loss was 0 to 0.48 Mg ha^{-1} on reclaimed lands and 0 to 0.46 Mg ha^{-1} on undisturbed grassland (Schroeder 1989). Near Zap, North Dakota on sandy loam rangelands, clay loam and silty clay loam spoils, and sandy loam topsoils runoff averaged 41%, 48%, and 71% of snow water equivalent, respectively (Gilley et al. 1976). Soil loss from the same areas averaged 0.09, 4.30, and 0.85 t ha^{-1}, respectively. Increases in slope on sandy clay loam spoil from 4.8 to 17.6% increased erosion from 2.22 to 6.42 t ha^{-1}. Soil content of the runoff was greatest near the end of the melt period. Gilley et al. (1977) then compared cultivated and noncultivated soils in the same sites. Cultivated spoil lost 15 t ha^{-1} and uncultivated spoil lost 21 t ha^{-1}. Sediment loss decreased 39% to 18% on cultivated and noncultivated sandy clay loam spoil when the slope decreased from 17% to 4.6%.

A straw mulch reduced erosion by 84%. Increasing topsoil from 6 to 25 cm decreased runoff 24% but increased soil loss 7%. The decreased soil loss on cultivated plots was attributed to increased surface roughness and improved infiltration.

In forested areas, much of the erosion is caused by poor timber harvest practices: tree removal methods, cutting policy, road design, and improper drainage design (Rothwell 1978). Although erosion prediction on agricultural fields is common using the Wischmeier equation, Gee et al. (1978) found it could not be used to predict erosion from spoils in North Dakota.

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15. CONCLUSIONS

Routine use of soil physical characterization is currently limited by a generally poor working knowledge of soil physical properties and how they are measured. Hopefully this document will improve this knowledge and clarify some of the issues related to soil physical property measurement. It should be clear that choices exist for each property measured and for measurement technique. Each technique has its own advantages and disadvantages and thus the techniques chosen for evaluation are often those of personal preference, considering resources and time available. Measurement accuracy must also be considered.

The effects of the various development/management activities on soil physical properties are similar. Research on any one of agricultural, forestry, and natural resource exploration and development activities is highly valuable to the understanding of the impact of the others and thus should not be conducted in isolation. Appropriate scaling of the various activities is, of course, required to take into account differences in area affected, depth of soil disturbed, time of maximum effect, and types of ecosystems affected.

To date, emphasis in reclamation research and monitoring has been mainly on soil chemical properties. It is not desirable that this continue nor that evaluation shift entirely to consideration of soil physical properties. Rather, it must be recognized that physical, chemical, biological, and mineralogical soil properties are all integral to the behaviour of soils in both natural and reclaimed states. The interrelationships between plant and soil must also be considered.

Therefore as Winston Churchill stated: "This is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning".

16. RECOMMENDATIONS

16.1. FUTURE NEEDS

Future needs in reclamation research and monitoring, in no particular order, include:

1. There is a great need for definition and standardization of terms used in studies of soil physical properties. When we are referring to density or strength, we should not be talking about compaction. We must separate process and property and we must recognize that some properties are static while others are dynamic. See Appendix 2 for definitions.
2. Benchmark sites are needed to permit comparison of soil physical properties disturbed by reclamation related activities. These sites must have detailed characterizations and be monitored over a long period of time. Reference sites, which are undisturbed by the reclamation activities being studied, are imperative in all reclamation research and monitoring.
3. Long-term studies are important and should be encouraged and funded. We know relatively little about the long-term effects of reclamation activities on soil properties. Intense monitoring is important in the first three to five years after reclamation, followed by periodic evaluations. This strategy should be considered when establishing study sites.
4. The importance of soil-plant-water interactions should not be underestimated. Future reclamation research should have a more interdisciplinary, holistic approach covering soil physical, chemical, biological, and mineralogical properties and conducted by appropriately trained professionals. This multidisciplinary approach will not only be more comprehensive but also more economical and time saving, in that a detailed site characterization will serve all disciplines, rather than each professional setting up his/her own independent site.
5. It is important to relate differences in soil physical properties to plant productivity, and establish ranges of criteria for soil capability assessment because currently many threshold values for soil physical (and chemical) properties are theoretical and not based on plant response. For instance, an increase in bulk density from 1.20 to 1.35 Mg m^{-3} may prove to be statistically significant, but yet might have very little impact on plant growth, depending on soil texture. Hence the importance of an interdisciplinary approach to future research.
6. A standard means of monitoring research sites and inspecting reclaimed fields should be encouraged. It is important that researchers, field personnel, and government regulators all measure the same soil property with the same method. Then comparisons among studies are truly valid. As well, values from various techniques at a given site should be compared and the results rationalized to permit the choice of the optimum measurement technique for the purpose at hand. This does not preclude trying new measurement techniques, nor does it preclude omitting a standard measurement from a study. Attempts should always be made to correlate results from new techniques to those from the standard ones. Antecedent conditions (e.g., soil

water) at the time of measurement are invaluable in method comparisons and understanding temporal variations thereof.

7. Useful, simple, fast, and inexpensive laboratory and field methods must become standard to help assess reclamation succcess. It should be recognized that some level of thoroughness must be sacrificed when such an approach is taken. A distinction should be made between measurements made for technique comparison and those merely for field assessments.

16.2. RESEARCH PRIORITIES

To this end, priorities for future research should be:

1. To investigate threshold (plant growth limiting) values for commonly measured soil physical properties relative to commonly grown vegetation. What are these values of bulk density, penetration resistance, soil water content, etc. for specific soil textures? What factors control and/or influence these values?
2. To establish a field-based comparison or assessment of methods on a reclaimed site that has some plant growth. Various soil physical measurements should be related to plant growth on and off the reclaimed area to determine which best describe what a Reclamation Officer sees. This should be conducted two or three times a year over a period of two to three years.

16.3 THRESHOLD VALUES

One resounding desire from Workshop participants was for the establishment of threshold values so that field personnel could establish whether or not a 'problem' existed from a physical perspective, considering plant growth as the overall concern. It is recognized that many factors affect whether a soil physical property at a given magnitude would pose a growth problem or not, and that such magnitudes might vary from location to location because of climate and vegetation. There is also an inherent danger in proposing threshold values, with the fear that they become 'written in stone'. In spite of these reservations and concerns, the authors propose the following rating scheme for trial consideration (Table 16.1). Bulk density and penetration resistance were chosen as the two indicator parameters because of their relative ease of measurement and the generally universal understanding of their interpretive value. The authors trust that the scheme will be used in the spirit in which it was intended; namely, as a starting point to foster more research into and discussion of soil physical properties. Field site visits to 'problem' areas and workshops are excellent mechanisms to foster such research and discussion.

Table 16.1. Threshold values for soil physical properties related to plant growth.

	Good	Fair	Poor	Limiting
1. Bulk Density (Mg m^{-3})				
Sandy Loam	≤1.50	>1.50 and ≤1.60	>1.60 and ≤1.70	>1.70
Loam	≤1.40	>1.40 and ≤1.50	>1.50 and ≤1.60	>1.60
Clay Loam	≤1.30	>1.30 and ≤1.40	>1.40 and ≤1.50	>1.50
2. Penetration Resistance (MPa)				
	≤2.0	>2.0 and ≤3.0	>3.0 and ≤4.0	>4.0

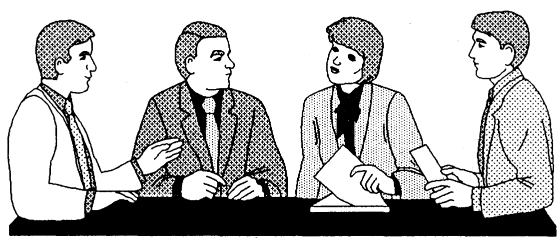
Note these measurements should be made under average antecedent soil water conditions (neither extremely dry nor exceedingly wet).

It is recommended that these measurements be made at a depth of 15 cm.

It is recommended that ASAE standards be followed in use of the penetrometer. (ASAE standard 30° cone, manually pushed, with either 0.5 or 0.2 sq inch cone.)

PART II

WORKSHOP PROCEEDINGS



17. PROCEEDINGS OF THE SOIL PHYSICAL PROPERTIES WORKSHOP

17.1 BACKGROUND

The Soil Physical Properties Workshop held November 21, 1991 at the J.G. O'Donoghue Building, Edmonton, Alberta was designed to provide a forum for the discussion of the effects of agriculture, industry, forestry, and reclamation related activities on soil physical properties. Sixty-four participants registered.

During the introductory segment of the program, chaired by D.S. Chanasyk of the University of Alberta, the following invited speakers provided their perspective on the effects of development/management activities as related to soil physical properties:

W.J. Hastie,TransAlta Utilities Corporation,
A.W. Fedkenheuer, NOVA Corporation of Alberta,
D.J. Pluth, University of Alberta,
M.A. Arshad, Agriculture Canada,
J.C. Hermans, Alberta Agriculture, and
A. Janz, Alberta Environment.

Workshop participants formed five working groups and discussed topics directed towards the assessment of the current knowledge of soil physical properties, appropriate courses of action, and future research needs. The discussion groups were led by Rick Ferster, LUSCAR Ltd.; Grant Gillund, Alberta Agriculture; Diana Brierley, Forestry, Lands and Wildlife; Bob Howitt, Alberta Research Council; and Tom Goddard, Alberta Agriculture. In general, the topics included: soil physical properties affected by anthropogenic activites, the effects of soil disturbance and reclamation-related activities on soil physical properties, positive and negative effects of changes in soil physical properties on the function of the soil ecosystem, and various methods of evaluating soil physical properties. The workshop session closed with reports from the five working groups and a general discussion of their comments followed by the chairman's summary.

The workshop provided an opportunity for multi-disciplinary discussions of soil physical properties and gave direction for the further development of the Soil Physical Properties in Reclamation document and for future education and research requirements.

17.2. INTRODUCTORY PRESENTATIONS

Unedited introductory presentations as prepared by the speakers are herein presented.

THE EFFECTS OF SURFACE MINING ON SOIL PHYSICAL PROPERTIES

Mr. W.J. Hastie
TransAlta Utilities Corporation

Introduction

It wasn't too many years ago that nobody wanted to talk about soil physics except for a few professors and their students, and then only within the confines of a soil physics laboratory! It is therefore delightful to see so many here today, prepared to discuss soil physical properties in relation to your area of business.

Today, I would like to briefly give you an overview of the surface mining process, based on my experience at TransAlta's Highvale coal mine, and then point out some of the key soil physical conditions that have resulted from mining's effect on soil physical properties, and leave you with a couple of thoughts for later in the day when we discuss research needs.

The Mining and Reclamation Process

At the Highvale Mine a total of 12 million tonnes of coal are mined each year to supply our Sundance and Keephills thermal power plants in the Lake Wabamun area of Alberta. The mining process begins with salvage of all topsoil in advance of the active mine, followed by the salvage of enough suitable subsoil to meet the needs of the reclaimed landscapes. A fleet of scrapers, supported by two D9 bulldozers and a grader, conduct all soil salvage at the Highvale mine.

The remaining material above the coal, overburden, is moved by dragline and dumped in spoil piles in the mined part of the pit. Our largest dragline has a 122 m boom and a bucket that can move 69 m^3 of overburden at a time. Once a sufficient amount of spoil is built up, it is levelled and contoured with D10 and D11 bulldozers into the shapes of the desired final landscapes.

Suitable subsoil is then replaced to depths ranging from 0.35 to 1.5 m depending on the desired agricultural capability. Finally, a 0.2 m layer of topsoil is replaced. The soil replacement is conducted by the same scraper fleet which was used to salvage the soil. In most cases today the soil is salvaged and replaced in one operation, avoiding the need to stockpile the soil.

Resulting Soil Physical Conditions

The majority of soils in the Highvale mine area are clay loam to clay in texture, with highly developed subsoil (B horizon) structure. Pockets of deep, medium to coarse textured soils occur over less than 30% of the mine area.

The salvage of topsoil and subsoil tends to destroy the structure of the soil, except in the case of well aggregated, cultivated topsoil, salvaged when it is relatively dry. The scrapers replace the soil in lifts, compacting each as they drive over the previous lift. The result is a compacted soil with massive structure and high bulk density. The penetration resistance also tends to be high, and moisture and root penetration into the subsoil layer are slow and limited.

In fields that are level or nearly level, excessive random ponding of water occurs after one of the frequently occurring high intensity summer rainstorms. With no surface outlet for the water, and little drainage through the compacted soil, the water remains ponded for extended periods, drowning seeded crops, and inhibiting normal field activities.

When the initially compacted topsoils are cultivated, they tend to become cloddy, with poor soil tilth. Dispersion of the clods is common after a rainfall, and crusting results during subsequent dry periods. This can lead to poor crop germination, patchy growth and weediness.

Remedial Measures

To avoid random ponding on level fields, we contour the soils to open surface drainage. This means providing a gently sloping landscape for meeting the agricultural capability goals.

Upon review of our reclamation process in 1985, and the behaviour of the fields we had reclaimed to that time, we felt that there were number of measures we could take to improve what we believed to be soil physical problems associated with our mining and reclamation at Highvale. The measures which we considered and implemented focussed on three main objectives:

1. Elimination of high clay content, high sodium content, subsoil from the salvage and replacement process
2. Minimization of mixing suitable and unsuitable subsoil and mixing topsoil with subsoil, and
3. Management of our reclaimed fields to improve subsoil drainage and topsoil tilth.

Up to 1986, suitable subsoil for use in reclamation was selected based on comparison of the subsoil properties with a set of largely chemical criteria. If any one subsoil property exceeded the criteria limit, the subsoil was considered unsuitable. The criteria limits were such that most subsoil, including Solonetzic B and C horizons, at Highvale were considered suitable. To reach the first objective, we re-examined the criteria, added a couple of key physical properties (clay content and consistence/plasticity) and considered the interactive effects of sodium and clay. This allowed us to focus our efforts on salvaging and replacing better quality subsoil, in quantities that allow us to achieve or exceed the agricultural capability objectives of our reclamation program. Not only that, but it is less costly to replace better subsoil!

In 1987 we hired a pedologist to work full time in the field with our contractors. The pedologist's prime responsibility is to ensure the second objective of precision and quality in the handling of the topsoil and suitable subsoil.

The management of our reclaimed land to improve drainage and tilth appeared more complex. In late 1985 and early 1986 we brainstormed with a number of soil scientists in the province before embarking on a land management plan. We concluded that deep ripping, together with a program of organic matter enhancement in the topsoil would achieve improved drainage and tilth, at least in the short term. We began the program in 1986 by deep ripping 40 ha.

Today all our reclaimed land at Highvale has been deep ripped, and we rip all new reclaimed fields as a matter of course. The results are evident immediately. In a field that took 3 weeks to dry after a heavy summer storm before ripping, we are now able to drive our tractors 3 days after a similar storm.

Our tilth improvement program also began in 1986, in conjunction with the ripping, and includes operationally applying manure to those fields with the poorest tilth, followed by seeding to a grass mixture with a high ratio of roots to top growth. The manure gives the topsoil improved physical properties (infiltration, density, porosity) immediately, while it is felt the root contribution will provide the long term organic matter components the soil needs for good tilth.

We do not know how long effects of management methods will last. We have undertaken a research program with the Soil Science Department at the University of Alberta to determine the magnitude and longevity of the beneficial effects of deep ripping and organic matter amendments.

Research Needs

No matter which soil physical property you believe is most important, and requires additional research, there are two thoughts I believe you should consider, those are:

1. The dynamic behavior of soils, and,
2. Interactions between soil physical properties and chemical, biological, microbiological, topographic, and climatic properties of the area you work in.

I believe it is most important, while researching most soil physical properties, to examine their dynamic behavior. For example, at Highvale we might ask the question; how have soil moisture holding properties changed from before mining to after reclamation, or after a period of reclaimed land management following soil replacement? Have the number and length of soil moisture stress periods changed as a result of mining and reclamation or as result of a period of reclaimed land management? The global question is really; what is the physical behavior of reclaimed soil in relation to pre-mined soil?

Reclamation is a multidisciplinary activity. I believe that the research on soil physical properties will be most effective and useful if it is done in the context of interactions of the physical properties with other components of the ecosystem or landscape in which the soils under study exist. In soil physical studies, we should not be afraid to seek ideas and input from specialists in soil organic matter, groundwater, microbiology, crop or plant science, climatology, economics or even engineering. Not only might we learn something from considering other interactions, but we in soil physics may find we can help other specialists with their concerns.

A recent example brought the value of this home to me. A bright young soil physicist was out one day at Highvale, reviewing some of our reclamation activities with our mine manager. The mine manager was heavily involved with a very difficult and high profile project at the time - seeking input from the relatives of people buried in the local cemetery as to whether TransAlta should move the cemetery or mine around it. The mine manager mentioned to the soil physicist that one of the most difficult problems he had encountered was that many of the graves were unmarked and the plot plan had burned in a house fire.

If the choice was to move the cemetery how would they know if they had found all the graves? The soil physicist had listened to this description of a problem with an interested and open mind. He immediately suggested to the mine manager that there was a very simple instrument in the soil physics laboratory at the University of Alberta that might solve his problem - the cone penetrometer. Within a couple of days the mine manager had arranged to borrow the penetrometer, and in no time he was able to precisely locate the unmarked graves. A soil physicist, reviewing reclamation with a miner, solves the miner's problem in a graveyard! The value of interdisciplinary brainstorming! That is why we are here today.

SOIL PHYSICAL PROPERTIES AND THE ALBERTA OIL AND GAS INDUSTRY

Dr. A.W. Fedkenheuer
NOVA Corporation of Alberta

Soil Physical Properties Important To Industry

1. Soil Quality Criteria Relative to Disturbance and Reclamation
   -soil profile should be described as to horizon thickness, soil colour, texture, structure, consistence, rooting abundance, and stoniness.
   - actual physical properties used to develop reclamation suitability rating are: texture, consistence, stoniness, saturation percentage, organic carbon.
2. Land Capability Classification for Agriculture (Pettapiece (ed.) 1987)
   - land evaluation uses physical properties of: texture, structure, consistence, organic matter, thickness of topsoil, horizon, drainage, stoniness.

Where Impacts Occur

1. Wellsites
   - mixing topsoil and subsoil during removal and replacement in construction of roads and sites.
   - loss of topsoil during storage, borrowed for other company uses, worked into field by farmer or, its location is not recorded at time of placement.
   - soil compaction due to traffic during drilling and working in wet conditions both on access road, and around drill hole while in turnaround areas.
   - spillage of drilling muds and other materials such as diesel fuel during drilling.
   - disposal of drilling fluids and muds on-site.
2. Pipelines
   - mixing of topsoil and subsoil during removal and replacement, on travel area in unfavorable conditions, and during storage, if angle of repose not considered when stockpiling material.
   - loss of topsoil during removal and replacement due to equipment and wind or water erosion.
   - soil compaction on R-o-W from heavy equipment, stringing trucks, other vehicular traffic.
   - loss of organic matter due to disturbance; in rangelands disturbing soil stimulates organic matter oxidation and nutrient release.
   - pulverization of topsoil due to travel of equipment and vehicles on the R-o-W.
   - on pipelines in peatlands, especially in intermittent permafrost, frozen lumps cause problems.

Which Properties Are Most Affected

At this stage I do not think we know. For example with soil compaction, is it structure, pore continuity, pore size, air or water flux, bulk density, soil strength, temperature, etc.? More importantly even if we know which properties are affected, we do not know those changes will impact the soil system or plants. For example, soil compaction does not simply change one physical property; a change in bulk density changes a number of parameters as illustrated above. Unfortunately, many of us want to treat the soil system as a static system which it is not. It is a very dynamic system, which makes it difficult, but not impossible, to deal with.

What Is Done To Alleviate/Eliminate Impacts

1. Compaction Related
   - shutdown work in unfavorable conditions (requires increased supervision).
   - where possible, schedule work for frozen conditions.
   - rip (or cultivate) topsoil after replacement.
   - add straw, manure, peat, rotovate (cultivate) into topsoil.
   - with topsoil removed, rip B, add straw or manure, cultivate, spread topsoil over this.
   - let time (one of five soil forming factors) pass.
2. Topsoil and Subsoil Mixing
   - increase supervision during soil moving.
   - put environmental inspector on job.
   - better education of contractor.
   - increase separation distance between storage piles.
   - use proper equipment for removal and replacement.
3. Loss of Topsoil
   - fence topsoil storage pile.
   - map and record location and volume.
   - increase supervision to ensure all is moved.
   - water, tackify, vegetate topsoil storage piles.
   - utilize mulches, windbreak, straw crimping, gouging.
4. Disposal of Drilling Wastes
   - change to less troublesome drilling mud systems (e.g., to gel based mud)
   - remove wellsite topsoil, spread drilling waste on sub-soil, cultivate, replace topsoil over this.
   - land farm sludges.
   - squeeze pits, more or less cover in place.
   - haul away.
   - sponsor research for better muds and disposal methods.
5. Spillage
   - increase supervision of activities.
   - impose penalties on contractors.

- develop and use spill response plans.

6. Pulverization
   - water R-o-W.
   - strip topsoil off full R-o-W and work on B horizon.

Further Physical Property Research On Wellsites And Pipelines

- baseline study to obtain "real" data (numbers) on problems, their magnitude and duration, on what soils do they occur? This study will help provide focus for subsequent research.
- what to do with old backfilled wellsite flare pits or with hydrocarbon based muds or high salts.
- what is the time involved for recovery of soil from a negative impact on a soil physical property.
- how to best assess (quantify) structure and the significance of changes to it.
- how is soil pore continuity best re-established.
- what are impacts of re-distributing organic matter within the soil profile.
- lack available information about equipment for alleviating compaction, develop bulletin, manual?
- effectiveness of various crops for alleviating compaction and structure.
- how do the impacts of R-o-W pipeline stripping compare with ditch and spoil techniques.

Summary Comments

- There is a consistent feeling that wellsites pose a larger problem than pipelines
- There are site specific problems, however it's clear that the significance and magnitude of impacts of oil and gas industry activities on soil physical properties are not known in a quantitative sense.
- Care must be taken in determining research needs to isolate those items which require little time (one of the five soil forming factors) to return to acceptable levels from those which time will not help and which thus may be higher priority for research.
- Care should also be taken to separate items which truly require research from those which simply require better implementation of current known techniques.
- Have got to get away from the notion that the province is homogeneous with respect to soils. Should propose establishing a group (alternative is to hire a consultant) to establish guidelines for working with/on each soil series and identifying problems anticipated with each series.

OVERVIEW OF FORESTRY AND SOIL PHYSICAL PROPERTIES

Dr. D.J. Pluth
Department of Soil Science, University Of Alberta

Preface

Soil disturbances are of greatest intensity and areal extent during timber harvest and site preparation stages of rotation. Stand tending (unwanted vegetation control, thinning, fertilization) and fire protection present sporadic, minor soil disturbances related to ground access mainly.

Conceptual Model

Conceptual model for net primary production in forest ecosystems biased towards soil disturbances and physical soil environment.

1. Two clusters of soil properties regulating processes which control forest growth and site productivity: soil porosity - macro is critical and site organic matter - aboveground and below ground biomass, forest floor, organic matter incorporated with mineral matter.
2. Although soil physical properties may be identified as regulating growth-limiting soil processes (e.g. aeration, N, mineralization rates), usually their influences are interrelated with chemical and biological properties.
3. Ultimate goal is knowledge of impact of soil disturbances upon vegetation (N, P, P, i.e. trees).

Soil Disturbances During Timber Harvesting

Activity, equipment, and earth structures

1. Felling and tree processing on-site.
2. Skidding to landing (central points in cutblock) or to roads (commonly temporary) within cutblocks for processing delimbing, sorting).
3. Borrow pit areas for road grade and landing construction.
4. Rehabilitation of borrow pits/areas.
5. Slash pile burning.

Kinds and altered physical properties

1. Compaction - reduction in total porosity (increased bulk density) to a possible extent of remolding the soil fabric
   - Pore volume decreases, macroporosity decreases, microporosity increases
   - Db increases
   - Soil strength increases
   - Soil aeration - gas fluxes decrease

- Saturated hydraulic conductivity decreases
- Water infiltration decreases
- Surface water erosion (sloped surface) increases

2. "Rutting" - short distance (<1 m) soil displacement and mixing effected by mostly wheeled equipment resulting in a shallow channel
   - Associated compaction?
   - Structure/porosity
   - Forest floor disturbed
   - Local ponding - anaerobic
3. Soil displacement - bulk removal of forest floor and possibly A and B horizons effecting a loss of site organic matter. Associated with construction and rehabilitation of elevated or depressed road grades;
   - Soil fertility (nutrient cycles) - tree nutrition
   - Soil water retention
   - Frost heave
   - Surface erosion

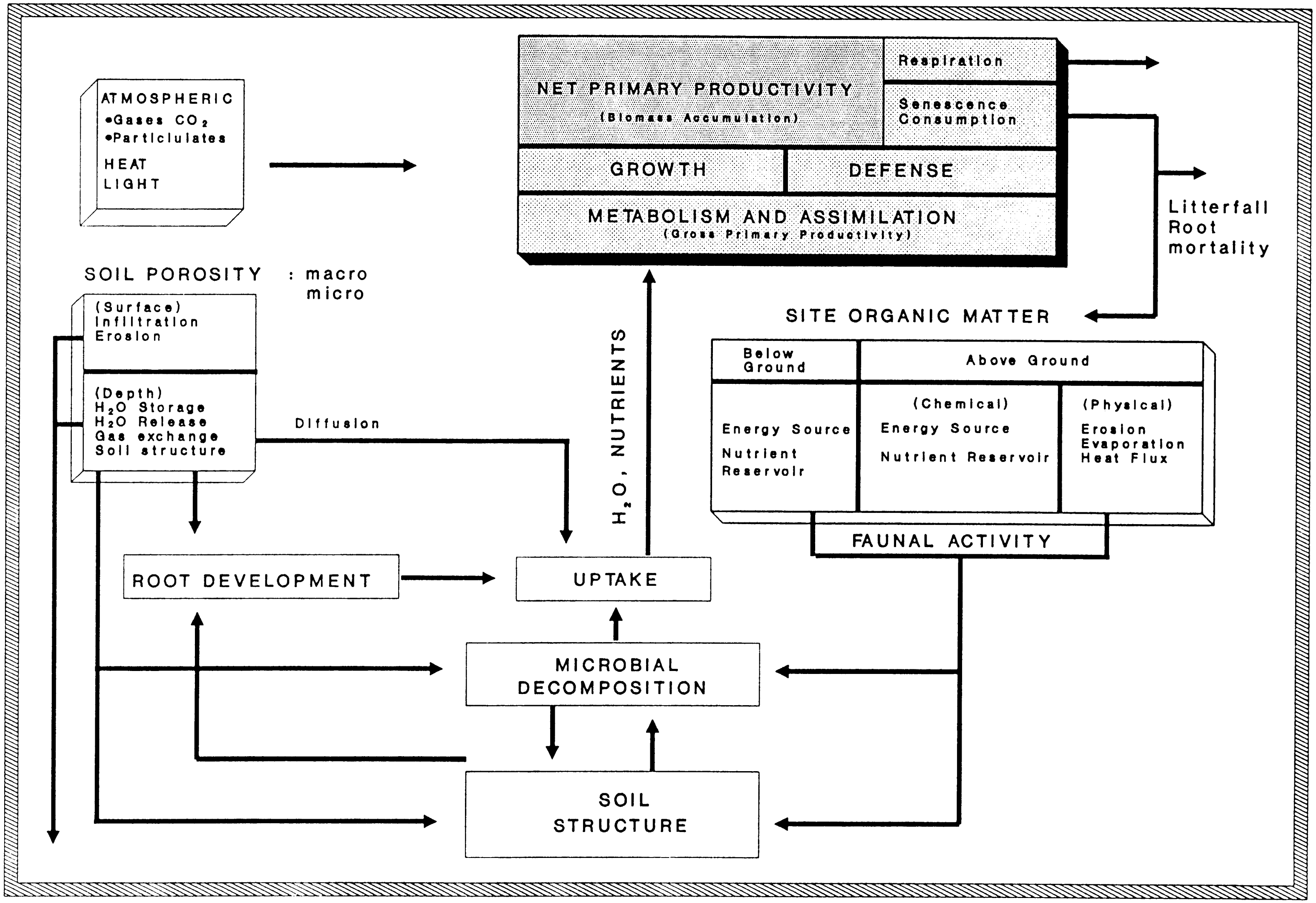
Minimizing (Preventative) Site Disturbances

- Timing of operations - seasonal and weekly
- "Terrain - sensitive" layout of skid trails, landings, roads, and borrows
- On site management of operations by silviculturalist/pedologist?
- Adapted equipment
- Equipment operators awareness of potential impacts of disturbances.

Reference

Powers, R.F. et al. 1990. Sustaining site productivity in North American forests: problems and prospects. IN: S.P. Gessel, et al. (Editors). Sustained productivity of forest soils. Proceedings of the 7th North Amererican Forest Soils Conference University of British Columbia, Vancouver, B.C.

A CONCEPTUAL MODEL OF SOIL POROSITY AND SITE ORGANIC MATTER REGULATION OF PROCESSES CONTROLLING FOREST SITE PRODUCTIVITY



(After Powers et al. 1990)

THE EFFECTS OF AGRICULTURAL DEVELOPMENT AND MANAGEMENT ON SOIL PHYSICAL PROPERTIES

Dr. M.A. Arshad
Agriculure Canada, Beaverlodge, Alberta

Summary

During the past 50 years, agriculture has moved from small scale farming systems to larger, more intensive systems of crop and livestock production. This shift towards more intensive agriculture has resulted in significant increases in productivity per unit area and total production. However, intensification of agriculture has had a negative environmental effect resulting mainly from over reliance on the technical advances in the farm machinery and heavy use of fertilizers and pesticides. Excessive tillage and some current cropping practices (summerfallowing, monoculture) have greatly altered the soil properties thus contributing to serious wind and water erosion, decline in organic matter, soil compaction/crusting and other forms of structural deterioration. This paper describes the impact of different farming systems, especially various cropping and tillage practices, on soil physical properties. The major study parameters include soil erosion, runoff, infiltration rate and storage, aggregate size distribution and stability, mechanical resistance, and bulk density. The results indicate that a continuous cropping under reduced tillage system appreciably increases organic matter, aggregate stability, water infiltration, and storage. The influence of these factors can be dramatic especially in Luvisols which have poor physical properties and are susceptible to soil crusting compaction and erosion.

The data presented herein are drawn from the work conducted by the Agriculture Canada research staff in Alberta.

Table 1: Annual Soil Loss Data for Beaverlodge Erosion Plots (kg/ha) (van Vliet et al. 1986)

Year	# of Events	Fescue	Canola-Barley	Fallow	Fescue	Canola-Barley	Fallow
1980	3	-	418	2903	-	-	-
1981	9	3057	970	5979	3373	1618	3171
1982	8	405	691	40012	574	1326	30273
1983	10	23	101	8234	45	75	9116
1984	6	54	42	527	4	108	1007
MEAN	(80-84)	885	444	11529	999	728	10892

Table 2: Annual runoff Data For Beaverlodge Erosion Plots (kl/plot) (van Vliet et al. 1986)

Year	# of Events	Fescue	Canola-Barley	Fallow	Fescue	Canola-Barley	Fallow
1980	3	-	6.969	6.747	-	-	-
1981	9	6.863	15.507	15.401	4.563	8.874	5.174
1982	8	12.685	6.075	12.760	10.383	8.310	18.550
1983	10	5.016	3.349	6.646	6.679	2.356	8.907
1984	6	9.330	0.110	9.476	0.260	0.330	1.440
MEAN	(80-84)	8.474	6.402	10.200	5.471	4.968	8.518

Table 3: Steady Infiltration Rate in Fall, After Harvest, and Before Tillage and Moisture Content at Summerfallow and Fresh Stubble Sites (Chang and Lindwall 1989)

	Rate (x10**-8 m s**-1)			Moisture Content (%) by Weight		
				Wheat	Barley	Mean
Treatment**	Wheat	Barley	Mean	before*after	before after	before after
Summerfallow						
NT	8.20	7.09	7.65a	13.86 23.19	15.36 24.73	14.61 23.96a
MT	6.68	4.78	7.31ab	14.14 24.23	15.57 23.90	14.85 24.07a
CT	3.31	3.56	3.44b	13.93 31.70	15.52 27.26	14.73 29.48b
Fresh Stubble						
NT	0.34	1.30a	0.82	15.29 23.07	20.15 23.28	17.72 23.33
MT	0.35	0.96ab	0.66	15.76 23.77	19.41 23.28	17.59 23.53
CT	0.42	0.71b	0.57	15.84 24.32	19.54 23.39	17.69 23.86

**NT = no till; MT = minimum tillage; CT = conventional tillage
*Before infiltration and 24 hours after infiltration
a,b Within each column, means followed by the same letter do not differ significantly ($P<0.05$)

Figure 1: Penetration Resistance
((N/cm^2) using base surface cone)
Object: J.B. Dawson Date: July 4,1990
1=JB#2 (zero) 2=JB#2(con.)
Cone #2

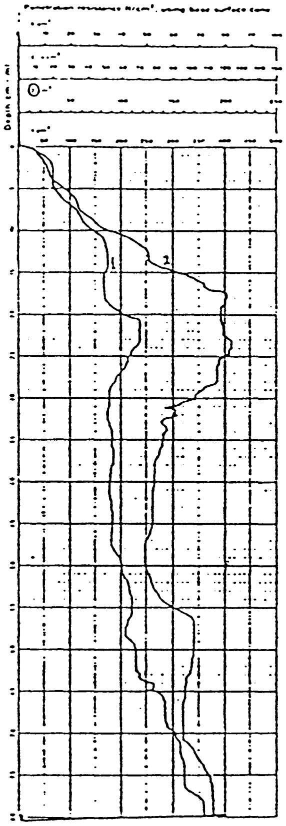


Figure 1: Penetration Resistance
((N/cm^2) using base surface cone)
Object: J.B. Dawson Date: July 4,1990
1=JB#3 (zero) 2=JB#4(con.)
Cone #2

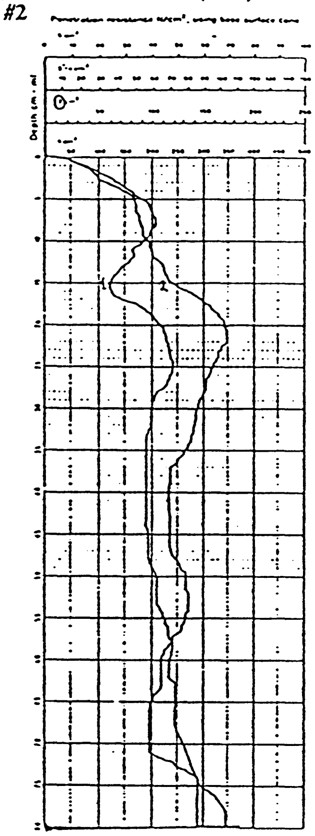


Figure 2: Effect of Tillage Systems on Soil Density

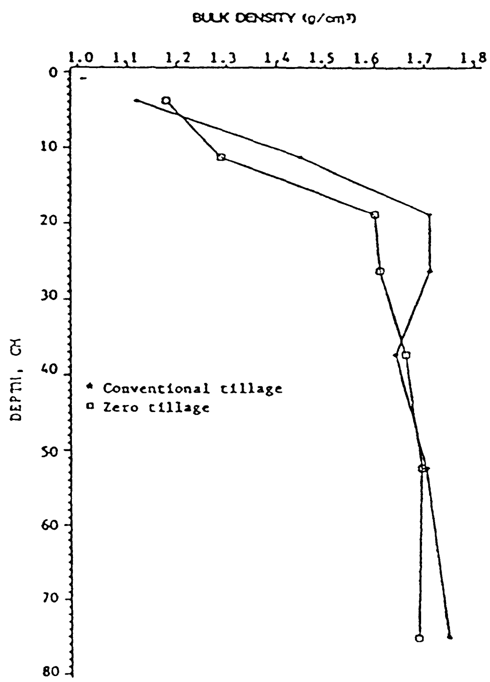


Figure 3: Soil Moisture Status (0 to 10 cm) in the Two Tillage Systems Under Continous Barley

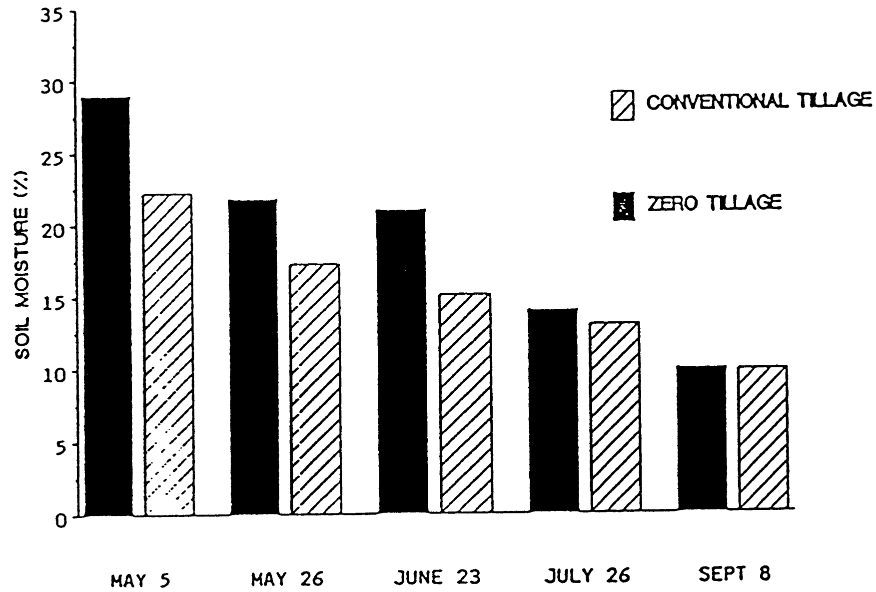
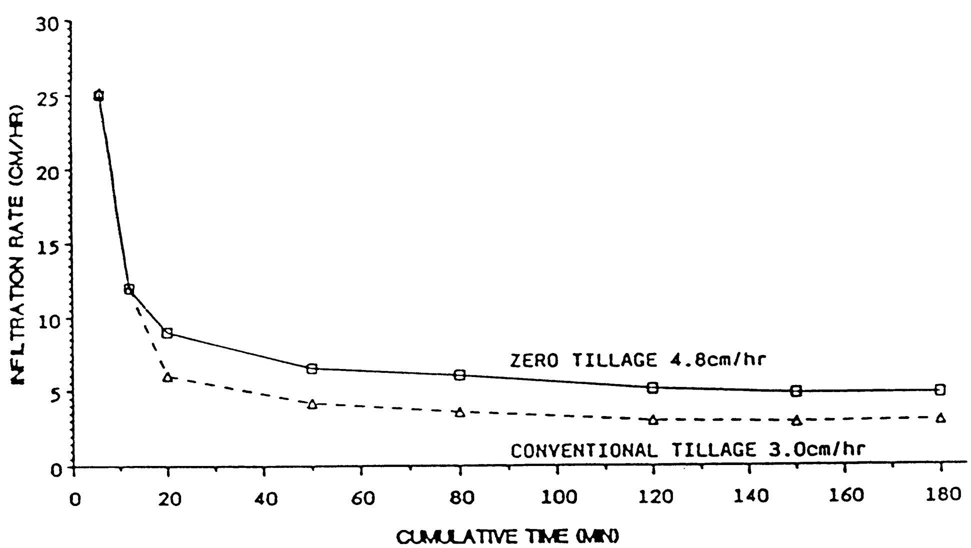


Figure 4: Infiltration Rates as Affected by Zero and Conventional Tillage Systems



ALBERTA AGRICULTURE'S ACTIVITIES, ISSUES, AND NEEDS REGARDING SOIL PHYSICAL PROPERTIES

Mr. J.C. Hermans
Conservation & Development Branch, Alberta Agriculture, Edmonton

Introduction

This report was prepared with input from the following Alberta Agriculture staff; Allan Howard, Soil Moisture Specialist, Lethbridge; Neil MacAlpine, Soil Water Management Engineer, Edmonton; David Neilson, Head, Farm Water Management Section, Edmonton; Tom Goddard, Conservation Planning Specialist, Edmonton; Brent Paterson, Head, Land Evaluation & Reclamation Branch, Lethbridge; Larry Speiss, Head, Resource Planning & Monitoring Section, Irrigation Section, Lethbridge; Randy Bjorkland, CASCI Coordinator, Edmonton; Jim Miller, Soil Salinity Specialist, Lethbridge; Russ Horvey, CARTT Coordinator, Edmonton; John Timmermans, Soil Conservation Specialist, Airdrie; Don Wentz, Soil Salinity Specialist, Lethbridge. Any technical follow-up in regard to their respective areas of responsibility is very much encouraged.

General Comments

From Alberta Agriculture's perspective the following points must be emphasized:

1. All of our interests focus on those physical properties that influence sustainable crop production
2. Several factors are interrelated with soil chemical and biochemical properties and therefore they become difficult to define as physical property issues; these include fertility, solute transport, and organic matter management.
3. Agriculture is concerned with systems for land management, and these include several factors; the physical properties of the soil are only part of a much bigger picture.
4. Our role is one that includes research, technology transfer, program support, and extension in order to increase and disseminate the information base regarding land management.

Soil Tilth

1. Our general areas of interest include physical properties that address the condition of soil aggregates, and can enhance or maintain their structural stability are of the most interest to us.
   - Effects of reduced tillage, alternate cropping systems, and increased surface residues on maintaining or improving soil tilth. For example, we are actively involved in researching the effects of incorporating legumes in crop rotations and reduced tillage on soil tilth.

- We are concerned with the effect of irrigation and irrigated land management on soil tilth. Land degradation is becoming an issue on irrigated land, mainly due to land management, however some may be a result of application techniques. Although it has been suggested even good quality irrigation water can negatively affect soil tilth, this is not an issue in Alberta.

2. Needs
   - Information that helps refine erosion prediction models
   - Information on infiltration and water retention in soil with poor tilth
   - We need information on understanding relationships between tilth and placement and function of herbicides. The success of using minimum surface disturbance placement techniques will be influenced by soil tilth, as will the dissolution and movement of herbicides. Development or adaptation of physical tests that help in the understanding of these relationships is needed.
   - A better understanding of the factors associated with irrigation and degradation

Compaction

1. Our interests include:
   - Identifying the impact of compaction on crop production
   - Determining the regional extent of compaction
   - Identifying land management activities and soil conditions that promote compaction (Agriculture Canada CARTT project)
   - Ientifying the best ways to prevent or manage compaction
2. Needs
   - Understanding water movement and root growth in compacted soils, how ripping (or other disturbance techniques) affects water movement and root growth, and under what conditions are the ameliorating effects expected to be short-lived or long-lived.
   - We need a definition of when a compacted soil becomes a problem to crop growth. Assuming agricultural activity results in some compaction in all cases, at what point does compaction significantly limit crop growth. This should be expressed as easy to measure properties such as penetration resistance.
   - With a definition and measurement standards set, the extent of compaction within an area can be determined as part of the soil survey activities
   - Criteria have to be established to enable field staff to recommend ripping/subsoiling under a given field condition and information should be available to allow them to predict the degree of success of crop performance that can be expected

Soil Water

1. Our interests include:

- How soil physical properties influence soil and water management. We work extensively with the application of relationships between soil physical properties and water movement, (e.g. role of macropores in enhancing infiltration, layering effects, root zone water storage, recharge, and impacts on water quality

2. Our soil water management activities include:
   - Soil moisture conservation
   - Surface water management
   - Drought monitoring and prediction; texture plays a major role on our assessment, other physical properties become factors in modelling activities (e.g. Solonetzic soil horizon density)
   - Deep tillage (e.g., deep plowing, ripping and subsoiling) where macropores are created to improve water movement and increase rooting depth
   - Subsurface drainage design uses physical properties as key criteria for depth and spacing, water quality
   - Classification of land for irrigation requires several physical factors including texture, density, layering, depth to bedrock
   - Relationships between water quality and soil concern dryland and irrigated agriculture, but, the magnitude of concern is greater in irrigated farming because of increased water volumes
3. Needs
   - Better understanding of spatial variability
   - Develop reliable field measurements to assess saturated and unsaturated hydraulic conductivity
   - Better information in soil survey reports; type of data in soil survey reports do not meet our current needs. We work with physically-based models for drainage and need good field measurements of infiltration, hydraulic conductivity, and water holding capacity as inputs.
   - A better understanding of soil temperature and its relationship to soil moisture is required, as is a better understanding of the snowmelt process, including infiltration of water into frozen soils, how infiltration varies with the water (ice) content of the frozen soil, influence of macropores created by soil disturbances, evaporation during low temperature-low humidity conditions.
   - A better understanding of how water uptake by various crops changes under very dry, and under saturated, soil conditions (soil physical properties are a factor in water infiltration, storage, and drainage).

Soils With Inherently Poor Physical Condition

1. We are concerned with:
   - How land management alters physical properties, and how long does it take to improve those properties important to crop production

- Improvement of crop productivity on soils with inherently-poor physical properties(e.g., Solontezic and gray wooded soils).

2. Needs
   - More information on the irrigability of Solonetzic soils in order to establish criteria to assess the suitability of a Solonetzic soil for irrigation
   - Better understanding of how to improve the physical properties important to crop productivity on Solonetzic and gray wooded soils in a cost-effective manner

Recommendations

1. We suggest that benchmark sites be established that represent typical soil conditions, land management, and agroclimatic zones in the province. Long term data on all of the above properties should be collected and made available to all users.

2. We are also identifying the need for cost-effective measurement and analysis techniques. As technical sophistication increases, capital outlay increases, often to the point of restricting or prohibiting the use of the technique/instrument. We would like to see effort directed into identifying conditions where precision can be reduced in favor of increased replication. In certain applications, especially in the realm of applied research, fundamental understanding of field conditions can be gained from a high number of lower precision measurements than from a few high precision measurements. For example the EM38 has become an extremely useful tool for understanding the behavior of saline seeps, despite having a lower degree of precision in the measurement of salinity than does the saturated paste electrical conductivity analysis.

SOIL PHYSICAL PROPERTIES - ALBERTA ENVIRONMENT PERSPECTIVE

Mr. A. Janz, Alberta Environment

Summary - Physical Soil Properties

Alberta Environment's Land Reclamation Division administers the conservation and reclamation of 2024 to 4049 hectares of land in Alberta each year associated with many types of industrial activity, including oil and gas leases, pipelines, access roads, borrow pits and mines. Proportionally, oil and gas leases make up the largest component of these disturbances.

In agricultural lands, physical soil degradation is common on these disturbances, especially on non-regulated operations associated with oil and gas leases. Soil quality reductions are primarily related to soil structure changes in the topsoil and subsoil. Soil responses to development, however, are also somewhat dependent on regional and climatic differences.

1. A variety of operational procedures are responsible for the degradation of soil physical properties. These could include:
- site development or operation in frozen soil conditions;
- site development or operation in saturated soil conditions;
- incorporation of drill mud constituents into upper subsoil;
- incorporation of residual or parent materials into the soil profile;
- a change in site contour;
- incorporation of contaminants into the topsoil and/or subsoil; and
- loss or depletion of organic matter

2. The most common soil degradation effects of these activities could include:
- reduced tilth quality (poor seedbed)
- reduced topsoil and subsoil porosity
- reduced topsoil and subsoil infiltration; and
- reduced root zone volume.

3. A number of physical soil degradation indicators are available for identification of degraded soil field conditions. These include visual observations such as restricted rooting, horizontally stratified topsoil and/or subsoil, presence of malformed roots, cloddy or powdery topsoil, sticky, structureless or dense topsoil and/or subsoil, presence of drill mud layers, water repellency, areas of rutting and/or ponding, reduced plant growth, evidence of waterlogged or droughty conditions causing late or early maturing crops, and colors indicative of anaerobic conditions.

4. In our experience one of the main factors affecting the physical properties of soils under construction is the change in structural orientation from vertical to horizontal, resulting in layering and stratification. Since machinery travel is normally perpendicular to the natural vertical pathways and cleavage lines which are essential for good root development and water and soil air movement, the soil structure remaining after site construction is generally oriented horizontally in stratified layers. Under drier conditions these layers may be easily separated when excavated but will remain resistant to vertical infiltration by water and air penetration by roots. Under wet conditions, these layers will be difficult to separate when excavated and may allow very little vertical water, gas and root movement. All of these processes may be further complicated by the loss of organic matter and the addition of contaminants such as sump fluids, drilling mud, oil, and parent materials from depths below the bottom of the original soil profile.

5. Several areas of research are recommended:

a. The development of simple, but accurate field tests to estimate infiltration and gas exchange within the soil profile.

b. The role of topsoil and organic matter in maintaining porosity and in facilitating the re-establishment of vertical pathways after construction.

c. The testing of various physical and chemical amendments for the purpose of re-establishing vertical pathways throughout the soil profile, and ameliorating repellent soils.

d. The testing of existing mechanical procedures to "decompact" soils, and the development of procedures that would facilitate permanent reconstruction of the vertical pathways (e.g., injection of organic materials into subsoiler rip lines).

e. Testing various plant species or crops for re-establishing vertical pathways in the soil profile.

f. The effect of various contaminants (drill mud, sump fluid, oil, parent materials) on soil structure in association with mechanical stratification.

g. The identification and mapping of regional soil differences in Alberta and responses to normal construction procedures under frozen, wet and dry conditions.

h. The identification of soil mineral types most susceptible to physical degradation by construction equipment.

i. The identification of soil textural combinations most susceptible to physical degradation by construction equipment.

j. Identification of root patterns and morphology which may indicate structure-caused stress.

k. Investigations to trace water, oxygen, carbon dioxide, and root movement in structurally damaged soils.

l. The identification and classification of the various degraded soil structure types (micro and macro) associated with site development operations in Alberta.

17.3 DISCUSSION GROUP QUESTIONS

1. Select the soil physical properties most affected by the activity sectors represented in the working group and rank the five properties most affected.

2. For each of the three highest ranking properties selected respond to questions 2a through 2g.
   a) What are the effects of the various activities on the soil physical property?
   b) What is the areal extent of the effects? What are the impacts/costs (direct/indirect)?
   c) What soil types and horizons are most affected?
   d) Are there differences between the anticipated effects and those observed in the field? What are the observed differences?
   e) Do spatial and temporal variability affect the property? What are the effects?
   f) What are the techniques used to measure the property? What problems are encountered in utilizing these techniques? What problems are encountered in interpreting data? Comment on the suitability of the method and the appropriateness of the data in assessing the problem?
   g) Discuss acceptance, prevention, remediation, and/or amelioration of the effects of development/management on the physical property.

3. a) Are there future research needs?
   b) Identify future research needs (i.e., What questions remain unanswered?)
   c) Are the research needs activity specific?
   d) Rank those research needs (identified in 3b above) as high, medium or low in priority.

17.4. DISCUSSION GROUP SUMMARIES

1. Affected soil physical properties selected by activity sectors represented in the working group.

Group 1
Aggregate Stability/Size
Bulk Density
Hydraulic Conductivity
Infiltration
Mechanical Impedance/Strength
Porosity
Structure
Water Holding Capacity
Gas Exchange
Heat Properties
Flux Properties
Water Transmission
Pentration Resistance

Group 2
Infiltration
Bulk Density
Structure
Strength
Displacement (splash)
Wind Erosion
Aggregation
Drainage
Impedance/Strength
Infiltration
Organic Matter
Fabric/Orientation
Strength

Group 4
Texture
Aggregation
Aggregate Stability
Compressibility
Bulk Density
Consistence
Hydraulic Conductivity
Infiltration
Mechanical Impedance
Porosity
Strength
Structure
Tilth

Group 3
Structure/Tilth
Tilth
Compressibility
Strength
Porosity
Aggregation/Aggregate Strength
Infiltration
Particle Size

Group 5
Water Transmission
Strength
Aggregation/Structure/Fabric
Bulk Density

2. The five properties most affected.

Group 1
Porosity
Aggregatation/Aggregate Stability
Structure
Particle Size/Discontinuity
Tilth & Compressibility

Group 2
Structure
Permeability/Infiltration
Aggregate Stability
Penetration Resistance
Particle Size Distribution

Group 3
Hydraulic Conductivity
Mechanical Impedance
Tilth
Aggregate Stability
Bulk Density

Group 4
Water Transmission
Strength
Aggregation/Structure
Bulk Density

Group 5
Porosity
Water Retention
Structure
Strength

3. The three highest ranking properties selected.

Group 1
Porosity
Aggregation/Aggregate Stability
Structure

Group 2
Hydraulic Conductivity
Mechanical Impedance
Tilth

Group 3
Structure
Aggregation/Aggregate Stability
Hydraulic Conductivity/Infiltration

Group 4
Water Transmission
Aggregation/Structure
Strength

Group 5
Porosity/Water Retention
Structure
Strength

SUMMARY OF SOIL PHYSICAL PROPERTIES CONSIDERED BY THE GROUPS:

The following summary is divided by soil physical property. Information for the summary was obtained from the notes taken in each working group at the workshop.

1. POROSITY

The effects of the various activities on the soil physical property.
- increased macroporosity with pipeline trench, cultivation, vegetation, zero till, weathering rate
- decreased macroporosity on pipeline travel side, mining, some geological materials, zero till, roads, cattle, wheel traffic, loading

The areal extent of the effects.
- Mining - Local
- Pipeline - Local, Provincial
- Forestry - Global
- Agriculture - Global
- Oil/Gas - Local, Provincial

The impacts/costs (direct/indirect). Mining has high impact with high remedial costs

Soil types and horizons most affected.
- Mining - All horizons
- Pipelines - A/B horizons, finer textured soils
- Forestry - Upper metre, finer textured soils
- Agriculture - A horizon and upper B horizon, peat and thin soils
- Oil/Gas - Upper meter, Luvisol, Solonetz, finer textured soils

Are there differences between the anticipated effects and those observed in the field. Yes

The observed differences. NA

Do spatial and temporal variability affect the property. Yes

The effects of spatial and temporal variability.
- Increase in soil moisture and/or clay content, decreases in soil porosity
- Freeze/Thaw cycles and wet/dry cycles increase porosity
- Sand lenses and horizon variability

The techniques used to measure the property.
- Direct - Pore Size Distribution via Cat Scan
- Indirect - pore density, infiltration, visual estimates, permeability, root distribution, penetometer, bulk density, sonar, micromorphology

Problems encountered in utilizing these techniques.
- No absolute measure, apply after the fact
- Except for pore size distribution, all are indirect measurements
- Time consuming, costly, require many replicates

Problems encountered in interpreting the data.
- No clear definition of what porosity should be without a control

The suitability of the method and the appropriateness of the data in assessing the problem. NA

Discussion of acceptance, prevention, remediation, and/or amelioration of the effects of development/management on the physical property.
- Prevention: operation procedures to minimize risks, equipment, timing, training, inspection
- Remediation: procedures, deep ripping, cultivation, organic matter, zero till, time, amendments

2. STRUCTURE

The effects of the various activities on the soil physical property.
- Change in aggregate size distribution and pulverization of soil structure with tillage
- Deep tillage and zero till improves soil structure, also crop rotations
- Scarification and exposure of mineral soil improves the establishment of forest soils
- Traffic on soil when too wet will puddle soil structure; occurs with pipelines, mines, agriculture

The areal extent of the effects. NA

The impacts/costs (direct/indirect). NA

Soil types and horizons most affected.
- Solonetzic soils
- Luvisolic soils, Ahe, Ae horizons
- High clay soils - more easily compacted
- Gleysolic soils are very sensitive to traffic and puddling Ah and Bg horizons

Are there differences between the anticipated effects and those observed in the field. Yes

The observed differences. NA

Do spatial and temporal variability affect the property. Yes

The effects of spatial and temporal variability. NA

The techniques used to measure the property.
- Visual classification, classification
- Size measurement, thin sections
- Aggregate size distribution (sieving), wet and dry sieving
- Tracer dye
- Bulk density, wax clods
- Root/pore descriptions
- Soil moisture characteristic curves

Problems encountered in utilizing these techniques.
- Subjective, qualitative, no such thing as an undisturbed sample, labs can't measure field structure
- Seasonal variability in the property, spatial and temporal variability
- Antecedent moisture conditions at the time of sampling

Problems encountered in interpreting the data.
- Dynamic property
- What does it mean to management
- Temporal and spatial variability

The suitability of the method and the appropriateness of the data in assessing the problem.
- Good for wind erosion, 0.84 mm for surface aggregates
- Good for off and on site comparisons, good for extremes but not good for gray areas

Discussion of acceptance, prevention, remediation, and/or amelioration of the effects of development/management on the physical property.
- Plan activity in winter, till soil when at proper moisture content
- Deep ripping and subsoiling becoming more and more accepted
- Shouldn't allow agriculture in areas with soils of poor surface structure and subject to erosion

3. AGGREGATE STABILITY

The effects of the various activities on the soil physical property.
- Conventional tillage reduces aggregate stability
- Fallow cropping reduces aggregate stability
- All factors affecting organic matter will affect structural stability
- Drilling muds may reduce stability due to bentonitic clays

The areal extent of the effects. NA

The impacts/costs (direct/indirect). NA

Soil types and horizons most affected
- Solonetzic
- Luvisolic soils
- High sodium soils
- Surface horizons Ah and Ap

Are there differences between the anticipated effects and those observed in the field. NA

The observed differences. NA

Do spatial and temporal variability affect the property. NA

The effects of spatial and temporal variability. NA

The techniques used to measure the property.
- Wet and dry sieving
- Water drop method
- Elutriation
- Penetration resistance
- Tensile strength
- Compressibility

Problems encountered in utilizing these techniques.
- Not consistent
- Expensive

Problems encountered in interpreting the data. Many!

The suitability of the method and the appropriateness of the data in assessing the problem. NA

Discussion of acceptance, prevention, remediation, and/or amelioration of the effects of development/management on the physical property.
- Legume plowdown and grasses in rotation are now accepted and are effective
- Manure application widely accepted and effective
- Duration of effects not well understood

4. WATER TRANSMISSION

The effects of the various activities on the soil physical property. Most activities decrease it

The areal extent of the effects.
- Increases in transmission occur to limited extent, very localized, i.e., pipeline trenching
- Decreases in transmission are activity dependent
- Agriculture, broad, not well understood and oil/gas localized

The impacts/costs (direct/indirect). NA

Soil types and horizons most affected.
- Subsoil, surface, 0 to 5 cm
- Fine textured soils
- Soils with impermeable layers
- Rare the soil that isn't affected, Chernozems least prone
- All horizons can be affected
- Shrink/swell soils
- Forested and biologically active
- horizons affected by activity, agricultural surface and below plow layer, mining subsoil, pipelines depends on activity on R-o-W, forestry rooting zone

Are there differences between the anticipated effects and those observed in the field.
- Plow layer compaction doesn't always happen
- No difference under ruts and between ruts and under canopy

The observed differences. NA

Do spatial and temporal variability affect the property. Yes, pipeline R-o-W highly variable

The effects of spatial and temporal variability. Tremendous variability

The techniques used to measure the property.
Direct: infiltrometer (field or lab), auger holes, runoff measurements, observation, tracer dyes
Indirect: bulk density, ecological indicators, i.e., crop growth, structure, porosity

Problems encountered in utilizing these techniques.
- Time and labor intensive
- Spatial and temporal variability

Problems encountered in interpreting the data.
- Spatial and temporal variability
- Method used and difficulty in comparing techniques and what part of soil is being measured

The suitability of the method and the appropriateness of the data in assessing the problem.
- Indirect methods: easier but how suitable, can't extrapolate what that means to water transmission
- Direct methods: don't mimic reality, i.e. rainfall intensity
- What are threshold values for management and are they needed for each technique.

Discussion of acceptance, prevention, remediation, and/or amelioration of the effects of development/management on the physical property.
- Amelioration: activity orientated, specialized equipment
- Acceptance: need for thresholds, different risk/ comfort levels, economics, cost benefit analysis
- Is it a problem? prevention vs rehabilitation

5. WATER RETENTION

The effects of the various activities on the soil physical property.
- Loading shifts curve and changes the shape

The areal extent of the effects.
- Regionally variable and with activity
- All cultivated areas on medium to fine texutral materials, all disturbed lands

The impacts/costs (direct/indirect).
Impacts of loading, changes in fluxes
- Decrease aeration
- Decrease infiltration, increase runoff
- Increase evaporation
- Decrease porosity, increase compaction
- Decrease compressibility

Soil types and horizons most affected.
- Clay soils (fine textured)
- All soils are affected (sandy soils less so)
- Replaced horizons (levels of soil replacement) and surface horizons (30 to 60 cm)
- Mineralogy differences; the impact endures differently in terms of time

Are there differences between the anticipated effects and those observed in the field.
- No knowledge but depth of the effect of loading may occur below plow level

The observed differences. NA

Do spatial and temporal variability affect the property. Yes, not always proportional to time

The effects of spatial and temporal variability.
- Very limited information, environmental parameters

The techniques used to measure the property.
- Visual observation, roots, layers
- Laboratory analysis of cores (undisturbed)
- Pressure plate, tensiometer, thermocouple, psychrometer

Problems encountered in utilizing these techniques.
- Getting undisturbed cores
- Pressure plate - difficulty at high potentials
- Shrink/swell (major source of error)
- Sample size: number of observations and physical size of soil sample

Problems encountered in interpreting the data.
- Scaling up - increasing larger sample/interpretation unit
- Sample to cut block/field interpretation
- Standard comparisions - normal versus impacted (critical values)

The suitability of the method and the appropriateness of the data in assessing the problem.
- Not enough data and research

Discussion of acceptance, prevention, remediation, and/or amelioration of the effects of development/management on the physical property. NA

6. PERMEABILITY/INFILTRATION

The effects of the various activities on the soil physical property.
- Tillage can either raise or lower hydraulic conductivity and infiltration
- Mining has major effects, both positive and negative

The areal extent of the effects. NA

The impacts/costs (direct/indirect). NA

Soil types and horizons most affected.
- Textural extremes, i.e., clayey and sandy

Are there differences between the anticipated effects and those observed in the field.
- Yes, knowledge is constantly being increased

The observed differences. NA

Do spatial and temporal variability affect the property. Variable spatially, less so temporally

The effects of spatial and temporal variability. NA

The techniques used to measure the property.
- Double ring infiltrometer
- Rainfall simulator
- Guelph permeameter
- Constant head
- Falling head permeameter
- Field observations
- New York test for septic tanks
- Pressure plate procedure on disturbed soils affects pore size distribution by grinding the sample

Problems encountered in utilizing these techniques.
- Too many ways to measure and therefore very subjective
- High degree of variability in data
- Procedure can't repeat analysis to get same numbers, precision
- Lack of standard procedures

Problems encountered in interpreting the data. NA

The suitability of the method and the appropriateness of the data in assessing the problem. NA

Discussion of acceptance, prevention, remediation, and/or amelioration of the effects of development/management on the physical property.
- Tile drainage and subsoiling are widely accepted
- Understanding water in soils and salinity
- Prevention techniques not applied

7. HYDRAULIC CONDUCTIVITY

The effects of the various activities on the soil physical property.
- Traffic decreases and corrective measures increase
- Concern for water quality if increased and movement of contaminants increases
- Agriculture needs to balance hydraulic conductivity to allow some movement but not too much
- Forestry wants water to move further to eliminate potential for erosion
- Pipelines assume negative effects except where trenching through a hard pan
- Mining mainly concerned with hydraulic conductivity of replaced layer

The areal extent of the effects. Province wide in all activits, grazing land may not have problems

The impacts/costs (direct/indirect).
- More aridity if hydraulic conductivity increases, wet zones if decreases, get extremes in moisture
- Loss of productivity, but require long term view of the problem especially in forestry

Soil types and horizons most affected
- Agriculture: A and interface with B, finer textured soils, probably Luvisols
- Mining: subsoil and spoil and interface, excavation types, B and C horizons
- Forestry: organic and A-horizon interface

Are there differences between the anticipated effects and those observed in the field.
- Yes where ripper makes a furrow but compacts soil between shanks
- Saw lateral flow in a ripped skid, flow because of hard pan at depth

Do spatial and temporal variability affect the property.
- Agriculture, yes, especially where textural discontinuities occur in profile
- temporal variability when soils freeze, snow trapping not useful if meltwater can't go into profile
- Lower hydraulic conductivity in wheel tracks vs crop row vs outside both

The effects of spatial and temporal variability. Difficult to measure/assess/predict the problem

The techniques used to measure the property
- Guelph permeameter: infiltration best field method, easier than probe, in situ measurement
- Constant head over undisturbed core
- Hillel tensiometer method, double ring and tensiometer

Problems encountered in utilizing these techniques
- Guelph permeameter is slow in soils with low hydraulic conductivity, bulky instrument, not functional in stony soils (maybe sandy soils)
- Constant head not a routine measure, research level, difficult to get undisturbed cores, must ensure larger pores maintained, horrendous variability

Problems encountered in interpreting the data. Guelph permeameter, variability due to soil type

The suitability of the method and the appropriateness of the data in assessing the problem. NA

Discussion of acceptance, prevention, remediation, and/or amelioration of the effects of development/management on the physical property.
- Ripping and cultivation to increase values, but in forests deep ripping costs prohibitive
- Gypsum to increase aggregation, increased infiltration leads to increased hydraulic conductivity
- Change rotations and tillage operations, manure applications
- Prevention cheapest - work when soil dry; construct in winter; horse logging; tire sizes/pressure
- Unclear as to how long it takes "problem" to reform, work to extrapolate from measure to field

8. MECHANICAL IMPEDANCE

The effects of the various activities on the soil physical property.
- An analog of root growth
- Related to soil strength
- Related to hydraulic conductivity because all the same pore space
- Generally a universal type of problem
- What is industry specific is the number/type of passes
- Eexcavation operations a different problem because of reconstruction
- Inherent characteristics of soil predisposed to problem
- What about agricultural equipment?
- Irony is that we want soils hard when running equipment but soft for plant growth
- Also need firm seedbed but soft for emergence and root growth

The areal extent of the effects. NA

The impacts/costs (direct/indirect). NA

Soil types and horizons most affected. NA

Are there differences between the anticipated effects and those observed in the field.
- Assume heavy traffic will increase soil strength but if very wet and ruts then soil pushed out of rut has low strength

The observed differences. NA

Do spatial and temporal variability affect the property.
- Yes especially with moisture content - can get up to three times change in resistance over moisture range common for plants

The effects of spatial and temporal variability NA

The techniques used to measure the property
- Penetrometer
- Modulus of rupture
- Vane shear

Problems encountered in utilizing these techniques.
- Penetrometer - need to redesign tips for each situation
- Must address moisture content and must measure moisture
- Difficult to use in dry soil

Problems encountered in interpreting the data.
- Penetrometer - don't know what it means
- Cones larger than root and how to relate the two
- Modulus - don't know what it means
- Vane shear - not related to roots

The suitability of the method and the appropriateness of the data in assessing the problem. NA

Discussion of acceptance, prevention, remediation, and/or amelioration of the effects of development/management on the physical property.
- Need more information on relation to effect on plant growth before deciding what to do

RESEARCH NEEDS

Are there future research needs? YES

Future research needs (i.e., What questions remain unanswered?)
High Priority:
- Definition and standardization of terms
- Alternative equipment to test effect on soil properties that result in compaction - porosity, structure (layering)
- Relate differences in properties to productivity and establish ranges of criteria for capability evaluation
- Standard sampling methods
- Standard methodology
- Quantitive values - baseline and threshold values
- Remedial actiion
- Literature review of work done elsewhere (transferability)
- Effects of frost action
- How do properties relate to productivity
- Role of LFM layer in forestry
- Overstripping/understripping
- Inventory/characteristics problem
- Duraton of effects/treatments
- Requirements of non-agricultural crops
- Threshold values
- Techniques
- Long term effects
- Effects of plant growth
- Water release curves - need data
- Field techniques to measure impact of loading

Medium:
- Field classification
- Management criteria
- Research techniques to measure water release curves
- Problem definition, threshold baseline research
- Longevity of remedial measures

Low:
- Development of quick field measurement techniques
- Economic values

Are the research needs activity specific?
- Group 1: No, loading is a generic issue
- Group 2: Yes, threshold values differ for different goals
- Group 3: Not usually
- Group 4: Yes, industries involved in reconstructing soil have different needs than those which only disturb the surface
- Group 5: No, need to be addressed in multidisciplinary terms

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18. APPENDICES

18.1 APPENDIX 1: COEFFICIENTS OF VARIATION

18.1 COEFFICIENTS OF VARIATION FOR SOIL PHYSICAL PROPERTIES

Parameter	Soil Type	Coefficient Of Variation (%)	Source
Bulk Density	Sandy loam	9	Cassell and Bauer 1975
	Silty clay	9	Cassell and Bauer 1975
	Silty loam	6	Cassell and Bauer 1975
	Loam silt loam	9 to 27	Terry et al. 1981
	Reclaimed coal mine spoil	3.7	Killpack 1982
	Soil series rock fragments (10 to 19%)	10 to 15	Irby 1967
	Flood plain rock fragments (30%)	10	Mollitor et al. 1980
	Soil map unit rock fragments (77 to 79%)	9 to 14	Wicherski 1980
Porosity	Clay loam	11	Nielson et al. 1973
	Sand	11	Russo and Bresler 1981
	Clay loam	7	Cameron 1978
	Loamy sand	10	Cassell 1983
Sand, silt, clay	18% clay	44	Mausbach et al. 1980
	18 to 35% clay	44	Mausbach et al. 1980
	35 to 60% clay	31	Mausbach et al. 1980
Infiltration Rate	Silt loam	50	Sharma et al. 1980
	Clay loam	94	Nielson et al. 1973
	Silty clay loam	71	Sisson and Wierenga 1981
	Loam	40	Viera et al. 1981
Saturated Hydraulic Conductivity	Clay loam	150	Nielson et al. 1973
	Sandy loam	178 to 190	Jury 1986
	Sand	69	Russo and Bresler 1981
	Loamy sand	69 to 105	Jury 1986
	Silty clay loam	48	Willardson and Hurst 1965
Unsaturated Hydraulic Conductivity	Sand	41 to 75	Jury 1986
	Loam	46	Jury 1986
	Silt loam	76	Jury 1986
	Clay loam	243 to 343	Jury 1986

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18.2. APPENDIX 2: GLOSSARY OF TERMS

We should have a great many fewer disputes in the world
if words were taken for what they are, the signs of our
ideas only, and not for things themselves.
John Locke

Adhesion
Molecular attraction that holds the surfaces of two dissimilar substances in contact, such as water and soil particles. (See: Cohesion).

Adsorption
The increased concentration of molecules or ions at a surface, including exchangeable cations and anions on soil particles.

Aeration, Soil
The process by which air in the soil is replaced by air from the atmosphere. In a well-aerated soil, soil air is similar in composition to the atmosphere above the soil. Poorly aerated soils usually contain a much higher percentage of carbon dioxide and a correspondingly lower percentage of oxygen than the atmosphere. The rate of aeration depends largely on the volume and continuity of pores from the surface and within the soil.

Aerobic
Growing or occurring only in the presence of molecular oxygen.

Air Encapsulation
The process whereby air remains in the transmission zone even under ponded infiltration.

Aggregate
A group of soil particles bound or cemented together in such a way that they behave mechanically as a unit. They may be bound together by organic substances, iron oxides, carbonates, clays, and/or silica. Aggregates may be spheres, blocks, plates, prisms, or columns. (See: Structure).

Aggregate Size Distribution
The proportion of aggregates in various size ranges.

Aggregate Stability
A measure of the vulnerability of aggregates to externally imposed disruptive processes. It is not measurable in absolute terms since it depends not only on the soil but also upon the nature of the forces and manner in which they are applied. Thus, it is a relative and partly subjective concept.

Aquifer
A sufficiently permeable formation storing, transmitting, and yielding ground water in useable quantities.

Aquitard
A leaky, semiconfining layer of low permeability that may contain and transmit water from one aquifer to another but cannot itself serve as an aquifer.

Anaerobic
Growing in the absence of molecular oxygen.

Anisotropy
Variation according to the direction of measurement.

Argillaceous
Containing appreciable clay.

Attenuation
Reduction in force.

Bearing Capacity
The average load per unit area that is required to rupture a supporting soil mass.

Brunisolic
An order of soils whose horizons are developed sufficiently to exclude the soils from the Regosolic order, but that lack the degrees or kinds of horizon development specified for soils of the other orders. These soils occur under a wide variety of climatic and vegetative conditions.

Bulk Density
Soil bulk density (D_b) is the ratio of the mass of dry soil solids to the total bulk volume of the soil. Bulk volume includes the volume of the solids and of the pore space. The mass is determined after drying to a constant weight at 105°C; the volume is that of the sample taken in the field and can be determined in a variety of ways. Measures of bulk density are expressed in SI units (kg m^{-3}) or units derived from them. Mg m^{-3} is preferred, with derived units of Mg m^{-3}, t m^{-3}, or g cm^{-3} numerically equal. D_b values generally range from 0.90 to 1.80 Mg m^{-3} (900 to 1800 kg m^{-3}). In commercial and engineering applications, D_b is often expressed in lb ft^{-3}.

Capability, Land
The suitability of land for use without permanent damage. It is an expression of the effect of physical land conditions, including climate, on the total suitability for use, without damage, for crops that require regular tillage, for grazing, for woodland, and for wildlife. Land capability involves consideration of the risks of land damage from erosion and other causes and the difficulties in land evaluation owing to physical land characteristics, including climate.

Capillary Fringe
A zone just above the water table that remains near saturation (zero gauge pressure). The extent and degree of definition of the capillary fringe depends upon the size distribution of pores. A zone, in which the pressure is less than atmospheric, overlying the zone of saturation and containing capillary interstices, some or all of which are filled with water that is continuous with the water in the zone of saturation, but is held above the zone by capillarity acting against gravity.

Capillary Conductivity
1. Physical property related to the readiness with which unsaturated soil transmits water.
2. Ratio of water velocity to driving force in unsaturated soil.

Chernozem
An order of soils formed in cool, subarid to subhumid grasslands, in which the principal diagnostic feature is a mineral surface horizon darkened by accumulating organic matter (Chernozemic A horizon).

Chiselling
A method of tillage in which hard, compact layers, usually in the subsoil, are shattered or loosened to depths below normal plough depth. (See: Subsoiling, Ripping).

Clastic
Consisting of fragments of rocks or organic structures moved individually from places of origin.

Clod
A compact, coherent mass of soil, ranging in size from 5 mm to 10 mm to as much as 200 mm to 250 mm; produced artificially by the activity of plowing and digging when the soils, especially clays, are either too wet or too dry for normal tillage operations. A term applied by miners to loosely consolidated shale commonly found in close conjunction with a coal bed.

Coefficient of Variation
The standard deviation divided by the mean, generally expressed as a percentage. It is a measure of relative data dispersion.

Cohesion
The attraction of a substance for itself; the mutual attraction among molecules or particles comprising a substance that allows it to cling together as a continuous mass. (See: Adhesion).
1. The resistance of a material, rock, or sediment against shear along a surface under no pressure.
2. The capacity to stick together. In effect the cohesion of soil or rock is that part of its shear strength which does not depend upon interparticle friction.

Cohesionless Soil
In engineering, soils with little clay or silt.

Cohesive Soil
In engineering, clay and silt rich soils.

Colluvium
A general term applied to deposits on a slope, or the foot of a slope or cliff, that were moved there chiefly by gravity.

Compactibility
The maximum density to which a soil can be packed by a given amount of energy. The standard method for determining soil compactibility is the Proctor test.

Compaction
The moving of soil particles closer together by external forces. In the compaction process, individual soil particles are packed closer together and soil aggregates are crushed, greatly reducing porosity. The major causes of soil compaction are: (1) natural consolidation during soil forming processes (e.g., the weight of glaciers during the ice ages); (2) trampling by animals and humans; (3) natural shrinkage of soil upon drying; or (4) use of heavy equipment.

Compressibility
The property of a soil pertaining to its susceptibility to decrease in bulk volume when subjected to a load. The change of specific volume and density under hydrostatic pressure; reciprocal of bulk modulus (volume elasticity; incompressibility modulus). Under increasing force per unit area a body will decrease in size but increase in density. The ease with which soil decreases in volume when subjected to a mechanical load. It is the slope of the straight line portion of void ratio, or bulk density vs. logarithm of stress.

Compressibility Index
The ratio of the pressure to void ratio on the linear portion of the curve relating these two variables.

Compression
A system of forces or stresses that tends to compact or decrease the volume of a substance, or the change in volume produced by such a system of forces. Compression of a saturated soil is consolidation, and compression of an unsaturated soil is compaction.

Cone Index
The force per unit basal area required to push a cone penetrometer through a specified increment of soil. (See: Mechanical Impedance and Penetration Resistance).

Confining Layer
A layer of material having a permeability lower than that of the associated aquifer. If the permeability is essentially zero, the confining layer is impermeable and may be an aquifuge or an aquiclude. If the permeability is small relative to that of the adjoining aquifer, the layer is said to be leaky and is called a aquitard.

Conservation Tillage
Any tillage sequence that reduces loss of soil or water relative to conventional tillage; often a form of non-inversion tillage that retains protective amounts of residue mulch on the surface.

Consistence
The attributes of soil material as expressed in its degree of cohesion and adhesion or in its resistance to deformation or rupture. Terms used in soil survey for describing consistence at various soil-water contents are:

Wet soil: non-sticky; slightly sticky; sticky; very sticky; non-plastic; slightly plastic; plastic and very plastic.
Moist soil: loose; very friable; friable; firm; very firm; and extremely firm.
Dry soil: loose; soft; slightly hard; hard; very hard; and extremely hard.
Cementation: weakly cemented; strongly cemented; and indurated.

Consolidation
The gradual reduction in volume of a soil mass resulting from an increase in compressive stress and/or expulsion of water. The adjustment of a saturated soil in response to increasing load. Involves the squeezing of water from pores and a decrease in the void ratio.

Conventional Tillage
A tillage system of combined primary and secondary tillage operations where the surface soil and crop residue are turned under, usually in the fall, and re-tilled the next spring, thus creating a smooth and residue-free surface.

Creep, Soil
Slow mass movement of soil down relatively steep slopes primarily under the influence of gravity, but facilitated by saturation with water and alternate freezing and thawing. (See: Solifluction)

Crust
A surface layer of soil, from a few millimeters to 2.5 cm (1") thick, that when dry is much more compact, hard and brittle than the material just under it. It is caused by raindrop impact, clay dispersion and clay translocation, which blocks pores.

Darcy's Equation
A formula stating that the flow rate of water through a porous medium is proportional to the hydraulic gradient. The factor of proportionality is the hydraulic conductivity.

Degradation
The changing of a soil to a more highly leached and weathered state, usually accompanied by morphological changes such as the development of an eluviated, light coloured A horizon or a decline in soil quality. Processes include wind and water erosion, salinity, organic matter depletion, acidification, and compaction. (See: Erosion).

Desorption
The release of a substance from the surface on which it is adsorbed.

Diagnostic Horizon
A soil horizon possessing a combination of specific soil characteristics used for the taxonomic classification of soils. Those which occur at the soil surface are called epipedons; those below the surface, diagnostic horizons.

Disperse
1. To cause aggregates to separate into individual soil particles.
2. A disperse soil is one in which at least one of the phases (solid, liquid, gas) is subdivided into numerous small particles, which together exhibit a very large interfacial area per unit volume.

Drainage
The frequency and duration of the periods when the soil is free of saturation or partial saturation. A measurable characteristic including rapidity and extent, but generally assessed from profile morphology, e.g., gleying and colour and land form. Commonly described in terms of subjective drainage classes extending from very poorly drained to excessively drained.

Effective Rooting Depth
The depth to which the majority of plant roots occur.

Eluviation
The removal of soil material in suspension from a layer or layers of a soil. (See: Illuviation, Leaching). The movement of soil material from one place to another in solution or in suspension by natural soil-forming processes. Soil horizons that have lost material through eluviation are referred to as eluvial.

Epipedon
A diagnostic horizon occurring at the surface of the soil.

Erodibility
A measure of a soil's susceptibility to erosion.

Erosion
1. The wearing away of the land surface by water, wind, ice or other geological agents, including such processes as gravitational creep.
2. Detachment and movement of soil or rock fragments by water, wind, ice or gravity. (See: Degradation).

Fabric, Soil
The physical constitution of a soil material expressed by the spatial arrangement of the solid particles and associated voids.

Firm
A term describing the consistence of a moist soil that offers distinctly noticeable resistance to crushing, but can be crushed with moderate pressure between the thumb and forefinger. (See: Consistence).

Fracture
The manner of breaking, and appearance of a mineral when broken, which is distinctive for certain minerals.

Fragipan
A natural subsurface soil horizon with high bulk density and/or high mechanical strength relative to the soil horizons above, seemingly cemented when dry, but when moist showing a moderate to weak brittleness.

Friable
A consistence term pertaining to the ease of crumbling of soils: a friable soil crushes easily under gentle pressure. (See: Consistence).

Fritted
The subsoil structural architecture characterized by trundled aggregates with agglomerative skins distinctive to constructed subsoils. The aggregates are loosely compressed together, leaving appreciable void spaces of extensive continuity.

Gleysolic
An order of soils developed under wet conditions and permanent or periodic chemical reduction. These soils have low chromas, or prominent mottling, or both, in some horizons.

Granulation
Granulation = aggregation (USA)

Gravity Flow
A type of glacier movement in which the flow of ice is caused by the downward slope component of gravity in an ice mass resting on a sloping floor.

Heat Capacity
Heat capacity is an indication of soil's ability to store thermal energy. Volumetric heat capacity is the amount of heat required to raise a unit volume of soil a unit temperature and is the product of specific heat capacity and density expressed as J m^{-3} $^{o}K^{-1}$.

Horizon, Soil
A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics, such as colour, structure, texture, consistency, kinds and number of organisms present, degree of acidity or alkalinity.

Hydraulic Conductivity
The ability of the soil to transmit water in liquid form through pores; includes properties of the fluid. The factor of proportionality in Darcy's equation relating flow velocity to hydraulic gradient having units of length per unit of time. A property of the porous medium and the water content of the medium. Hydraulic conductivity is sometimes referred to as the coefficient of permeability.

Hydraulic Head
The energy per unit weight of water made up of the sum of the pressure potential (head), velocity potential (head), and elevation potential (head). The velocity head is often negligible and taken as zero for subsurface flow. Hydraulic head is often referred to as water potential.

Hysteretic Function
The difference between water content and water pressure relations in unsaturated porous media due to antecedent conditions, i.e., wetting or drying.

Humus
The more or less stable fraction of the decomposed soil organic material, generally amorphous, colloidal, and dark coloured.

Illuviation
The process of deposition of collodial soil material, removed from one horizon and moved to another in the soil, usually from an upper to a lower horizon in the soil profile. (See: Eluviation, Leaching). The deposition in an underlying layer of soil of mineral or organic matter. Soil horizons that have gained material through illuviation are said to be illuvial.

Impervious Soil
A soil through which water, air, or roots cannot penetrate. No soil is impervious to water and air all the time.

Induced Crust
Crust formation due to the action of beating raindrops on unprotected soil, or due to the trampling action of livestock, humans, or vehicle traffic.

Indurated
Soil material cemented into a hard mass that will not soften on wetting. (See: pans)

Infiltration
The downward entry of water from the surface into the soil. (See: Percolation). It connotes flow into the soil in contradistinction to percolation, which connotes flow through a porous substance.

Infiltration Rate
A soil characteristic determining or describing the rate at which water can enter the soil under specified conditions, including the presence of excess water. It has the dimensions of velocity.

Infiltration Capacity
The maximum rate at which the soil, when in a given condition, can absorb water.

Intrinsic Permeability
A quantitative measure of water-transmitting ability of a porous medium that is related to the size and interconnectedness of the void openings.

Leaching
The downward removal of materials in solution from the root zone by water percolating through the soil.

Lift
Removal of topsoil and subsoil prior to overburden removal or pipeline installation. Lifts can be made in a series of stages, e.g., one-lift or two-lift operations.

Luvisol
An order of soils in which the predominating or diagnostic profile features are the result of eluviation and illuviation, principally of silicate clay. These soils developed under forest or forest-grassland transition in a moderate to cool climate.

Malformed Roots
Root formation that deviates from normal structural variation due to disease, nutrient deficiency, or physical restrictions.

Matric Potential
The amount of work an infinitesimal quantity of water in the soil can do as it moves from the soil to a pool of free water of the same composition and at the same location. This work is less than zero, or negative work, and thus is reported in negative values. (Matric suction is the negative of matric potential).

Massive State
A nonstructural state in soils that contain cohesive particles occurring in a continuous mass having no well-defined cleavage pattern. When crushed, massive soil breaks into irregular fragments of unpredictable size and shape.

Measurements/Devices
Gamma Probe: An instrument for measuring soil water or soil density by relating the fraction of emitted radiation received by the detector to the soil wetness.
Lysimeter: A device to measure the quantity or the rate of water movement through or from a block of soil, usually undisturbed or in situ, or to collect such percolated water for quality analysis.
Neutron Probe: A radioactive instrument for measuring soil water content indirectly through measurement of the slowing or thermalization of neutrons by hydrogen nuclei.
Permeameter: A device for confining a sample of soil or porous medium, and subjecting it to fluid flow, in order to measure the hydraulic conductivity or intrinsic permeability of the soil or porous medium for the fluid.
Penetrometer: A rod with specified size cone on its tip for measuring the resistance of a soil to penetration, giving an integrated index of soil compaction, moisture content, texture and type of clay mineral. The amount of penetration per unit force applied to a given soil will vary with the shape and kind of instrument used.
Piezometer: A tube placed in the soil with its end open for measuring the hydraulic head at different points in the soil.
Psychrometer: An instrument for determining atmospheric humidity by the reading of two thermometers, the bulb of one being kept moist and ventilated.
Tensiometer: A device for measuring the negative pressure, or the tension of water in soil in situ; a porous, permeable ceramic cup connected through a tube to a manometer or vacuum gauge.

Mechanical Impedance
Resistance of a soil to penetration. (See: Cone Index).

Morphology
The physical constitution, particularly the structural properties of a soil profile, as exhibited by the kinds, thickness, and arrangement of the horizons in the profile, and by the texture, structure, consistence, and porosity of each horizon.

Mulch
Any loose covering on the surface of the soil, whether natural, e.g., litter, or deliberately applied like organic residues (grass, straw, sewage sludge, etc.) or artificial materials, e.g., cellophane, glass wool, etc. Used mainly to conserve moisture, check weed growth, prevent erosion and protect from winter climate.

Organic Matter
The organic fraction of the soil. Organic matter includes plant and animal residues at various stages of decomposition, cells and tissues of various soil organisms, and substances synthesized by the soil population. It is usually determined on soils that have been sieved through a 2.0 mm sieve.

Overburden
Any material, consolidated or unconsolidated, that overlies a deposit of useful materials, ores, or coal, especially those deposits that are mined from the surface by open cuts. It is also often referred to as the mantle.

Pans
Horizons or layers in soils that are strongly compacted, indurated or very high in clay content:

Caliche: A near-surface layer, more or less cemented by secondary carbonates of calcium or magnesium precipitated from the soil solution. It may be a soft, thin soil horizon, a hard thick bed beneath the solum, or a surface layer exposed by erosion but is not a geological deposit.

Claypan: A dense compact layer in the subsoil having a much higher clay content than the overlying material from which it is separated by a sharply defined boundary; usually hard when dry, and plastic and sticky when wet. It usually impedes the movement of water and air and the growth of plant roots. High clay content does not necessarily result in the formation of a claypan, as much depends on soil structure as well as texture.

Fragipan: A natural subsurface layer having a higher bulk density than the solum above; seemingly cemented when dry but showing moderate to weak brittleness when moist. The layer is low in organic matter, mottled, and slowly or very slowly permeable to water; it usually has some polygon-shaped bleached cracks. It is found in profiles of either cultivated or virgin soils but not in calcareous material.

Induced Pan: Also called pressure pan or traffic pan. A subsurface horizon or soil layer having a higher bulk density and a lower total porosity than the soil directly above or below it, as a result of pressure that has been applied by normal tillage operations or other artificial means. It is also referred to as plough pan, plough sole, or traffic pan.

Particle Density
Mass per unit volume of the soil solid particles. Also referred to as bulk specific gravity.

Particle Size
The effective diameter of a particle measured by sedimentation, sieving or micrometric methods.

Sand: a soil particle between 0.05 and 2.00 mm in diameter.

Silt: a soil separate consisting of particles between 0.05 and 0.002 mm in diameter.

Clay: a size fraction less than 0.002 mm in diameter.

Particle Size Analysis
The determination of the various amounts of separates in a soil sample, usually by sedimentation, sieving, micrometer, or combinations of these methods. Particle size analysis has been called grain size analysis or mechanical analysis. A textural triangle is then used to determine soil texture.

Particle Size Distribution
The amount of the various soil separates in a soil sample, usually expressed as weight percentages.

Ped
A unit of soil structure, such as a prism, block, or granule, which is formed by natural processes, in contrast with a clod which is formed artificially.

Penetrability
The ease with which a probe can be pushed into the soil. It may be expressed in units of distance, speed, force, or work, depending on the type of penetrometer used.

Penetration Resistance
The resistance of a soil to penetration. Varies with shape and kind of instrument used. (See: Mechanical Impedance)

Perched Aquifer
A localized unconfined aquifer formed above a relatively impermeable layer. May be seasonal due to recharge patterns and leakage through and flow around the restricting layer.

Perched Water Table
A water table separated from an underlying body of ground water by unsaturated rock or impermeable layer of compacted soil.

Percolation
The downward movement of water through soil.

Permeability
The ease with which gases and liquids penetrate or pass through a bulk mass or layer of soil. Differs from hydraulic conductivity in that fluid properties (density and viscosity) are taken into account. Sometimes referred to as intrinsic permeability.

Phreatic Surface
Same as water table.

Plasticity
The ability to change shape continuously under the influence of an applied stress, and to retain the impressed shape on removal of the stress.

Atterberg limits: Engineering classification of soil consistence at different water contents.
Shrinkage limit: Maximum water content at which a reduction in water will not cause a decrease in volume of soil mass; defines arbitrary limit between solid and semi-solid states.
Plastic limit: (1) The water content corresponding to an arbitrary limit between the plastic and semisolid states of consistence of a soil. (2) The water content at which a soil will just begin to crumble when rolled into a thread approximately 3 mm in diameter.
Liquid limit: (1) The water content corresponding to an arbitrary limit between the liquid and plastic states of consistence of a soil. (2) The water content at which a pat of soil, cut by a standard sized groove, will flow together for a distance of 12 mm under the impact of 25 blows in a standard liquid limit apparatus.
Plasticity index: The numerical difference between the liquid limit and the plastic limit, indicates a range of values over which the soil is plastic.
Shrinkage index: The numerical difference between the plastic and shrinkage limits.

Podzolic
An order of soils having podzolic B horizons in which amorphous combinations of organic matter, Al, and Fe are accumulated. The sola are acid and B horizons have a high pH dependent charge.

Ponding
Formation of a small body of still water at the soil surface.

Pore Size Distribution
A measure of the various sizes of pores in a soil, often expressed as a percentage of bulk volume.

Pore Space
The space in soil not occupied by soil particles; filled with either air or water.

Porosity
The total volume of pore space divided by the total soil volume, usually expressed as a percentage.

Primary Tillage
Tillage operation that cuts and breaks soil into relatively large clods. It penetrates the soil more deeply than succeeding tillage operations and may be used to incorporate soil amendments more deeply. The soil surface is usually left in a rough condition with many large open spaces between soil lumps. Primary tillage is done by moldboard or chisel plows, subsoilers or rippers, heavy disc plows or rotary tillers which often leave the soil in poor seedbed condition.

Productivity, Soil
The capacity of a soil, in its normal environment, for producing a specified plant or sequence of plants under a specified system of management. The "specified" limitations are needed because no soil can produce all crops with equal success and a single system of management cannot produce the same effect on all soils. Productivity emphasizes the capacity of the soil to produce crops and is expressed in terms of yield.

Puddled Soil
A dense soil, dominated by massive or single grain structure, almost impervious to air and water, resulting from handling a soil when it is in a wet, plastic condition, so that when it dries it becomes hard and cloddy.

Reclamation
The process of reconverting disturbed lands to their former use, or other productive uses.

Regolith
Mantle rock; saprolith. The layer or mantle of loose, incoherent rock material, of whatever origin, that nearly everywhere forms the surface of the land in the absence of true soil and rests on bedrock. It comprises rock waste of all sorts, volcanic ash, glacial drift, etc.

Residual Parent Material
Unconsolidated and partly weathered mineral materials accumulated by disintegration of consolidated rock in place.

Residual Soil
Soil formed from, or resting on, consolidated rock of the same kind as that from which it was formed and in the same location. Soil formed in place by the disintegration and decomposition of rocks and the consequent weathering of the mineral materials.

Revegetation
The restablishment and development of vegetative cover naturally or artificially.

Rheology
Science dealing with the flow and deformation of matter.

Rhizosphere
The micro-environment of the roots.

Root Zone
A loose term for that part of the soil invaded by plant roots.

Ripping
A tillage operation used to break up plough pans or other impermeable layers. Often a chisel is used to break up the soil to a depth of 0.5 m and at spacings of 1.0 m. Ripping will also improve infiltration and percolation of water into the soil and thus improve vegetative growth. (See also: Chiselling, Subsoiling).

Saturated Flow
Flow of water under conditions where all the voids between soil particles are filled with a liquid. Flow in saturated soils takes place in the direction of decreasing potential, the rate of flow is proportional to the potential gradient, and is largely influenced by pore geometry.

Saturation Percentage
The amount of water, by weight, necessary to form a flowable mud from dry soil materials. Typically this amount is greater than that held by in situ soil materials that contain the maximum amount of water. Saturation percentage can be used as an indicator of soil water holding properties and swelling capacity, and of the soil to water ratio at which the saturation extract is made.

Secondary Tillage
Additional tilling which must be done after primary tillage to reduce the large soil lumps, eliminate the large air spaces, level the soil surface, and make the soil firmer in order to produce a suitable seedbed. The implements used in this operation can be one or more of the following: disc harrow, spike-tooth harrow, spring-tooth harrow, tine harrow, roller harrow, or drag. This second tillage operation should be done as soon as possible after the first, in order to reduce soil water loss.

Seepage
Slow percolation of fluid.

Self-mulching Soil
A soil in which the surface layer becomes so well aggregated that it does not crust and seal under the impact of rain, but serves as a surface mulch when it dries.

Shear Strength
The maximum internal resistance of a soil to the movement of its particles; that is, resistance to slipping or sliding of soil over soil. The forces that resist shear are internal or intergranular friction and cohesion.

Single-Grained State
A non-structural state normally observed in soils containing a preponderance of large particles such as sand. Because of a lack of cohesion, the sand grains tend not to assemble in aggregate form.

Slake
The crumbling and disintegration of earth materials exposed to air or water. More specifically, the breaking up of dried clay when saturated with water, due either to compression of entrapped air by inwardly migrating capillary water, or the progressive swelling and sloughing off of outer layers.

Sodic
A soil containing sufficient sodium to interfere with the growth of most crop plants.

Soil
The unconsolidated mineral material on the immediate surface of the earth that serves as a natural medium for the growth of land plants.

Solifluction
The slow downhill flow or creep of soil and other loose materials that become saturated.

Solonetz
An order of soils developed mainly under grass or grass-forest vegetation in semiarid to subhumid climates. The soils have a stained brownish Solonetzic B horizon and a saline C horizon.

Solum
The upper horizons of a soil in which the parent material has been modified and in which most plant roots are contained. It usually consists of the A and B horizons.

Sorptivity
Sorptivity is the slope of the straight line portion of the curve relating accumulated infiltration to the square root of time.

Spoil
The overburden or non-ore material removed in gaining access to ore or mineral material in surface mining. The pile of soil produced by mining operations and stacked at the surface of a mine in conical heaps or layered deposits is called the spoil heap. This term is also used in pipelining.

Stability
The resistance of a structure, spoil heap, or a clay bank to sliding, overturning, or collapsing. A structure is only as stable as its foundations and those in turn upon the soil or rock on which they are constructed. Soil stability of mountain slopes, spoil heaps, and embankments, depends on the shearing strength of the material which in turn is a function of internal strength and cohesion.

Stratification
A structure produced by deposition of sediments in beds or layers (strata), laminae, lenses, wedges, and other essentially tabular units.

Strength, Soil
Resistance of the soil to deformation.

Strip Mining
In coal mining, the removal of the earth, rock, and other material from above a seam of coal, generally by power shovels. Generally practised only where the coal seam lies close to the surface. Strip mining types include contour stripping, mountain top removal, and area stripping.

Structure, Soil
The combination or arrangement of primary soil particles into secondary particles, units, or peds. These peds may be, but usually are not, arranged in the profile in such a manner as to give a distinctive characteristic pattern. The peds are characterized and classified on the basis of size, shape, and degree of distinctness into classes, types, and grades. Structural units include:

Blocky: Cubelike blocks of soil up to 10 cm in size, sometimes angular with well-defined planar faces, sometimes with curved surfaces and corners (subangular blocky).
Columnar: Vertically oriented pillars, often six-sided, up to 15 cm in diameter with rounded tops. Such structures are common in B horizons of clayey soils in semiarid regions.
Granular: Rounded aggregates, generally not much larger than 2 cm in diameter, often found in a loose condition in the A horizon. Where particularly porous, such units are called crumbs.
Platy: Horizontally layered, thin and flat aggregates resembling wafers. Such structures occur, for example, in recently deposited clay soils.
Prismatic: Vertically oriented pillars, often six-sided, up to 15 cm in diameter, with flat tops to the pillars; common in the B horizon of clayey soils in semiarid regions.

Structureless
Lacking in formation of a hierarchical development of particle and void arrangement.

Stubble Mulch
The stubble of crops or crop residues left essentially in place on the land, providing a protective surface cover before and during the preparation of the seedbed and at least partially during the growing of a succeeding crop.

Subsoil
The B horizons of soils with distinct profiles. In soils with weak profile development, the subsoil is below the ploughed soil (or its equivalent of surface soil), in which roots normally grow.

Subsoiling
The tillage of subsurface soil, without inversion, for the purpose of breaking up dense layers that restrict water movement and root penetration. This is usually done with a chisel. (See: Chiselling, Ripping).

Succession
The natural sequence or evolution of plant communities, each stage dependent on the preceding one, and on environmental and management factors.

Surface Mining
Surface excavation for the purpose of removal of minerals. Techniques for surface mining include several operations: open pit, dredging, hydraulic mining, strip mining, and auger mining.

Texture, Soil
The relative portions of the soil separates, sand, silt and clay.

Thermal Conductivity
Thermal conductivity is a measure of the soil's ability to transport heat and is measured as the quantity of heat that flows through a unit area in a unit time under a unit temperature gradient and is expressed as $W\ m^{-1}\ {}^{o}K^{-1}$.

Thermal Diffusivity
The ratio of thermal conductivity and heat capacity is thermal diffusivity D_t, expressed as $m^2\ s^{-1}$. A high value of D_t implies a capability for rapid and considerable changes in temperature.

Thixotropy
The reforming of bonds over time.

Tillage
Any mechanical manipulation of soil that changes its structure, strength, or position to improve conditions for crop production. Four primary aims of tillage are: weed control, organic matter incorporation, enhancement of soil structure to improve soil-water and soil-air relations, and to provide a seedbed.

Tilth
The physical state of the soil as it relates to plant growth. A variable characteristic, it is subject to natural change as well as to modification by artificial means such as plowing and cultivation. In concept, good tilth implies a soil state that provides for an adequate supply of both air and water.

Topsoil
The uppermost or cultivated layer of soil. A specified depth of soil from the natural surface. The A horizon, often of relatively dark colour.

Traction
The driving force developed by a wheel or other means as it acts upon a surface.

Trafficability
The ability of the ground surface to support vehicular traffic.

Unsaturated Flow
Fluid transmission in soil under unsaturated conditions due to subatmospheric pressure or suction which is equivalent to a negative pressure potential. The negative pressure potential or matric suction is due to the physical affinity of water and soil-particle surfaces and capillary pores. Vapor transfer is also a mechanism of water movement in unsaturated flow, particularly at the surface.

Void Ratio
The ratio of the volume of pores to the volume of the solids.

Water Content
The amount of water held in a soil, expressed on a weight or volume basis. Generally, gravimetric water contents are expressed relative to the oven-dry weight of soil.

Available Water: Generally that portion of soil water that can be readily absorbed by plant roots; as a specific soil water value, the mathematical difference in the amounts of water a soil holds at field capacity and permanent wilting point.

Field Capacity: The amount of water remaining in a soil after it has been saturated and drained freely for one or two days. Usually expressed as a percentage in terms of weight or volume. Often estimated at -1/3 bar water potential.

Gravitational Water: Water which moves into, through, or out of the soil under the influence of gravity. The water between field capacity and saturation.

Hygroscopic Water: Water so tightly held by the attraction of soil particles that it cannot be removed except as a vapor, by raising the temperature above the boiling point of water. It is unavailable to plants and lies between permanent wilting point and oven dry.

Permanent Wilting Point: The water content of a soil at which plants wilt and fail to recover their turgidity when placed in a dark, humid atmosphere. The percentage of water at wilting point approximates the minimum water in soils under plants in the field at depths below the effects of surface evaporation. It is approximated by soil water content at -15 bar potential.

Water Logging
A process or condition in which the water table reaches or rises above the ground surface or its capillary fringe is near the surface. Any condition of the soil where, due to its water content, aeration does not suffice to maintain the health of a given plant species.

Water Potential, Soil
Sum of matric, gravitational and osmotic potentials. Equal to hydraulic head, if osmotic potential equals zero or is ignored. (See Matric Potential).

Water Table
The surface defining the location where the pressure potential is atmospheric for an unconfined aquifer. Equivalent to the phreatic surface. The water table is the top of an unconfined aquifer.

Water Retention
The relationship between matric potential and soil water content is represented graphically as the soil moisture characteristic curve or the soil water retention curve.

Wetting Front
The advancing boundary between dry soil and wetted soil during infiltration.

Wheel Compaction
The compression-induced decrease in volume of an unsaturated soil by wheeled equipment. Wheel track compaction effects are proportional to axle load, contact area, and loading frequency.

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RECLAMATION RESEARCH REPORTS

1. **RRTAC 79-2: Proceedings: Workshop on Native Shrubs in Reclamation. P.F. Ziemkiewicz, C.A. Dermott and H.P. Sims (Editors). 104 pp. No longer available.**

The Workshop was organized as the first step in developing a Native Shrub reclamation research program. The Workshop provided a forum for the exchange of information and experiences on three topics: propagation; outplanting; and, species selection. Seven papers and the results of three discussion groups are presented.

2. **RRTAC 80-1: Test Plot Establishment: Native Grasses for Reclamation. R.S. Sadasivaiah and J. Weijer. 19 pp. No longer available.**

The report details the species used at three test plots in Alberta's Eastern Slopes (one at Caw Creek Ridge and two at Cadomin). Site preparation, experimental design, and planting method are also described.

3. **RRTAC 80-3: The Role of Organic Compounds in Salinization of Plains Coal Mining Sites. N.S.C. Cameron et al. 46 pp. $10.00**

This is a literature review of the chemistry of sodic mine spoil and the changes expected to occur in groundwater.

4. **RRTAC 80-4: Proceedings: Workshop on Reconstruction of Forest Soils in Reclamation. P.F. Ziemkiewicz, S.K. Takyi and H.F. Regier (Editors). 160 pp. $10.00**

Experts in the field of forestry and forest soils report on research relevant to forest soil reconstruction and discuss the most effective means of restoring forestry capability of mined lands.

5. **RRTAC 80-5: Manual of Plant Species Suitability for Reclamation in Alberta. L.E. Watson, R.W. Parker and D.F. Polster. 2 vols, 541 pp. No longer available; replaced by RRTAC 89-4.**

Forty-three grass, fourteen forb, and thirty-four shrub and tree species are assessed in terms of their suitability for use in reclamation. Range maps, growth habit, propagation, tolerance, and availability information are provided.

6. **RRTAC 81-2: 1980 Survey of Reclamation Activities in Alberta. D.G. Walker and R.L. Rothwell. 76 pp. $10.00**

This survey is an update of a report prepared in 1976 on reclamation activities in Alberta, and includes research and operational reclamation, locations, personnel, etc.

7. **RRTAC 81-3: Proceedings: Workshop on Coal Ash and Reclamation. P.F. Ziemkiewicz, R. Stein, R. Leitch and G. Lutwick (Editors). 253 pp. $10.00**

Presents nine technical papers on the chemical, physical, and engineering properties of Alberta fly and bottom ashes, revegetation of ash disposal sites, and use of ash as a soil amendment. Workshop discussions and summaries are also included.

8. **RRTAC 82-1: Land Surface Reclamation: An International Bibliography. H.P. Sims and C.B. Powter. 2 vols, 292 pp. $10.00**

Literature to 1980 pertinent to reclamation in Alberta is listed in Vol. 1 and is also on the University of Alberta computing system (in a SPIRES database called RECLAIM). Vol. 2 comprises the keyword index and computer access manual.

9. **RRTAC 82-2: A Bibliography of Baseline Studies in Alberta: Soils, Geology, Hydrology and Groundwater. C.B. Powter and H.P. Sims. 97 pp. $5.00**

This bibliography provides baseline information for persons involved in reclamation research or in the preparation of environmental impact assessments. Materials, up to date as of December 1981, are available in the Alberta Environment Library.

10. **RRTAC 83-1: Soil Reconstruction Design for Reclamation of Oil Sand Tailings. Monenco Consultants Ltd. 185 pp. No longer available**

Volumes of peat and clay required to amend oil sand tailings were estimated based on existing literature. Separate soil prescriptions were made for spruce, jack pine, and herbaceous cover types. The estimates form the basis of field trials.

11. **RRTAC 83-3: Evaluation of Pipeline Reclamation Practices on Agricultural Lands in Alberta. Hardy Associates (1978) Ltd. 205 pp. No longer available.**

Available information on pipeline reclamation practices was reviewed. A field survey was then conducted to determine the effects of pipe size, age, soil type, construction method, etc. on resulting crop production.

12. **RRTAC 83-4: Proceedings: Effects of Coal Mining on Eastern Slopes Hydrology. P.F. Ziemkiewicz (Editor). 123 pp. $10.00**

Technical papers are presented dealing with the impacts of mining on mountain watersheds, their flow characteristics, and resulting water quality. Mitigative measures and priorities were also discussed.

13. **RRTAC 83-5: Woody Plant Establishment and Management for Oil Sands Mine Reclamation. Techman Engineering Ltd. 124 pp. No longer available.**

This is a review and analysis of information on planting stock quality, rearing techniques, site preparation, planting, and procedures necessary to ensure survival of trees and shrubs in oil sand reclamation.

14. **RRTAC 84-1: Land Surface Reclamation: A Review of the International Literature. H.P. Sims, C.B. Powter and J.A. Campbell. 2 vols, 1549 pp. $20.00**

Nearly all topics of interest to reclamationists including mining methods, soil amendments, revegetation, propagation and toxic materials are reviewed in light of the international literature.

15. **RRTAC 84-2: Propagation Study: Use of Trees and Shrubs for Oil Sand Reclamation. Techman Engineering Ltd. 58 pp. $10.00**

This report evaluates and summarizes all available published and unpublished information on large-scale propagation methods for shrubs and trees to be used in oil sand reclamation.

16. **RRTAC 84-3: Reclamation Research Annual Report - 1983. P.F. Ziemkiewicz. 42 pp. $5.00**

This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

17. **RRTAC 84-4: Soil Microbiology in Land Reclamation. D. Parkinson, R.M. Danielson, C. Griffiths, S. Visser and J.C. Zak. 2 vols, 676 pp. $10.00**

This is a collection of five reports dealing with re-establishment of fungal decomposers and mycorrhizal symbionts in various amended spoil types.

18. **RRTAC 85-1: Proceedings: Revegetation Methods for Alberta's Mountains and Foothills. P.F. Ziemkiewicz (Editor). 416 pp. $10.00**

Results of long-term experiments and field experience on species selection, fertilization, reforestation, topsoiling, shrub propagation and establishment are presented.

19. **RRTAC 85-2: Reclamation Research Annual Report - 1984. P.F. Ziemkiewicz. 29 pp. $5.00**

This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

20. **RRTAC 86-1: A Critical Analysis of Settling Pond Design and Alternative Technologies. A. Somani. 372 pp. $10.00**

The report examines the critical issue of settling pond design, and sizing and alternative technologies. The study was co-funded with The Coal Association of Canada.

21. **RRTAC 86-2: Characterization and Variability of Soil Reconstructed after Surface Mining in Central Alberta. T.M. Macyk. 146 pp. No longer available.**

Reconstructed soils representing different materials handling and replacement techniques were characterized, and variability in chemical and physical properties was assessed. The data obtained indicate that reconstructed soil properties are determined largely by parent material characteristics and further tempered by materials handling procedures. Mining tends to create a relatively homogeneous soil landscape in contrast to the mixture of diverse soils found before mining.

22. **RRTAC 86-3: Generalized Procedures for Assessing Post-Mining Groundwater Supply Potential in the Plains of Alberta - Plains Hydrology and Reclamation Project. M.R. Trudell and S.R. Moran. 30 pp. $5.00**

In the Plains region of Alberta, the surface mining of coal generally occurs in rural, agricultural areas in which domestic water supply requirements are met almost entirely by groundwater. Consequently, an important aspect of the capability of reclaimed lands to satisfy the needs of a residential component is the post-mining availability of groundwater. This report proposes a sequence of steps or procedures to identify and characterize potential post-mining aquifers.

23. **RRTAC 86-4: Geology of the Battle River Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze, R. Li, M. Fenton and S.R. Moran. 86 pp. $10.00**

This report summarizes the geological setting of the Battle River study site. It is designed to provide a general understanding of geological conditions adequate to establish a framework for hydrogeological and general reclamation studies. The report is not intended to be a detailed synthesis such as would be required for mine planning purposes.

24. **RRTAC 86-5: Chemical and Mineralogical Properties of Overburden: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 71 pp. $10.00**

This report describes the physical and mineralogical properties of overburden materials in an effort to identify individual beds within the bedrock overburden that might be significantly different in terms of reclamation potential.

25. **RRTAC 86-6: Post-Mining Groundwater Supply at the Battle River Site: Plains Hydrology and Reclamation Project. M.R. Trudell, G.J. Sterenberg and S.R. Moran. 49 pp. $5.00**

The report deals with the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is in the Battle River Mining area in east-central Alberta.

26. **RRTAC 86-7: Post-Mining Groundwater Supply at the Highvale Site: Plains Hydrology and Reclamation Project. M.R. Trudell. 25 pp. $5.00**

This report evaluates the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is the Highvale mining area in west-central Alberta.

27. **RRTAC 86-8: Reclamation Research Annual Report - 1985. P.F. Ziemkiewicz. 54 pp. $5.00**

This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

28. **RRTAC 86-9: Wildlife Habitat Requirements and Reclamation Techniques for the Mountains and Foothills of Alberta. J.E. Green, R.E. Salter and D.G. Walker. 285 pp. No longer available.**

This report presents a review of relevant North American literature on wildlife habitats in mountain and foothills biomes, reclamation techniques, potential problems in wildlife habitat reclamation, and potential habitat assessment methodologies. Four biomes (Alpine, Subalpine, Montane, and Boreal Uplands) and 10 key wildlife species (snowshoe hare, beaver, muskrat, elk, moose, caribou, mountain goat, bighorn sheep, spruce grouse, and white-tailed ptarmigan) are discussed. The study was co-funded with The Coal Association of Canada.

29. **RRTAC 87-1: Disposal of Drilling Wastes. L.A. Leskiw, E. Reinl-Dwyer, T.L. Dabrowski, B.J. Rutherford and H. Hamilton. 210 pp. No longer available.**

Current drilling waste disposal practices are reviewed and criteria in Alberta guidelines are assessed. The report also identifies research needs and indicates mitigation measures. A manual provides a decision-making flowchart to assist in selecting methods of environmentally safe waste disposal.

30. **RRTAC 87-2: Minesoil and Landscape Reclamation of the Coal Mines in Alberta's Mountains and Foothills. A.W. Fedkenheuer, L.J. Knapik and D.G. Walker. 174 pp. No longer available.**

This report reviews current reclamation practices with regard to site and soil reconstruction and re-establishment of biological productivity. It also identifies research needs in the Mountain-Foothills area. The study was co-funded with The Coal Association of Canada.

31. **RRTAC 87-3: Gel and Saline Drilling Wastes in Alberta: Workshop Proceedings. D.A. Lloyd (Compiler). 218 pp. No longer available.**

Technical papers were presented which describe: mud systems used and their purpose; industrial constraints; government regulations, procedures and concerns; environmental considerations in waste disposal; and toxic constituents of drilling wastes. Answers to a questionnaire distributed to participants are included in an appendix.

32. **RRTAC 87-4: Reclamation Research Annual Report - 1986. 50 pp. No longer available.**

This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

33. **RRTAC 87-5: Review of the Scientific Basis of Water Quality Criteria for the East Slope Foothills of Alberta. Beak Associates Consulting Ltd. 46 pp. $10.00**

The report reviews existing Alberta guidelines to assess the quality of water drained from coal mine sites in the East Slope Foothills of Alberta. World literature was reviewed within the context of the East Slopes environment and current mining operations. The ability of coal mine operators to meet the various guidelines is discussed. The study was co-funded with The Coal Association of Canada.

34. **RRTAC 87-6: Assessing Design Flows and Sediment Discharge on the Eastern Slopes. Hydrocon Engineering (Continental) Ltd. and Monenco Consultants Ltd. 97 pp. $10.00**

The report provides an evaluation of current methodologies used to determine sediment yields due to rainfall events in well-defined areas. Models are available in Alberta to evaluate water and sediment discharge in a post-mining situation. SEDIMOT II (Sedimentology Disturbed Modelling Techniques) is a single storm model that was developed specifically for the design of sediment control structures in watersheds disturbed by surface mining and is well suited to Alberta conditions. The study was co-funded with The Coal Association of Canada.

35. **RRTAC 87-7: The Use of Bottom Ash as an Amendment to Sodic Spoil. S. Fullerton. 83 pp. No longer available.**

The report details the use of bottom ash as an amendment to sodic coal mine spoil. Several rates and methods of application of bottom ash to sodic spoil were tested to determine which was the best at reducing the effects of excess sodium and promoting crop growth. Field trials were set up near the Vesta mine in East Central Alberta using ash readily available from a nearby coal-fired thermal generating station. The research indicated that bottom ash incorporated to a depth of 30 cm using a subsoiler provided the best results.

36. **RRTAC 87-8: Waste Dump Design for Erosion Control. R.G. Chopiuk and S.E. Thornton. 45 pp. $5.00**

This report describes a study to evaluate the potential influence of erosion from reclaimed waste dumps on downslope environments such as streams and rivers. Sites were selected from coal mines in Alberta's mountains and foothills, and included resloped dumps of different configurations and ages, and having different vegetation covers. The study concluded that the average annual amount of surface erosion is minimal. As expected, erosion was greatest on slopes which were newly regraded. Slopes with dense grass cover showed no signs of erosion. Generally, the amount of erosion decreased with time, as a result of initial loss of fine particles, the formation of a weathered surface, and increased vegetative cover.

37. **RRTAC 87-9: Hydrogeology and Groundwater Chemistry of the Battle River Mining Area. M.R. Trudell, R.L. Faught and S.R. Moran. 97 pp. No longer available.**

This report describes the premining geologic conditions in the Battle River coal mining area including the geology as well as the groundwater flow patterns, and the groundwater quality of a sequence of several water-bearing formations extending from the surface to a depth of about 100 metres.

38. **RRTAC 87-10: Soil Survey of the Plains Hydrology and Reclamation Project - Battle River Project Area. T.M. Macyk and A.H. MacLean. 62 pp. plus 8 maps. $10.00**

The report evaluates the capability of post-mining landscapes and assesses the changes in capability as a result of mining, in the Battle River mining area. Detailed soils information is provided in the report for lands adjacent to areas already mined as well as for lands that are destined to be mined. Characterization of the reconstructed soils in the reclaimed areas is also provided. Data were collected from 1979 to 1985. Eight maps supplement the report.

39. **RRTAC 87-11: Geology of the Highvale Study Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 78 pp. $10.00**

The report is one of a series that describes the geology, soils and groundwater conditions at the Highvale Coal Mine study site. The purpose of the study was to establish a summary of site geology to a level of detail necessary to provide a framework for studies of hydrogeology and reclamation.

40. **RRTAC 87-12: Premining Groundwater Conditions at the Highvale Site. M.R. Trudell and R. Faught. 83 pp. $10.00**

This report presents a detailed discussion of the premining flow patterns, hydraulic properties, and isotopic and hydrochemical characteristics of five layers within the Paskapoo Geological Formation, the underlying sandstone beds of the Upper Horseshoe Canyon Formation, and the surficial glacial drift.

41. **RRTAC 87-13: An Agricultural Capability Rating System for Reconstructed Soils. T.M. Macyk. 27 pp. $5.00**

This report provides the rationale and a system for assessing the agricultural capability of reconstructed soils. Data on the properties of the soils used in this report are provided in RRTAC 86-2.

42. **RRTAC 88-1: A Proposed Evaluation System for Wildlife Habitat Reclamation in the Mountains and Foothills Biomes of Alberta: Proposed Methodology and Assessment Handbook. T.R. Eccles, R.E. Salter and J.E. Green. 101 pp. plus appendix. $10.00**

The report focuses on the development of guidelines and procedures for the assessment of reclaimed wildlife habitat in the Mountains and Foothills regions of Alberta. The technical section provides background documentation including a discussion of reclamation planning, a listing of reclamation habitats and associated key wildlife species, conditions required for development, recommended revegetation species, suitable reclamation techniques, a description of the recommended assessment techniques and a glossary of basic terminology. The assessment handbook section contains basic information necessary for evaluating wildlife habitat reclamation, including assessment scoresheets for 15 different reclamation habitats, standard methodologies for measuring habitat variables used as assessment criteria, and minimum requirements for certification. This handbook is intended as a field manual that could potentially be used by site operators and reclamation officers. The study was co-funded with The Coal Association of Canada.

43. **RRTAC 88-2: Plains Hydrology and Reclamation Project: Spoil Groundwater Chemistry and its Impacts on Surface Water. M.R. Trudell (Compiler). 135 pp. $10.00**

Two reports comprise this volume. The first "Chemistry of Groundwater in Mine Spoil, Central Alberta," describes the chemical make-up of spoil groundwater at four mines in the Plains of Alberta. It explains the nature and magnitude of changes in groundwater chemistry following mining and reclamation. The second report, "Impacts of Surface Mining on Chemical Quality of Streams in the Battle River Mining Area," describes the chemical quality of water in streams in the Battle River mining area, and the potential impact of groundwater discharge from surface mines on these streams.

44. **RRTAC 88-3: Revegetation of Oil Sands Tailings: Growth Improvement of Silver-berry and Buffalo-berry by Inoculation with Mycorrhizal Fungi and N_2-Fixing Bacteria. S. Visser and R.M. Danielson. 98 pp. $10.00**

The report provides results of a study: (1) To determine the mycorrhizal affinities of various actinorrhizal shrubs in the Fort McMurray, Alberta region; (2) To establish a basis for justifying symbiont inoculation of buffalo-berry and silver-berry; (3) To develop a growing regime for the greenhouse production of mycorrhizal, nodulated silver-berry and buffalo-berry; and, (4) To conduct a field trial on reconstructed soil on the Syncrude Canada Limited oil sands site to critically evaluate the growth performance of inoculated silver-berry and buffalo-berry as compared with their un-inoculated counterparts.

45. **RRTAC 88-4: Plains Hydrology and Reclamation Project: Investigation of the Settlement Behaviour of Mine Backfill. D.R. Pauls (compiler). 135 pp. $10.00**

This three part volume covers the laboratory assessment of the potential for subsidence in reclaimed landscapes. The first report in this volume, "Simulation of Mine Spoil Subsidence by Consolidation Tests," covers laboratory simulations of the subsidence process particularly as it is influenced by resaturation of mine spoil. The second report, "Water Sensitivity of Smectitic Overburden: Plains Region of Alberta," describes a series of laboratory tests to determine the behaviour of overburden materials when brought into contact with water. The report entitled "Classification System for Transitional Materials: Plains Region of Alberta," describes a lithological classification system developed to address the characteristics of the smectite rich, clayey transition materials that make up the overburden in the Plains of Alberta.

46. **RRTAC 88-5: Ectomycorrhizae of Jack Pine and Green Alder: Assessment of the Need for Inoculation, Development of Inoculation Techniques and Outplanting Trials on Oil Sand Tailings. R.M. Danielson and S. Visser. 177 pp. $10.00**

The overall objective of this research was to characterize the mycorrhizal status of Jack Pine and Green Alder which are prime candidates as reclamation species for oil sand tailings and to determine the potential benefits of mycorrhizae on plant performance. This entailed determining the symbiont status of container-grown nursery stock and the quantity and quality of inoculum in reconstructed soils, developing inoculation techniques and finally, performance testing in an actual reclamation setting.

47. **RRTAC 88-6: Reclamation Research Annual Report - 1987. Reclamation Research Technical Advisory Committee. 67 pp. No longer available.**

This annual report describes the expenditure of $500,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

48. **RRTAC 88-7: Baseline Growth Performance Levels and Assessment Procedure for Commercial Tree Species in Alberta's Mountains and Foothills. W.R. Dempster and Associates Ltd. 66 pp. $5.00**

Data on juvenile height development of lodgepole pine and white spruce from cut-over or burned sites in the Eastern Slopes of Alberta were used to define reasonable expectations of early growth performance as a basis for evaluating the success of reforestation following coal mining. Equations were developed predicting total seedling height and current annual height increment as a function of age and elevation. Procedures are described for applying the equations, with further adjustments for drainage class and aspect, to develop local growth performance against these expectations. The study was co-funded with The Coal Association of Canada.

49. **RRTAC 88-8: Alberta Forest Service Watershed Management Field and Laboratory Methods. A.M.K. Nip and R.A. Hursey. 4 Sections, various pagings. $10.00**

Disturbances such as coal mines in the Eastern Slopes of Alberta have the potential for affecting watershed quality during and following mining. The collection of hydrometric, water quality and hydrometeorologic information is a complex task. A variety of instruments and measurement methods are required to produce a record of hydrologic inputs and outputs for a watershed basin. There is a growing awareness and recognition that standardization of data acquisition methods is required to ensure data comparability, and to allow comparison of data analyses. The purpose of this manual is to assist those involved in the field of data acquisition by outlining methods, practices and instruments which are reliable and recognized by the International Organization for Standardization.

50. **RRTAC 88-9: Computer Analysis of the Factors Influencing Groundwater Flow and Mass Transport in a System Disturbed by Strip Mining. F.W. Schwartz and A.S. Crowe. 78 pp. $10.00**

Work presented in this report demonstrates how a groundwater flow model can be used to study a variety of mining-related problems such as declining water levels in areas around the mine as a result of dewatering, and the development of high water tables in spoil once resaturation is complete. This report investigates the role of various hydrogeological parameters that influence the magnitude, timing, and extent of water level changes during and following mining at the regional scale. The modelling approach described here represents a major advance on existing work.

51. **RRTAC 88-10: Review of Literature Related to Clay Liners for Sump Disposal of Drilling Wastes. D.R. Pauls, S.R. Moran and T. Macyk. 61 pp. $5.00**

The report reviews and analyses the effectiveness of geological containment of drilling waste in sumps. Of particular importance was the determination of changes in properties of clay materials as a result of contact with highly saline brines containing various organic chemicals.

52. **RRTAC 88-11: Highvale Soil Reconstruction Project: Five Year Summary. D.N. Graveland, T.A. Oddie, A.E. Osborne and L.A. Panek. 104 pp. $10.00**

This report provides details of a five year study to determine a suitable thickness of subsoil to replace over minespoil in the Highvale plains coal mine area to ensure return of agricultural capability. The study also examined the effect of slope and aspect on agricultural capability. This study was funded and managed with industry assistance.

53. **RRTAC 88-12: A Review of the International Literature on Mine Spoil Subsidence. J.D. Scott, G. Zinter, D.R. Pauls and M.B. Dusseault. 36 pp. $10.00**

The report reviews available engineering literature relative to subsidence of reclaimed mine spoil. The report covers methods for site investigation, field monitoring programs and lab programs, mechanisms of settlement, and remedial measures.

54. **RRTAC 89-1: Reclamation Research Annual Report - 1988. 74 pp. $5.00**

This annual report describes the expenditure of $280,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

55. **RRTAC 89-2: Proceedings of the Conference: Reclamation, A Global Perspective. D.G. Walker, C.B. Powter and M.W. Pole (Compilers). 2 Vols., 854 pp. $10.00**

Over 250 delegates from all over the world attended this conference held in Calgary in August, 1989. The proceedings contains over 85 peer-reviewed papers under the following headings: A Global Perspective; Northern and High Altitude Reclamation; Fish & Wildlife and Rangeland Reclamation; Water; Herbaceous Revegetation; Woody Plant Revegetation and Succession; Industrial and Urban Sites; Problems and Solutions; Sodic and Saline Materials; Soils and Overburden; Acid Generating Materials; and, Mine Tailings.

56. **RRTAC 89-3: Efficiency of Activated Charcoal for Inactivation of Bromacil and Tebuthiuron Residues in Soil. M.P. Sharma. 38 pp. $5.00**

Bromacil and Tebuthiuron were commonly used soil sterilants on well sites, battery sites and other industrial sites in Alberta where total vegetation control was desired. Activated charcoal was found to be effective in binding the sterilants in greenhouse trials. The influence of factors such as herbicide:charcoal concentration ratio, soil texture, organic matter content, soil moisture, and the time interval between charcoal incorporation and plant establishment were evaluated in the greenhouse.

57. **RRTAC 89-4: Manual of Plant Species Suitability for Reclamation in Alberta - 2nd Edition. Hardy BBT Limited. 436 pp. $10.00**

This is an updated version of RRTAC Report 80-5 which describes the characteristics of 43 grass, 14 forb and 34 shrub and tree species which make them suitable for reclamation in Alberta. The report has been updated in several important ways: a line drawing of each species has been added; the range maps for each species have been redrawn based on an ecosystem classification of the province; new information (to 1990) has been added, particularly in the sections on reclamation use; and the material has been reorganized to facilitate information retrieval. Of greatest interest is the performance chart that precedes each species and the combined performance charts for the grass, forb, and shrub/tree groups. These allow the reader to pick out at a glance species that may suit their particular needs. The report was produced with the assistance of a grant from the Recreation, Parks and Wildlife Foundation.

58. **RRTAC 89-5: Battle River Soil Reconstruction Project Five Year Summary. L.A. Leskiw. 188 pp. $10.00**

This report summarizes the results of a five year study to investigate methods required to return capability to land surface mined for coal in the Battle River area of central Alberta. Studies were conducted on: the amounts of subsoil required, the potential of gypsum and bottom ash to amend adverse soil properties, and the effects of slope angle and aspect. Forage and cereal crop growth was evaluated, as were changes in soil chemistry, density and moisture holding characteristics.

59. **RRTAC 89-6: Detailed Sampling, Characterization and Greenhouse Pot Trials Relative to Drilling Wastes in Alberta. T.M. Macyk, F.I. Nikiforuk, S.A. Abboud and Z.W. Widtman. 228 pp. $10.00**

This report summarizes a three-year study of the chemistry of freshwater gel, KCl, NaCl, DAP, and invert drilling wastes, both solids and liquids, from three regions in Alberta: Cold Lake, Eastern Slopes, and Peace River/Grande Prairie. A greenhouse study also examined the effects of adding various amounts of waste to soil on grass growth and soil chemistry. Methods for sampling drilling wastes are recommended.

60. **RRTAC 89-7: A User's Guide for the Prediction of Post-Mining Groundwater Chemistry from Overburden Characteristics. M.R. Trudell and D.C. Cheel. 55 pp. $5.00**

This report provides the detailed procedure and methodology that is required to produce a prediction of post-mining groundwater chemistry for plains coal mines, based on the soluble salt characteristics of overburden materials. The fundamental component of the prediction procedure is the geochemical model PHREEQE, developed by the U.S. Geological Survey, which is in the public domain and has been adapted for use on personal computers.

61. **RRTAC 90-1: Reclamation Research Annual Report - 1989. 62 pp. $5.00**

This annual report describes the expenditure of $480,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

62. **RRTAC 90-2: Initial Selection for Salt Tolerance in Rocky Mountain Accessions of Slender Wheatgrass and Alpine Bluegrass. R. Hermesh, J. Woosaree, B.A. Darroch, S.N. Acharya and A. Smreciu. 40 pp. $5.00**

Selected lines of slender wheatgrass and alpine bluegrass collected from alpine and subalpine regions of Alberta as part of another native grass project were evaluated for their ability to emerge in a saline medium. Eleven slender wheatgrass and 72 alpine bluegrass lines had a higher percentage emergence than the Orbit Tall Wheatgrass control (a commonly available commercial grass). This means that as well as an ability to grow in high elevation areas, these lines may also be suitable for use in areas where saline soil conditions are present. Thus, their usefulness for reclamation has expanded.

63. **RRTAC 90-3: Natural Plant Invasion into Reclaimed Oil Sands Mine Sites. Hardy BBT Limited. 65 pp. $5.00**

Vegetation data from reclaimed sites on the Syncrude and Suncor oil sands mines have been summarized and related to site and factors and reclamation methods. Natural invasion into sites seeded to agronomic grasses and legumes was minimal even after 15 years. Invasion was slightly greater in sites seeded to native species, but was greatest on sites that were not seeded. Invasion was mostly from agronomic species and native forbs; native shrub and tree invasion was minimal.

64. **RRTAC 90-4: Physical and Hydrological Characteristics of Ponds in Reclaimed Upland Landscape Settings and their Impact on Agricultural Capability. S.R. Moran, T.M. Macyk, M.R. Trudell and M.E. Pigot, Alberta Research Council. 76 pp. $5.00**

The report details the results and conclusions from studying a pond in a reclaimed upland site in Vesta Mine. The pond formed as a result of two factors: (1) a berm which channelled meltwater into a series of subsidence depressions, forming a closed basin; and (2) low hydraulic conductivity in the lower subsoil and upper spoil as a result of compaction during placement and grading which did not allow for rapid drainage of ponded water. Ponds such as this in the reclaimed landscape can affect agricultural capability by: (1) reducing the amount of farmable land (however, the area covered by these ponds in this region is less than half of that found in unmined areas); and, (2) creating the conditions necessary for the progressive development of saline and potentially sodic soils in the area adjacent to the pond.

65. **RRTAC 90-5: Review of the Effects of Storage on Topsoil Quality. Thurber Consultants Ltd., Land Resources Network Ltd., and Norwest Soil Research Ltd. 116 pp. $10.00**

The international literature was reviewed to determine the potential effects of storage on topsoil quality. Conclusions from the review indicated that storage does not appear to have any severe and longterm effects on topsoil quality. Chemical changes may be rectified with the use of fertilizers or manure. Physical changes appear to be potentially less serious than changes in soil quality associated with the stripping and respreading operations. Soil biotic populations appear to revert to pre-disturbance levels of activity within acceptable timeframes. Broad, shallow storage piles that are seeded to acceptable grass and legume species are recommended; agrochemical use should be carefully controlled to ensure soil biota are not destroyed.

66. **RRTAC 90-6: Proceedings of the Industry/Government Three-Lift Soils Handling Workshop. Deloitte & Touche. 168 pp. $10.00**

This report documents the results of a two-day workshop on the issue of three-lift soils handling for pipelines. The workshop was organized and funded by RRTAC, the Canadian Petroleum Association and the Independent Petroleum Association of Canada. Day one focused on presentation of government and industry views on the criteria for three-lift, the rationale and field data in support of three- and two-lift procedures, and an examination of the various soil handling methods in use. During day two, five working groups discussed four issues: alternatives to three-lift; interim criteria and suggested revisions; research needs; definitions of terms. The results of the workshop are being used by a government/industry committee to revise soils handling criteria for pipelines.

67. **RRTAC 90-7: Reclamation of Disturbed Alpine Lands: A Literature Review. Hardy BBT Limited. 209 pp. $10.00**

This review covers current information from North American sources on measures needed to reclaim alpine disturbances. The review provides information on pertinent Acts and regulations with respect to development and environmental protection of alpine areas. It also discusses: alpine environmental conditions; current disturbances to alpine areas; reclamation planning; site and surface preparation; revegetation; and, fertilization. The report also provides a list of research and information needs for alpine reclamation in Alberta.

68. **RRTAC 90-8: Plains Hydrology and Reclamation Project: Summary Report. S.R. Moran, M.R. Trudell, T.M. Macyk and D.B. Cheel. 105 pp. $10.00**

This report summarizes a 10-year study on the interactions of groundwater, soils and geology as they affect successful reclamation of surface coal mines in the plains of Alberta. The report covers: Characterization of the Battle River and Wabamun study areas; Properties of reclaimed materials and landscapes; Impacts of mining and reclamation on post-mining land use; and, Implications for reclamation practice and regulation. This project has led to the publication of 18 RRTAC reports and 22 papers in conference proceedings and referred journals.

69. **RRTAC 90-9: Literature Review on the Disposal of Drilling Waste Solids. Monenco Consultants Limited. 83 pp. $5.00**

This report reviews the literature on, and government and industry experience with, burial of drilling waste solids in an Alberta context. The review covers current regulations in Alberta, other provinces, various states in the US and other countries. Definitions of various types of burial are provided, as well as brief summaries of other possible disposal methods. Environmental concerns with the various options are presented as well as limited information on costs and monitoring of burial sites. The main conclusion of the work is that burial is still a viable option for some waste types but that each site and waste type must be evaluated on its own merits.

70. **RRTAC 90-10: Potential Contamination of Shallow Aquifers by Surface Mining of Coal. M.R. Trudell, S.R. Moran and T.M. Macyk. 75 pp. $5.00**

This report presents the results of a field investigation of the movement of salinized groundwater from a mined and reclaimed coal mine near Forestburg into an adjacent unmined area. The movement is considered to be an unusual occurrence resulting from a combination of a hydraulic head that is higher in the mined area than in the adjacent coal aquifer, and the presence of a thin surficial sand aquifer adjacent to the mine. The high hydraulic head results from deep ponds in the reclaimed landscape that recharge the base of the spoil.

71. **RRTAC 91-1: Reclamation Research Annual Report - 1990. Reclamation Research Technical Advisory Committee. 69 pp. $5.00**

This annual report describes the expenditure of $499 612 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program. The report lists the 70 research reports published under the program.

72. **RRTAC 91-2: Winter Soil Evaluation and Mapping for Regulated Pipelines. A.G. Twardy. 43 pp. $5.00**

Where possible, summer soil evaluations are preferred for pipelines. However, when winter soil evaluations must be done, this report lays out the constraints and requirements for obtaining the best possible information. Specific recommendations include: restricting evaluations to the time of day with the best light conditions; use of core- or auger-equipped drill-trucks; increased frequency of site inspections and soil analyses; and, hiring a well-qualified pedologist. The province's soils are divided into four classes, based on their difficulty of evaluation in winter: slight (most soils); moderate; high; and, severe (salt-affected soils in the Brown and Dark Brown Soil Zones).

73. **RRTAC 91-3: A User Guide to Pit and Quarry Reclamation in Alberta. J.E. Green, T.D. Van Egmond, C. Wylie, I. Jones, L. Knapik and L.R. Paterson - The Delta Environmental Management Group. 151 pp. $10.00**

Sand and gravel pits or quarries are usually reclaimed to the original land use, especially if that was better quality agricultural or forested land. However, there are times when alternative land uses are possible. This report outlines some of the alternate land uses for reclaimed sand and gravel pits or quarries, including: agriculture, forestry, wildlife habitat, fish habitat, recreation, and residential and industrial use. The report provides a general introduction to the industry and to the reclamation process, and then outlines some of the factors to consider in selecting a land use and the methods for reclamation. The report is not a detailed guide to reclamation; it is intended to help an operator determine if a land use would be suitable and to guide him or her to other sources of information.