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Describing and interpreting the macrostructure of mineral soils - a preliminary report

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Describing and interpreting the macrostructure of mineral soils - a preliminary report

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SUMMARY

A revised approach is presented for the description and interpretation of soil macrostructure. Structure is defined so as to include the size, shape and arrangement of voids as well as aggregates. Limits are suggested of the minimum sizes of voids and peds that can be described reliably in the field. The importance is emphasized of a decision on the purpose before soil macrostructure is described and two levels of detail of description are presented. The simple system of macrostructure description outlined is considered to be adequate for many applied purposes. The detailed system presented is required for thorough characterization of benchmark pedons and for some applied purposes. The concept is supported that descriptions of macrostructure should be used in estimating soil properties important to the purpose at hand. Guidelines are proposed for estimating properties such as saturated hydraulic conductivity, available water, and air capacity from information on structure and other soil properties readily determined in the field. Measurements of soil properties are required periodically to check estimates based upon guidelines and to improve the guidelines if necessary. The usefulness of soil macrostructure description in assessing effects of land use on soil physical condition is documented.

RESUMÉ

Les auteurs présentent une démarche modifiée pour la description et l'interprétation de la macrostructure du sol. On englobe dans le terme structure le calibre, la forme et la disposition des vides ainsi que des agrégats. Des limites sont proposées concernant les calibres minimaux des vides et agrégats pouvant se décrire de façon certaine sur le terrain. Il est très important au départ de connaître le degré de complexité recherché et, a cet effet, deux niveaux de détail de description sont présentés. Le modèle simple est jugé suffisant pour beaucoup de travaux de recherche appliquée, tandis que le système détaillé s'impose pour la caractérisation approfondie des pédons repères ainsi que pour quelques travaux de nature appliquée. Les auteurs sont d'avis que les descriptions macrostructurales devraient être utilisées pour estimer les propriétés du sol importantes pour les fins recherchées. Des lignes directrices sont proposées pour l'estimation des propriétés comme la conductivité hydraulique en milieu saturé, l'eau disponible, la porosité en air, è partir d'information sur la structure et sur les autres propriétés du sol facilement déterminées sur le terrain. Des mesures doivent être prises périodiquement pour vérifier les estimations basées sur les lignes directrices et, au besoin, pour améliorer ces dernières. Les auteurs scrutent, bibliographie A l'appui, la valeur de la description macrostructurale dans l'évaluation des effets de l'utilisation de la terre sur l'état physique du sol.

INTRODUCTION

Structure description has been a part of the field characterization of soils in Canadian soil survey operations for half a century (Joel *et al.*, 1936; Wyatt *et al.*, 1939). In the first U.S. Soil Survey Manual, used also in Canada, Kellogg (1937) wrote this about structure, "Its importance in soil classification and as a determinant of soil productivity can scarcely be overemphasized". More recent manuals prepared in the United States (Soil Survey Staff, 1951, 1981) and in Canada (Day, 1983) have refined the format for describing soil structure. In spite of the apparent recognition of its importance, structure is not described uniformly by different pedologists (McKeague and Wang, 1982; Table 1). Furthermore, there is little evidence that structure is used consistently in developing interpretations of soil survey information. To a large extent, structure information is recorded as a routine part of soil description during soil survey operations in Canada and is not considered further.

Focus on research related to soil structure is cyclic. For example, in 1959 the proceedings of an international symposium on soil structure summarized much of the western European work of that decade (see, for example Jongerius, 1959 and Peerlkamp, 1959). Following a decline in the 60's and early 70's soil structure research has increased recently due, in part, to concern about soil compaction under current farming systems.

The purposes of this bulletin are to summarize the current state-of-the-art on the description and interpretation of soil macrostructure and to propose improvements for consideration by the soil survey community and others concerned with soil interpretations in Canada. This bulletin summarizes most of the information reported by McKeague and Wang (1982) and goes on to specific proposals of definitions, and of procedures to use in describing and interpreting soil macrostructure. The term macrostructure encompasses those aspects of soil structure that are discernable in the field mainly by the unaided eye but including features visible with the aid of a low-power magnifier (approximately 10x).

REVIEW OF CONCEPTS AND DEFINITIONS

Concepts of soil structure fall mainly into two groups: (1) those restricted to the size, shape and arrangement of solid soil constituents, and (2) those including the size, shape, and arrangement of both solid constituents and voids. The first of these concepts prevails in North America as illustrated by the following definitions from Soil Survey organizations in Canada and the United States.

a) "Soil structure refers to the aggregation of primary soil particles into compound particles, which are separated from adjoining aggregates by planes of weakness." (Day, 1983).

Table 1: Descriptions of macrostructure of a Brandon pedon by seven pedologists[1].

	Pedologist						
Horizon	A	B	C	D	E	F	G
Ap 0-17 cm	mod-str fine sbk	mod-str fine and med gran	weak fine-med sbk to weak fine sbk	weak co sbk to mod fine-med sbk	weak-mod v fine-fine gran	str fine gran to weak v fine gran	mod-str fine sbk and gran
Bg1 17-24 cm	weak med sbk, weak fine pl in situ	weak fine sbk	weak fine-med sbk	weak med sbk to mod fine sbk	weak v fine-fine abk	str med sbk to str fine-med gran	weak fine pris to mod fine-med sbk
Bg2 24-53 cm	weak fine and med sbk	weak-mod fine and med sbk	weak-mod med-co sbk to weak fine- med sbk	weak-mod sbk to mod fine sbk	v weak v fine-fine abk	mod-str co sbk to mod fine-med sbk	weak co sbk to mod-weak fine sbk
BCg 53-75 cm	mod med sbk	mod fine- med sbk	mod med-co sbk	weak med-co sbk to mod fine-med sbk	weak fine-v fine abk	mod co sbk to mod fine-med sbk	weak co sbk to mod-str med abk
Cg 75-100 cm	str med abk co pl in situ	mod-str med abk	mod med-co sbk	str med-co col to mod- str med sbk	mod-str med- co abk to mod fine-med abk	str med-co abk to mod- str fine-med abk	mod med abk to mod-str fine abk

[1] Some terms are abbreviated for convenience, e.g. mod for moderate; abk and sbk indicate angular and subangular blocky respectively. "To" in the description indicates compound structure, the larger units parting to form the smaller ones. The pedon was described on May 31 and June 1, 1979 when the water table was at 52 cm (McKeague and Wang, 1982).

b) Soil structure (pedality) refers to the natural organization of soil particles into units. These are separated by surfaces of weakness. The surfaces persist through more than one cycle of wetting and drying in place. An individual natural unit is called a ped (Soil Survey Staff, 1981).

The second concept, including voids as an aspect of soil structure, prevails in much of western Europe. The term "voids" is used for those parts of the soil volume not occupied by solids; the equivalent term "pores" is used in many publications. Jongerius (1959) of The Netherlands Soil Survey Institute defined structure as, "the spatial arrangement of the elementary constituents and any aggregates thereof and of the cavities occurring in the soil". The British Soil Survey Handbook (Hodgson, 1976) states that, "soil structure refers to the shape, size and degree of development of the aggregation, if any, of the primary soil particles into naturally or artificially formed structural units (peds, clods, artificial and natural fragments), and the spatial arrangement of those units including the description of voids (pores and fissures) between and within the aggregates."

Systems for Describing Pedality

The system outlined in the U.S. Soil Survey Manual (Soil Survey Staff, 1951) is summarized as it provides the framework on which most current systems are built. The system focuses on three attributes of soil aggregates or peds, which are distinguished from clods, fragments and concretions. These attributes are:

1. Type (shape and arrangement of peds) - platy, prismlike, block-like, and spheroidal or polyhedral with unaccommodated faces (for example, a convex curved ped face against a planar ped face). Subdivisions of the basic types include:

columnar -	prismatic with rounded top
granular -	spheroidal, or polyhedral with unaccommodated faces, relatively nonporous
crumb -	spheroidal, very porous
subangular blocky -	a type of blocky with many rounded vertices

2. Class (size) - most types are subdivided into four size classes.
For example: Angular blocky - fine <10 mm, medium 10-20 mm, coarse 20-50 mm, very coarse >50 mm

3. Grade (strength) includes both durability of the aggregates and proportions between aggregated and unaggregated material. Grade terms defined are: structureless, weak, moderate and strong. Assignment of grade is based on observations of the soil in place and of disturbed soil material.

Provision is made for describing compound structure. For example: strong, coarse, angular blocky parting to moderate fine and medium angular blocky.

U.S. System (Soil Survey Staff, 1981) - The system for describing pedality is nearly identical to that in the 1951 manual, but the attributes of pedality are called shape, size and grade. Additional information is give on distinguishing clods (caused by disturbance) and fragments (bounded by ephemeral planes) from peds; all these units are to be described.

British Soil Survey Handbook (Hodgson, 1976) - The system of describing pedality follows that of the 1951 Soil Survey Manual in general. Provision is made for describing clods and artificial or natural fragments in terms of size, shape and consistence.

Canada Expert Committee on Soil Survey (Day, 1983) - The system differs from that outlined by the U.S. Soil Survey Staff (1951) in these respects:

- "Kind" is used as a subdivision of "Type" of ped, e.g. subangular blocky is a "kind" of the "type", blocklike.
- Pseudo, stratified, bedded and laminated are used as modifiers of "kind" of pedality.
- Cloddy is introduced to indicate the condition (undefined) of some plowed surfaces.
- Blocky and granular indicate shape of peds only, not accommodation. (In the U.S. system "granular" includes peds of various shapes if ped faces are unaccommodated).

Systems for Describing Voids

Description of voids was not included in the 1951 edition of the U.S. Soil Survey Manual, which was used widely in Canada. Johnson *et al.*(1960) outlined a system for describing soil voids, and a similar system appears in the draft of the new manual (Soil Survey Staff, 1981). Voids are described in terms of quantity, size and shape as follows:

Quantity (number of voids per cm^2 for voids <2 mm in diameter, and per dm^2 for voids >2 mm).
Three classes are defined: few - less then 1, common - 1 to 5, many - more than 5.

Size (diameter). Four classes are designated:
very fine, less than 0.5 mm; fine, 0.5 to 2 mm; medium, 2 to 5 mm; coarse, more than 5 mm. Pores larger than 10 mm may be counted separately. Voids smaller than 0.075 mm are microvoids; they are not described in the field.

Shape. Most voids described are either vesicular (spherical or elliptical), or tubular (approximately cylindrical). Some may be irregular. Only inped voids are described in most instances.

The current Canadian system for describing soil voids (Day, 1983) differs from that of the United States in some respects.

1. Total porosity of mineral soils is estimated: slightly porous, <40% pore space by volume; moderately porous, 40 to 60% pore space; highly porous, >60% pore space.

2. Air porosity (percentage of soil volume occupied by air at -5kPa) of mineral soils is estimated, and general guidelines are suggested for assigning classes. The classes are: low, <5%, medium, 5-15% and high, >15%; they differ from those used by the British Soil Survey (Hodgson, 1976).

3. Provision is made for describing voids in terms of abundance and size. The 5 size classes range from micro (<0.1 mm) to coarse (5-10 mm).

4. Other void attributes that may be described are:

Orientation:	vertical, horizontal, random, oblique
Distribution:	inped, exped
Morphology:	simple, dendritic, closed
Continuity:	continuous through the horizon, discontinuous
Types:	vesicular, interstitial, tubular; the emphasis is on non-planar voids.

In the British system (Hodgson, 1976) voids are included as part of the description of structure. The system of estimating and recording the nature of voids differs from those described previously in several respects.

1. The volumes of voids greater than 0.2 µm and greater than 60 µm (equivalent to air filled voids at approximately -1500 and -5 kPa respectively) are estimated from packing density and texture.

2. Both planar and tubular or spherical voids are described and classified according to size as follows:

   Planar voids (fissures) between peds or clods: very fine <1 mm wide, fine 1-3 mm, medium 3-5 mm, coarse 5-10 mm, very coarse >10 mm.

   Tubular or other non-planar voids: very fine <0.5 mm, fine 0.5-2 mm, medium 2-5 mm, coarse >5 mm.

3. Figures are provided that facilitate the estimation of the volume percentage of voids in a given size range (Fig. 1). As in the other systems, noting the continuity and orientation of voids is recommended when possible.

EVALUATION OF SYSTEMS FOR DESCRIBING SOIL STRUCTURE

(Including Pedality And Porosity).

This evaluation focuses on the systems outlined by soil survey organizations of the United States (Soil Survey Staff, 1981), Britain (Hodgson, 1976) and Canada (Day, 1983). It is based on our assessment of both the principles involved and of the application of the systems in soil survey. In principle it seems that systems including porosity as an integral part of soil structure are preferable to those that do not. Porosity is the most important aspect of the physical organization of soil with respect to air-water relationships. The soil may be considered as a system of holes in which water and air may flow or be retained. The sizes, shapes and arrangements of the holes are intimately associated with those of the primary particles and aggregates. Thus porosity is an integral part of soil structure, probably the most important part for practical purposes.

It may appear to be a matter of no practical consequence whether voids are described as a part of soil structure or as a separate aspect of soil morphology, but this is not so. In describing the pedality of a soil, pedologists look for traces of planar voids that partly or completely separate peds. In examining differences between ped surfaces and interiors, they see inped voids larger than 0.5 mm or so. The voids can be noted more efficiently during the process of describing pedality than as an independent operation. Conversely, and perhaps more appropriately, peds can be observed and described during the process of describing voids.

Another argument in favor of including porosity as a part of structure is that it might lead pedologists to give as much attention to the description of voids as to the description of peds. Even since the introduction of systems of describing soil porosity in North America, the application of those systems in most soil descriptions is weak, if voids are described at all. This can be verified by scanning a few randomly-selected, recent soil survey reports.

Another important principle in soil structure description for soil survey is that the focus must be on direct observation of features that can be seen readily by the unaided eye combined, if possible, with estimates of features too small to be seen from soil properties that can be felt. Examples of the latter are the estimation of clay content from the feel of wet soil, and the estimation of voids larger than 0.2 µm from packing density and texture (Hodgson, 1976). In the past, much attention has been given to squinting at fragments of peds through a hand lens to observe very fine voids, if voids were described at all. Usually the macrovoids such as earthworms channels and major planar voids were ignored.

Based on the principles stated, our evaluation of the three systems of describing soil structure favors the British system (Hodgson, 1976) for two main reasons. Porosity is included in the concept of structure and procedures similar to those of the British System.

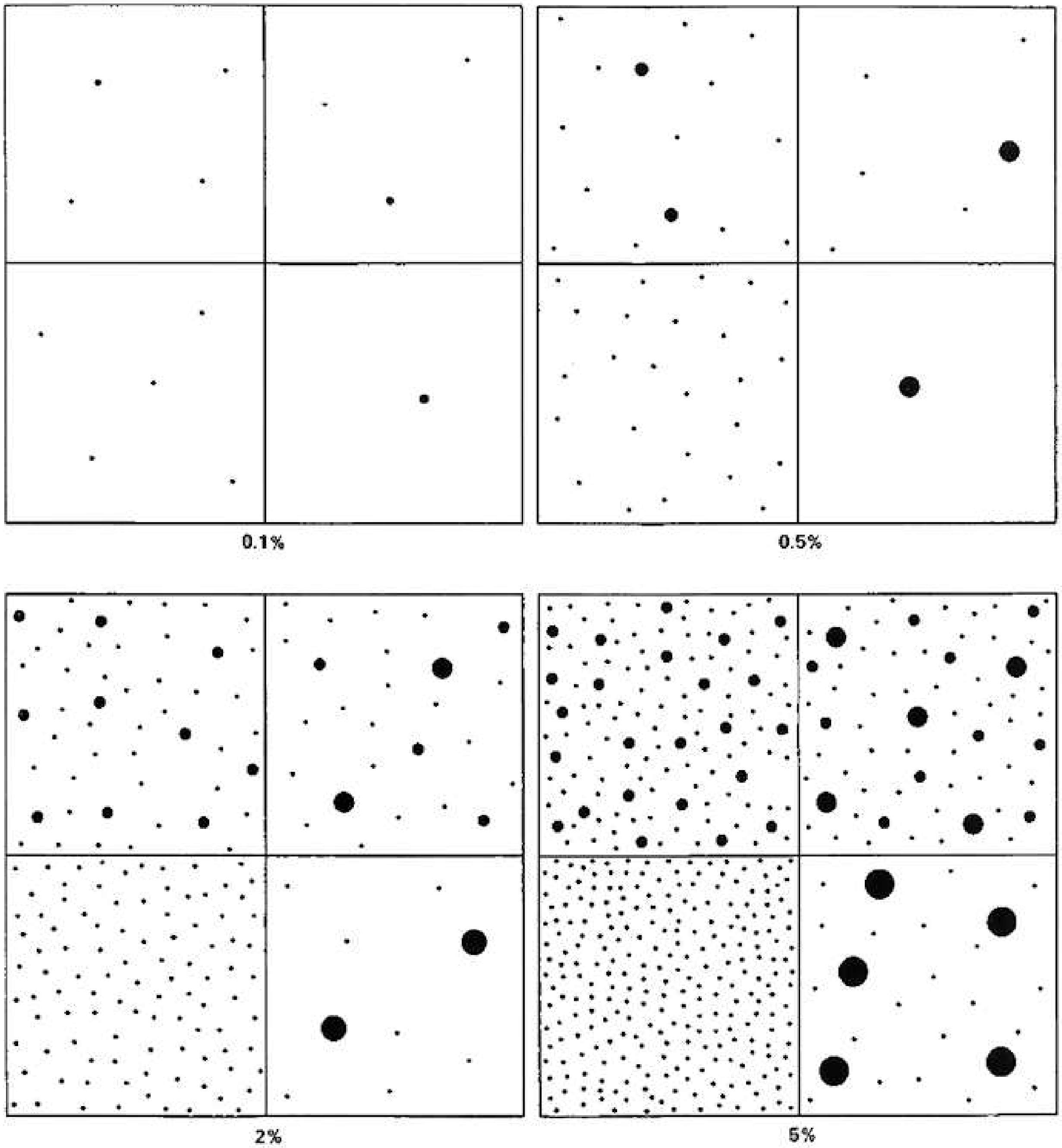

Figure 1. Charts to aid in estimating the areal percentage of rounded al voids in a soil section, usually horizontal (adapted from Hodgson, 1976).

Some advantages of and some problems associated with each of the systems are outlined.

British System (1976)

The two major advantages of the British system were stated in the preceding paragraph. Another is that it includes the description of fragments and clods as part of the description of structure. This indicates an acceptance of the fact that it is not always clear whether soil aggregates are peds, clods, or fragments. Peds are said to persist through several cycles of wetting and drying, but the persistence of peds is difficult to assess, especially weakly-formed peds. The British system, if applied correctly, ensures the description of size, shape and arrangement of aggregates and voids whether they are thought to be "natural" or "artificial". Aggregates of cultivated surface horizons are designated as fragments (or clods). It should be noted that "fragments" in the British system means small (<10 cm) clods. Clods are aggregates formed by cultivation, freezing and thawing, etc. that are less permanent than peds.

Some problems with the British system are listed.

1. Like the Canadian and U.S. systems, it is not adequately explicit on the operations involved in assessing the grade of structure to ensure adequate uniformity of characterization.

2. Limits between platelike and block-like; and between block-like and prism-like are not stated specifically. This results in a degree of ambiguity. For example, is a ped 2.5 cm x 2 cm x 1 cm high block-like or plate-like? The same problem applies to the Canadian and United States systems.

3. The dimension of block-like and prism-like peds to be measured for determining size is not stated. Consider a ped in the form of a 19 mm cube. If the orthogonal axes of the cube are the key dimensions, it is medium blocky; but if the oblique dimension of the cube is the key, it is coarse blocky.

4. Two attributes (degree of organization of the soil mass into distinct peds and strength of peds) are combined in the concept of grade. Suppose that the soil mass is composed almost entirely of distinct, readily separated, medium subangular blocky peds but the peds can be crushed very easily. It is not clear whether the grade of structure is weak, moderate or strong. This problem applies to the other two systems.

5. It implies that voids 0.06 to 0.5 mm in width or diameter can be described in the field. It is not feasible to observe directly the size, shape and abundance of such voids.

United States System (Soil Survey Staff, 1981)

The terms used are well defined and the dimensions that determine size classes of peds are stated. There are several problems associated with the system.

1. Though the differences of peds, fragments and clods are defined, it is most unlikely that these are applied consistently by pedologists. Thus one pedologist might describe a C horizon as having moderate, very coarse platy structure, and another, judging that the platy units were fragments, might describe the horizon as structureless.

2. Porosity is not treated as an aspect of structure and planar voids are not usually described as a part of the description of porosity.

3. It is implied that the quantity, size and shape of voids 0.075 to 0.5 mm in diameter can be assessed in the field but no directions are given.

4. The operations involved in describing structure are not presented in a way that is likely to lead to consistent descriptions by different pedologists. For example, a paragraph on structureless soils includes the following: "no peds are observable in place or after the soil has been gently disturbed, as by tapping a spade containing a slice of soil against a hard surface, dropping a large fragment on the ground, or tossing a fragment up in the air and catching it." Anyone who has seen these directions applied by a group of pedologists knows that the conclusions differ. Perhaps it is not possible to formulate consistently applicable directions on the description of grade of pedality.

Canadian System (Day, 1983)

The Canadian system has most of the advantages and weaknesses of the United States system. Some additional problems associated with the Canadian system are:

1. Structure that is thought to be of non-pedological origin, usually inherited, is distinguished from structure thought to be pedological. The following modifiers are used with "kind" (shape) of ped terms to indicate non-pedological structure: pseudo (inherited from parent material), stratified (layered), bedded (layers thicker than 1 cm) laminated (layers less than 1 cm thick). Commonly, it is difficult to assess whether aggregates in the lower horizons of a soil are due to pedological processes, geological process, or both of these. There is a low degree of consistency in the application of "pseudo". For the description of the physical organization of soils, the origin of the organization is not important. Furthermore, terms such as stratified, bedded and laminated should not be used as modifiers of kinds of ped; these layers are not peds, though they are an important aspect of the physical organization of soil.

2. Though the introduction of air porosity is a step forward, guidelines for its estimation are vague.

3. The coding forms used in soil description provide space for recording only one kind of void per horizon.

PROPOSED SYSTEM FOR SOIL MACROSTRUCTURE

The material that follows is a proposal for improved definitions and an improved framework for describing soil macrostructure.

Definition of Soil Structure (from Brewer, 1964)

Soil structure is the physical constitution of the soil material as expressed by the size, shape and arrangement of the solid particles (including primary and compound particles) and voids. Fabric is the element of structure that deals with arrangement.

Soil macrostructure is the part of soil structure that can be seen by eye or with the aid of a low power hand lens; it is the aspect of soil structure that is described in the field. Macrostructure includes solid units larger than 0.5 mm, more-or-less cylindrical or spherical voids larger than 0.5 mm and planar voids wider than 0.2 mm. Widths of planar voids may change with drying and wetting of the soil. It is desirable to estimate the water content of each horizon described, or at least to indicate whether it is dry (drier than -1500 kPa), moist (-1 to -1500 kPa) or wet (wetter than -1 kPa).

Soil microstructure is concerned with that part of soil structure that can not be seen readily in the field. It encompasses the size, shape and arrangement of solid units and voids smaller than 0.5 mm. Microstructure may be described with the aid of micromorphological techniques (Brewer, 1964). Some aspects of microstructure may be estimated from other soil properties assessed in the field as indicated in the section on interpreting structure.

The above definition of soil structure implies a different concept of structure than that held currently in Canada (Day, 1983). The differences are:

- the inclusion of voids as a part of structure,
- the inclusion of primary as well as compound units as an element of structure. (The sizes, shapes and arrangement of primary particles are described if they occur as isolated units as in some gravelly materials).
- the suggestion of a lower limit of particle, aggregate and void sizes that can be described in the field (macrostructure).

Simple System

An ideal system for describing soil macrostructure would facilitate characterization of structure at different levels of detail, combine voids and solid particles in a single scheme, and provide the information necessary for making interpretations. At the least-detailed level, the system should be simple and applicable by non-specialists. An outline of a tentative simple scheme follows. Structure is subdivided among 7 classes and 14 subclasses. Each horizon should be described as dry, moist or wet.

I Lacks an organized system of macrovoids and peds.

- IA The material is massive and coherent
- IB The material is loose or single-grained

II Has a system of more-or-less vertical, tubular voids (channels) in apedal material.

- IIA Channels 0.5 mm or larger in diameter occupy 0.1 to 0.5% of the volume. The volume of tubular voids can be estimated by using dot charts (Fig. 1, adapted from Hodgson, 1976).
- IIB Channels as specified above occupy more than 0.5 % of the volume.

III A system of more of less vertical cracks traverses the horizon; horizontal planar voids are weakly-developed or absent.

- IIIA The cracks occupy less than 1% of the volume and vertical channels larger than 0.5 mm occupy less than 0.1% of the volume. (Volume of cracks can be estimated by measuring the total width of cracks in a 1 m transect; for example, four cracks 2 mm wide in 1 m would indicate a crack volume of 0.8%).
- IIIB The cracks occupy more than 1% of the volume or cracks occur but occupy less than 1% of the volume and channels larger than 0.5 mm occupy more than 0.1% of the volume.

IV A system of more-or-less horizontal planar voids partially or completely divides the material into platy units with less than 0.1% vertical tubular voids.

- IVA Planar voids are weakly expressed
- IVB Planar voids are strongly expressed

V A system of planar voids in more-or-less horizontal and vertical directions partly to completely separates the material into blocky or prismatic peds with less than 0.1% vertical tubular voids.

- VA The planar voids are weakly developed and the partly-formed peds adhere.
- VB A well developed planar void system separates most of the material into peds.

VI Vertical tubular voids occupy 0.1 to 0.5% of the volume and system of vertical and horizontal planar voids occur.

VIA Planar voids are weakly developed and the partly-formed platy blocky or prismatic peds adhere.

VIB Planar voids are well developed and most of the material occurs as peds.

VII Vertical tubular voids occupy more than 0.5% of the volume and systems of vertical and horizontal planar voids occur.

VIIA Planar voids are weakly developed and the partly-formed peds adhere.

VIIB Planar voids are well developed and most of the material occurs as peds.

Interpretations of K_{sat} and other air-water properties of soil could be based on the simple system outlined. For example, class VIIB would have a very high vertical K_{sat} value.

Detailed System

Structure description at a more detailed level should include separate information on the size, shape and arrangement of both voids and solid components. The elements required are in one or more of the systems summarized in a previous section. In the proposal that follows we selected, and modified in some cases, elements of the systems used in Britain, the United States and Canada.

Describing Macrovoids

Macrovoids are described in terms of quantity, size, shape and orientation, including continuity within the horizon being described. Size, both width and length, of planar voids depends on the water content of the soil at the time of description and this should be estimated or measured. The sizes of tubular and spherical voids are more independent of soil water content.

Planar Voids: These include both interped planes and shrinkage cracks. Quantity can be recorded in both vertical and horizontal directions

Few: Fewer than 1 plane per 10 cm.
Common: 1 to 4 planes per 10 cm.
Many: more than 4 planes per 10 cm.

Size (width) is classified as follows.

Very Fine: <0.2 mm wide (inferred from peds or seen with hand lens)
Fine: 0.2 - 0.5 mm wide
Medium: 0.5 - 2 mm wide
Coarse: 2-5 mm wide
Very coarse: 5-10 mm
Extremely coarse: wider than 10 mm (state widths)

Orientation and continuity: Describe in terms such as vertical, horizontal, oblique, continuous through horizon, or discontinuous. A possible description might be common, continuous, vertical and horizontal, fine, planar voids.

Tubular and Other Non-Planar Voids. Voids 0.5 mm or larger in diameter are recorded. Quantity and size terms (Table 2) are from Day (1983) but classes smaller than fine are not included. Voids larger than 10 mm in diameter are counted in an appropriate area.

Table 2. Abundance and size classes of voids.

Class	Fine 0.5-2 mm	Medium 2-5 mm	Coarse 5-10 mm
	Average number per square decimeter		
Few	<10	<1	<1
Common	10-50	1-5	1-3
Many	50	≥5	≥3

Another approach combining size and abundance is to estimate the percentage of the volume occupied by voids of different sizes using dot charts (Fig. 1).

Shape and continuity are indicated by using common words: tubular, spherical, irregular-shaped, continuous through the horizon, isolated, branching.

Thus, a large earthworm channel might be described as a simple, coarse, vertical, tubular void continuous through the horizon. Abundance of tubular voids of different sizes might be estimated from charts (Fig. 1) and expressed as follows: Fine and medium tubular voids occupy approximately 0.5% of the volume.

Notes should be made on the extent to which planar and other voids are interconnected.

Description of the Structure of Solid Components

The system outlined is to be applied to peds, clods and fragments defined as follows:

Peds are natural soil units that persist from season to season. They can commonly be distinguished from fragments and clods as follows: peds remain approximately the same through different seasons, their sizes and shapes commonly fall within a relatively narrow range, their surfaces are commonly smoothed and they may be coated (this is not common for peds of or Ap horizons). In some cases, it is not possible to distinguish between peds and clods or fragments. Clods and fragments are soil units caused by disturbance; clods are larger than 10 cm in mean cross section and fragments are smaller than 10 cm. The soil units in recently (a few months) cultivated Ap horizons are considered to be fragments or clods, no peds.

Peds are described under four headings: distinctness, consistence, shape and size; the same attributes are noted for clods and fragments. Distinctness and consistence replace "grade" (Day, 1983) because grade includes both the degree to which the material separates into peds and the durability of the peds. The terms are defined:

Distinctness - the degree to which the soil mass separates readily into peds.

- strong - peds are clearly visible *in-situ* and at least ¾ of the mass separates readily into unbroken peds;
- moderate - peds are visible in-situ and more than ¼ but less than ¾ of the material separates readily to unbroken peds. (The proportion of peds can be checked by gently sieving through a nest of sieves of appropriate sizes.)
- weak - peds are barely observable *in-situ* and less than ¼ of the material separates readily into unbroken peds. In some horizons of weak pedality, the material is composed of partly-formed peds that adhere strongly. The planar voids partly separating such peds are narrow and of limited significance in conducting water.
- apedal - this is the term for zero expression of pedality. Peds are not visible either *in-situ* or in broken soil material.

Intergrades are defined as follows:

"Moderate to strong" well over half of the mass separates into unbroken peds.
"Weak to moderate" almost ¼ of the mass separates readily into complete peds.
"Very weak" some partly-formed peds are visible in almost apedal material.

Consistence

Record the consistence of the primary, secondary, etc. peds (Table 3). For apedal horizons determine the consistence of a 25 mm cube of soil.

Shape

Platy: The units are flat and usually oriented horizontally. The thinnest dimension is less than ½ that of the mean of the other two dimensions (Fig. 2). For example, if the x, y and z dimensions are 5 x 4 x 2 cm, the unit is platy $2/[(5+4)/2] < ½$

Lenticular platy - Plates are thickest in the middle (at least 50% thicker than the average thickness near the edge of the unit).

Prismatic - The peds are bounded by relatively flat vertical faces most of which intersect at sharp angles; the z dimension exceeds the mean of the x and y dimensions by more than 1.5 times (Fig. 2). Tops of the prisms are usually flat.

Columnar - The peds are like prisms except that vertical edges near the tops are rounded; the tops may be either rounded or flat.

Angular Blocky - The polyhedral peds are more-or-less equi-dimensional and accommodated (the flat to slightly rounded ped faces are casts of adjoining faces). Most (>50%) of the faces intersect at sharp angles. The z dimension of the units is between 0.5 and 1.5 times the mean of the x and y dimensions.

Subangular Blocky: The same as angular blocky except that most (>50%) of the angles between faces are rounded.

Granular: The peds are either more-or-less spherical or blocky with unaccommodated faces.

Table 3: Ped consistence classes (based on draft of the U.S. Soil Survey Manual, Soil Survey Staff, 1981).

Field test	Force (Newtons)	Ped Consistence	
		Air-dry	0.1 bar
Ped crushes or breaks under very slight pressure	8N	soft	very friable
Ped crushes or breaks under slight force applied by thumb and forefinger	8-20N	slightly hard	friable
Ped crushes or breaks under moderate force applied by thumb and forefinger	20-40N	slightly hard	firm
Ped crushes or breaks under strong force applied by thumb and forefinger	40-80N	hard	very firm
Ped cannot be broken by thumb and forefinger but can be by squeezing between hands	80-160N	very hard	extremely firm
Ped cannot be broken in hands but can be crushed underfoot by person weighing 80 kg applying weight slowly.	160-800N	extremely hard	extremely hard

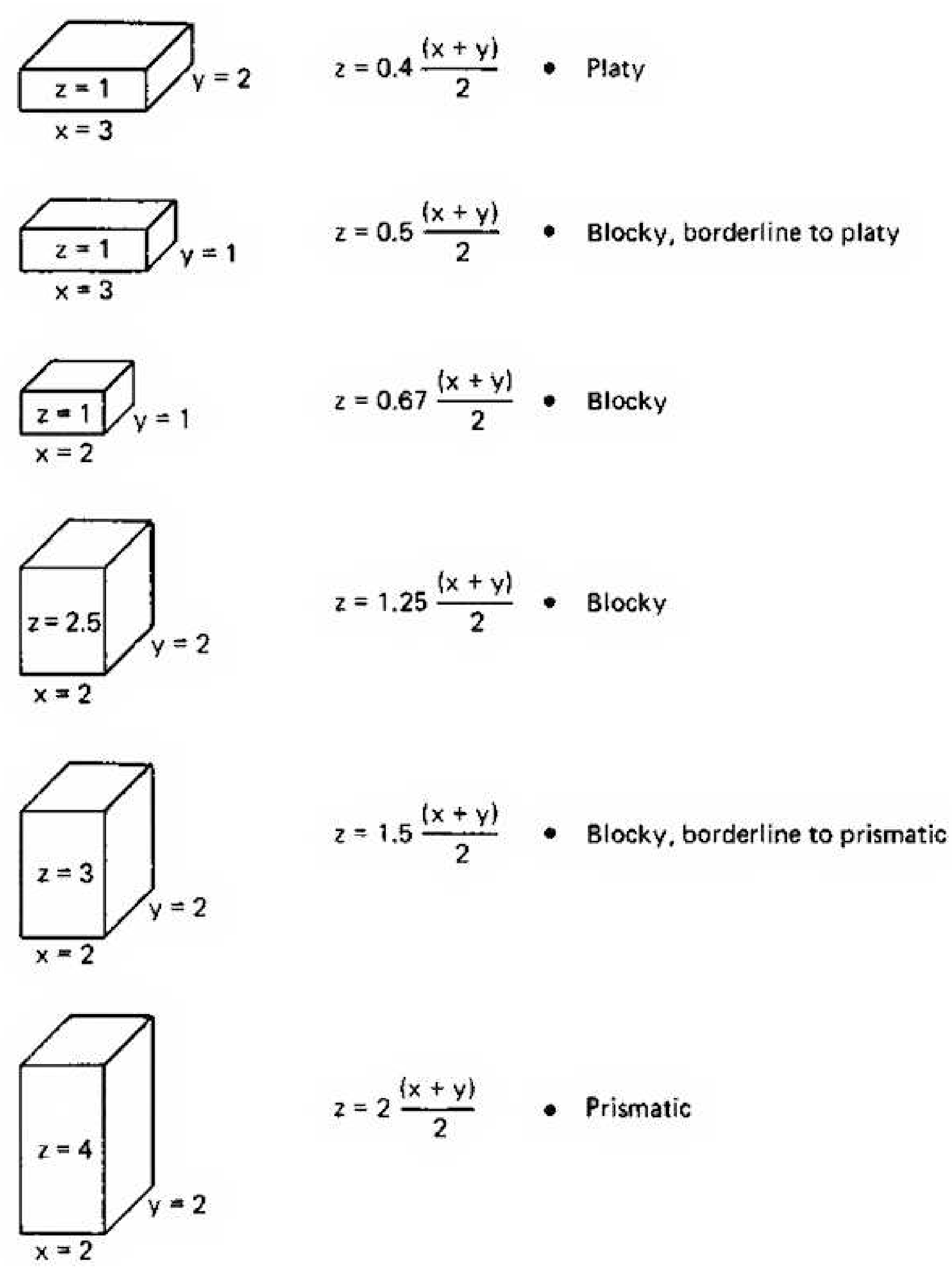

Fig. 2. Limits between ped shape classes.

Size

The size range of fine, medium, coarse and very coarse peds differs according to shape (Table 4 and Fig. 3). Note that the dimension that determines the size class is specified (Table 4).

Table 4: Size classes of peds according to shape.

	Ped Shape			
	Smallest dimension (mm)		Largest dimension (mm)	
	Platy [1]	Prismatic and Columnar	Blocky	Granular
Fine	<2	<20	<10	<2
Medium	2-5	20-50	10-20	2-5
Coarse	5-10	50-100	20-50	5-10
Very coarse	>10	>100	>50	>10

[1] For lenticular platy measure the thickest part of the plate.

GUIDELINES FOR INTERPRETING SOIL STRUCTURE IN RELATION TO AIR-WATER PROPERTIES OF SOILS

Structure is commonly described as a part of the basic characterization of soils. Description of soil structure is useful to the extent that it contributes to reliable assessment of air-water properties of soils such as: air capacity at - 5kPa, saturated hydraulic conductivity in both vertical and horizontal directions, and water retention capacity in the range of water availability to plants. Information on structure might also be useful in assessing susceptibility of soil to erosion and compaction. Guidelines are proposed for making some of these interpretations; testing of them has been limited and undoubtedly improvements can be made. Assessment and progressive revision of the guidelines is required as data become available on morphology in relation to measured properties of a wide range of soils in all regions of Canada.

Saturated Hydraulic Conductivity (K_{sat})

Tentative guidelines developed by McKeague *et al.* (1982) for estimating vertical K_{sat} (K_v) from structure and other soil properties have been tested further in Alberta, Southern Ontario and the Atlantic Provinces and revised. Guidelines for estimating horizontal K_{sat} (K_h) are based on preliminary testing in the Ottawa area only (Wang *et al.* 1985). The modified K_{sat} classes currently accepted by the Expert Committee on Soil Survey (Eilers, 1985) are used in estimating K_{sat}. The guidelines were developed by relating soil morphology to K_{sat}

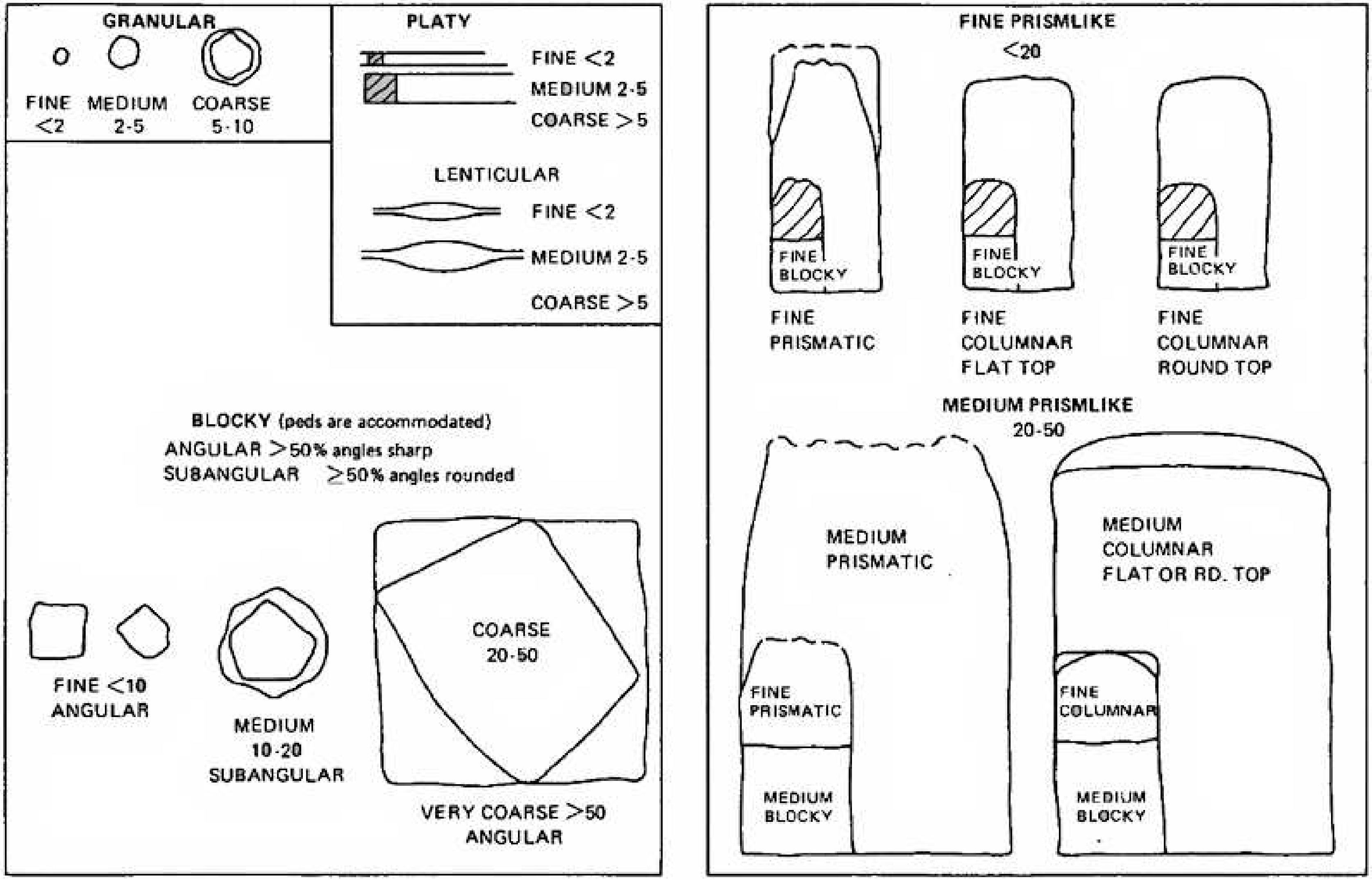

Fig. 3. Shapes and sizes (in mm) of peds.

values measured by the air-entry permeameter (Topp and Binns, 1976) for K_v or the modified piezometer method (Topp and Sattlecker, 1983) for K_h.

The guidelines for K_{sat} (K_v and K_h) are based upon relationships between measured values for specific horizons and their structure (porosity and pedality), texture, consistence, compaction, and combinations of these properties. Structure is assessed as outlined in this bulletin and texture is estimated by hand texturing, including calibration using reference samples.

Macroporosity is obviously of primary importance in determining K_{sat}. Assessment of the abundance, size and continuity of macropores requires examination of vertical and horizontal sections through horizons. The abundance of channels, cylindrical voids, can be estimated by comparing a cleaned horizontal section 30 cm x 30 cm with Fig. 1. In the guidelines specific limits are given for percentage of area occupied by channels. The boundary percentages are:

0.5%	approximately 400 4 mm diameter channels. m^{-2}
0.2%	approximately 160 4 mm, or 640 2 mm channels. m^{-2}
0.1%	approximately 80 4 mm, or 1280 1 mm channels. m^{-2}
0.02%	approximately 16 4 mm, 64 2 mm, 250 1 mm or 1000 0.5 mm channels. m^{-2}

It is not possible to estimate exactly the percentage of an area occupied by channels but precise limits avoid ambiguity. The continuity of channels must be assessed by careful observation or use of dyed water; 0.1% methylene blue is suitable.

Pedality is significant in relation to K_{sat} both because distinctness of peds indicates completeness and continuity of interped planar voids and because size of peds indicates spacing of such voids. In some cases, particularly in relatively dry, clayey horizons, widths of interped planar voids can be estimated directly (planes wider than 0.2 mm). In most cases, however, widths of interped planes are inferred from distinctness of pedality. In horizons with strong blocky or prismatic structure, for example, the major planar voids are commonly 100 to 500 µm wide, based on limited current data. Planar voids in horizons with weak blocky structure are commonly less than 50 µm wide and not continuous.

Shrinkage cracks are considered to contribute to high K_{sat} values even though the cracks probably close when the soil becomes fully saturated. For strongly cracked horizons, it is useful to estimate K_{sat} both for the soil mass including cracks and for the prisms or blocks bounded by cracks. The latter estimate is probably comparable to that for the saturated soils with cracks closed. The guidelines on cracks and other planar voids do not apply to solonetzic B horizons, or probably to other loamy or clayey horizons that swell rapidly on wetting. Testing in Alberta showed that solonetzic B horizons with coarse columnar peds separated by planar voids swelled on addition of water and had K_v values, if measurable, in the L classes.

Consistence is rated according to standards (Day, 1983). It is related to the abundance of voids in the 50 to 500 µm range; these can not be seen easily but they affect K_{sat}. Compaction is rated by observation and feel. A compact horizon has closely-packed particles, it is usually massive and of firm to very firm consistence in loamy or clayey materials, and its bulk density is high in relation to its texture. Roots penetrate a compact horizon sparingly if at all.

In applying the guidelines, it is essential to use the definitions given in this bulletin. For example, chernozemic A horizons (Ah or Ap) are commonly considered to have strong, fine granular structure and some have such structure. The aggregates in many cultivated chernozemic A horizons, however, are <0.5 mm in diameter and it is not clear whether they are micropeds or microfragments. Such horizons should be designated as structureless or apedal according to the concepts in this bulletin. Any friable material breaks readily into small fragments; these should not be considered as peds, unless they are distinct natural units that can be seen and described consistently.

The guidelines do not encompass all combinations of soil properties and judgment is required in assigning a K_{sat} class to some horizons. Some examples of features to consider in making judgments are listed.

1. The widths of planar voids and the distance between them are critical in horizons with few <0.02% channels. For example, horizons with very coarse prisms (such as 30 cm across) bounded by planes of weakness but no open planar voids usually differ little from massive horizons in K_{sat}. Similarly, narrow planar voids that do not extend through the horizon contribute little to K_{sat}.

2. The amount of fine material (silt, clay, humified organic matter, organic-mineral complexes) in fine sandy materials has a major influence on K_{sat}. For example, K_{sat} of fine sand containing only 5% silt plus clay and of bulk density 1.4 $Mg.m^{-3}$ is likely to be in the H1 class. The same material with approximately the same bulk density but with 3 or 4% by weight of humified organic matter or other amorphous material partially filling intergranular spaces is likely to have a K_{sat} value in the M3 class.

Note that the guidelines apply to soil horizons. The vertical K_{sat} of a pedon, is approximately that of the horizon of lowest K_{sat} within the pedon.

Guidelines for K_v

Any one of the features or combinations of features itemized under each K_v class is associated with K_v values within that class. The guidelines are summarized in Table 5.

Table 5. Guidelines for Estimating Vertical Saturated Hydraulic Conductivity (K_v)[1].

Any one of the features or combinations of features itemized under each class is associated with K_v values within that class.

H2 >50cm/h (>139 µm/s)

1. Medium sand or coarser, loose to friable, no fine strata, and sandy to coarse loamy podzolic B horizon with bulk density <1.0 $Mg.m^{-3}$, or
2. Cracks ≥2 mm wide extend through the horizon; cracks are ≤20 cm apart, or
3. More than 0.5% of the horizon is channels ≥0.5 mm in diameter; more than half the channels traverse the horizon, or
4. Strong, fine blocky, or granular; peds separate easily, or
5. Combinations of cracks, channels, pedality equivalent to 2, 3, or 4.

H1 15-50 cm/h (42-139 µm/s)

1. Fine to medium sand with little finer material, or of loamy medium or coarser sand, loose to friable, not compact, or
2. Visible cracks narrower than 2 mm through the horizon ≤20 cm apart, or
3. Channels ≥0.5 mm in diameter occupy 0.2-0.5% of the horizon; more than half of them traverse the horizon, or
4. Moderate to strong, fine to medium blocky or fine prismatic, or
5. Combinations of features equivalent to 2,3 or 4.

M3 5-15 cm/h (14-42 µm/s)

1. Loamy fine sand to sandy loam, structureless, no fine strata, not compact, or
2. Channels ≥0.5 mm occupy 0.1 to 0.2%,more than half traverse the horizon; channels larger than 5 mm are rare, structureless to weak structure, texture finer than fine sandy loam if not compact, or
3. Loamy, structureless to weakly structured; many voids ≤0.5 mm, friable, low bulk density, <0.1% channels ≥0.5 mm, or
4. Moderate fine to medium blocky or moderate to strong medium to coarse blocky, <0.1% channels, finer than fine sandy loam if not compact, or
5. Combinations of features equivalent to 2,3 or 4.

M2 1.5-5 cm/h (4.2-14 µm/s)

1. Fine sand to loamy sand, thin finer strata, structureless or platy, friable, <0.1% channels, or
2. Moderately packed loam to clay, weak pedality, 0.02-0.1% channels, or
3. Moderate, medium to coarse blocky loam or clay, firm peds, <0.02% channels, or
4. Combinations of properties equivalent to the above

M1 0.5-1.5 cm/h (1.4-4.2 µm/s)

1. Structureless, stratified loamy sand, strata of finer material thicker than 1 mm, friable, <0.02% channels, or
2. Structureless loamy material, bulk density 1.5 ± 0.1 $Mg.m^{-3}$, not compact, <0.02% channels, or
3. Clay, weak to moderate blocky or prismatic, firm, tightly-accommodated adherent peds, <0.02% channels.

L3 0.15-0.5 cm/h (0.42-1.4 µm/s)

1. Sandy material with silty or clayey strata ≥1 cm thick, >0.02% channels, or
2. Massive to weak coarse blocky or prismatic, non-compact, firm, loamy or clayey material, <0.02% channels.

L2 0.05-0.15 cm/h (0.14-0.42 µm/s)

1. Cemented or strongly compact, massive, sandy to loamy material, bulk density of 1.6 $Mg.m^{-3}$ or more, no channels, or
2. Massive, compact loamy or clayey material, bulk density 1.4 $Mg.m.^{-3}$ or more and no channels

L1 <0.05 cm/h (<0.14 µm/s)

1. Indurated sandy to loamy material, fine material fills intergranular spaces, no macropores, or
2. Massive, compact clayey material with no macropores, or
3. Continuous placic horizon.

[1] These guidelines do not apply to solonetzic B horizons; the few measured fall in L classes regardless of structure. See the text for details on guidelines

H2 >50 cm/h (>139 µm/s)

1. Texture of medium sand or coarser, loose to friable, no strata of finer material, or very friable, sandy to coarse loamy podzolic B horizons with bulk densities of 1.0 $Mg.m^{-3}$ or less, or
2. Large cracks (≥2 mm) extend through the horizon; cracking pattern forms polygons <20 cm across, or
3. More than 0.5% of the horizon is occupied by channels (tubular voids) ≥0.5 mm in diameter; at least one-half of the channels extend through the horizon, or
4. Strong, fine blocky (or granular); the material separates readily into peds, or
5. Combinations of channels, cracks, and pedality that together are equivalent to 2, 3, or 4. For example, 0.2% channels ≥2 mm and moderate fine to medium blocky structure would probably give a K_v value in the H2 class.

H1 15 - 50 cm/h (42-139 µm/s)

1. Texture of fine to medium sand with very little finer material or of loamy medium or coarser sand, loose to friable, not compact, or
2. Cracks narrower than 2 mm but visible to the naked eye through the horizon; polygons outlined by the cracks are <20 cm across, or
3. Channels ≥0.5 mm in diameter occupy 0.2 to 0.5% of the volume of the horizon and at least one-half of them are continuous through the horizon (large numbers of smaller channels or a few large channels ≥5 mm may be equivalent), or
4. Moderate to strong, fine to medium blocky or fine prismatic (nearly continuous, open planar voids between peds are implied), or
5. Combinations of cracks, channels, and interped voids that together are equivalent to 2, 3, or 4.

M3 5-15 cm/h (14-42 µm/s)

1. Texture of loamy fine sand to sandy loam, structureless, no strata of fine material, not compact, or
2. Approximately 0.1 to 0.2% channels ≥0.5 mm, at least half of which extend through the horizon; <0.02% large (≥5 mm) channels; structureless or weak structure; texture finer than fine sandy loam if not compact, or
3. Loamy, structureless, weakly structured, or platy with many very fine voids (<0.5 mm) in friable material of low bulk density with <0.1%channels >0.5 mm.
4. Moderate fine or medium blocky with weakly adherent peds, or moderate to strong, medium to coarse blocky; <0.1% channels extend through the horizon; texture finer then fine sandy loam if not compact, or
5. Combinations of features that together are equivalent to 1, 2, 3 or 4.

M2 1.5-5 cm/h (4.2-14 µm/s)

1. Fine sand to loamy sand with thin strata of finer material (use a land lens), structureless or platy, friable, <0.1% channels through the horizon.
2. Moderately packed loamy to clayey material with weakly developed pedality (adherent partly-formed peds); 0.02-0.1% channels ≥0.5 mm some of which traverse the horizon, or
3. Moderate, medium to coarse blocky, loamy or clayey material with firm, dense peds, <0.02% channels, or
4. Combinations of channels and interped voids that are equivalent to 2 or 3.

M1 0.5-1.5 cm/h (1.4-4.2 µm/s)

1. Structureless, stratified loamy sand with the finer strata thicker than 1 mm, friable, with <0.02% channels that traverse the horizon, or
2. Structureless loamy material, friable, bulk density 1.5 ± 0.1 $Mg.m^{-3}$, not compact, <0.02% channels, or
3. Clayey material with weak to moderate medium to coarse blocky or prismatic structure, firm tightly accommodated, adherent peds, <0.02% channels that traverse the horizon.

L3 0.15-0.5 cm/h (0.42-1.4 µm/s)

1. Sandy material with continuous silty or clayey strata 1 cm thick or more and <0.02% channels, or
2. Massive to weak, medium or coarse blocky or prismatic non-compact loamy or clayey material with tightly accommodated peds (if any), <0.02% channels >0.5 mm, and few very fine voids visible with a hand lens, or
3. Some solonetzic B horizons.

L2 0.05-0.15 cm/h (0.14-0.42 µm/s)

1. Cemented or strongly compact sandy to loamy material with bulk density of 1.6 or more, and with most of the interparticle voids filled by fine material, and no channels traversing the horizon, or
2. Massive to very coarse blocky or prismatic with essentially closed planes of weakness between peds, as in some fragipans, compact loamy or clayey material with no channels and bulk density of 1.4 $Mg.m^{-3}$ or more, or
3. Some solonetzic B horizons.

L1 <0.05 cm/h (<0.14 µm/s)

1. Indurated sandy to loamy material with enough fine material to fill intergranular spaces (some duric horizons), or
2. Massive, compact clayey material with no visible conducting voids, or
3. A continuous, strongly cemented placic horizon.
4. Some solonetzic B horizons.

Table 6. Guidelines for Estimating Horizontal Saturated Hydraulic Conductivity (K_h)[1]. Any one of the features or combinations of features itemized under each class is associated with Kh values within that class.

H2 >50cm/h (>139 µm/s)
1. medium sand or coarser, loose to friable, or
2. Cracks >2 mm wide and <20 cm apart extend through the horizon, or
3. Stratified with >50% of thickness medium sand or coarser.

H1 15-50 cm/h (42-139 µm/s)
1. Fine to medium sand, little finer material, or loamy medium or coarser sand, friable, not compact, or
2. Visible cracks ≤2 mm wide and ≤20 cm apart extend through the horizon, or
3. Fine sandy material with thin strata of medium or coarse sand, or
4. Moderate to strong, fine to medium blocky or strong platy.

M3 5-15 cm/h (14-42 µm/s)
1. Loamy fine sand to sandy loam, structureless, friable, not compact, or
2. Sandy loam with thin strata of fine sand or loamy fine sand, or
3. Loamy structureless to weakly friable, low bulk density, many voids <0.5 mm, or
4. Moderate fine or medium blocky, or moderate to strong medium to coarse blocky loamy to clayey material.

M2 1.5-5 cm/h (4.2-14 µm/s)
1. Moderately packed, loamy to clayey material, weak pedality, friable, not compact, or
2. Moderate, medium to coarse blocky loam to clay with firm peds.

M1 0.5-1.5 cm/h (1.4-4.2 µm/s)
1. Structureless, loamy, bulk density 1.5 ± 0.1 $Mg.m^{-3}$, friable, not compact, no coarser strata, or
2. Clay, weak to moderate blocky or prismatic, tightly accommodated moderately adherent peds.

L3 0.15-0.5 cm/h (0.42-1.4 µm/s)
1. Massive, moderately compact, loamy material, or
2. Massive to weak medium or coarse blocky or prismatic, non-compact clay with tightly accommodated peds.

L2 0.05-0.15 cm/h (0.14-0.42 µm/s)
1. Cemented or strongly compact sandy to loamy material, bulk density 1.6 $Mg.m^{-3}$ or more, or
2. Massive moderately compact loamy to clayey material with very few or no macrovoids.

L1 <0.05 cm/h (<0.14 µm/s)
1. Indurated, massive sandy to loamy material, fine material fills inter-granular space, or
2 Massive strongly compact clay with no macrovoids.

[1] The guidelines for L classes have not been tested. Based on limited testing of K_v of solonetzic B horizons, they probably fall into L classes for K_h. Guidelines for H and M classes should not be applied to solonetzic B horizons.

Guidelines for K_h (tested less than those for K_v)

These guidelines are summarized in Table 6.

<u>H2 >50 cm/h</u> (>139 µm/s)

1. Texture of medium sand or coarser, loose to friable, or very friable sandy to coarse loamy podzolic B horizons with bulk densities of 1.0 $mg.m^{-3}$ or less, or
2. Large cracks (≥2 mm) extend through the horizon; cracks are ≤20 cm apart, or
3. Strata of medium sand or coarser material are thicker than or similar in thickness to those of finer sandy material, or
4. Strong, fine blocky, granular, or platy.

H1 15-50 cm/h (42-139 µm/s)

1. Texture of fine to medium sand with very little finer material or of loamy medium or coarser sand, friable, not compact, or
2. Visible cracks narrower than 2 mm and ≤20 cm apart extend through the horizon, or
3. Thin strata of medium sand or coarser material and thicker strata of finer sandy material, or
4. Moderate to strong, fine to medium blocky or platy.

M3 5-15 cm/h (14-42 µm/s)

1. Texture of loamy fine sand to sandy loam, structureless, friable, not compact, or
2. Thin strata of fine sand or loamy fine sand in dominantly sandy loam material, or
3. Loamy, structureless or weakly structured, friable, low bulk density, many very fine voids (<0.5 mm), or
4. Moderate fine or medium blocky, or moderate to strong medium to coarse blocky loamy to clayey material with narrow interped voids.

M2 1.5-5 cm/h (4.2-14 µm/s)

1. Moderately packed, loamy to clayey material with weakly developed pedality, friable and not compact, or
2. Moderate, medium to coarse blocky, loamy or clayey material with firm, dense peds.

M1 0.5-1.5 cm/h (1.4-4.2 µm/s)

1. Structureless, loamy material with bulk density of 1.5 ± 0.1 $Mg.m^{-3}$, friable, not compact, and without strata of coarser material, or
2. Clayey material with weak to moderate blocky or prismatic structure, peds tightly accommodated and moderately adherent.

L3 0.15-0.5 cm/h (0.42-1.4 µm/s)

1. Massive, moderately compact loamy material, or
2. Massive to weak, medium or coarse blocky or prismatic, non-compact clayey material with tightly accommodated peds, or
3. Some solonetzic B horizons.

L2 0.05-0.15 (0.14-0.42 µm/s)

1. Cemented or strongly compact sandy to loamy material with bulk density of 1.6 $Mg.m^{-3}$ or more, and with most interparticle voids filled by fine material, or
2. Massive or very coarse blocky or prismatic with essentially closed planes of weakness between peds as in some fragipans, moderately compact loamy to clayey material with very few or no macrovoids, or
3. Some solonetzic B horizons.

L1 <0.05 cm/h (<0.14 µm/s)

1. Indurated massive sandy or loamy material with enough fine material to fill intergranular spaces (some duric horizons), or
2. Massive strongly compact clayey material with no macrovoids traversing the horizon, or
3. Some solonetzic B horizons.

The guidelines for K_v, and especially those for K_h, do not include a complete list of soil morphological features that would be associated with the pertinent K_{sat} class. In applying the guidelines, it is necessary to extrapolate from the features listed to those seen in the horizon under consideration. Simpler and more specific guidelines may be developed for particular regions and suggestions for improvements are sought.

Application of the guidelines has resulted in estimates of the correct K_{sat} class ± 1 class in more than 80% of cases. (McKeague and Wang, 1982; Wang *et al.* 1985 a and b).

Bulk Density

The weight of oven-dry mineral soil per unit volume at the time of sampling (now expressed as $Mg.m^{-3}$ formerly as $g.cm^{3}$) may be estimated to the nearest 0.1 $Mg.m^{3}$ in the field. Estimates are made on the basis of the weight of a clod of soil as judged by feel in relation to its wetness and by comparison with clods from horizons of measured bulk density. No clear guidelines can be stated but reasonable estimates can be made by checking the "feel" of clods against measured values periodically. Obviously clays retain much more water than sandy soils at the same pressure. Thus a 5 cm cube of clay at -5 kPa will be considerably heavier than a 5 cm cube of medium sand at the same pressure if the two samples have the same bulk density.

A few examples are given of bulk densities associated with properties of horizons.

Less than 1.0 $Mg.m^{-3}$:	Some very friable podzolic B horizons with high contents of amorphous materials.
1.0 ± 0.1 $Mg.m^{-3}$:	Some very friable loamy to clayey Ah or Ap horizons with more than 5% organic matter.
1.2 ± 0.1 $Mg.m^{-3}$:	Some fine loamy to fine clayey, friable B horizons with moderate to strong, fine blocky peds.
1.4 ± 0.1 $Mg.m^{-3}$:	Some clay loam to clay B horizons with firm, moderate, medium prismatic peds.
1.6 ± 0.1 $Mg.m^{-3}$:	Some compact clays to loams; some friable loamy sand to sandy loam lower B and C horizons.
1.8 ± 0.1 $Mg.m^{-3}$:	Some fragipans and loamy lodgment tills
2.0 ± 0.1 $Mg.m^{-3}$:	Some duric horizons and some strongly compacted materials with a wide range of particle sizes.

Testing of the feasibility of estimating bulk density is limited but preliminary results are promising. Bulk densities of ⅔ of the horizons tested were estimated within 0.1 $Mg.m^{-3}$ of the measured value (mean of values for 3 cores).

Air Porosity

Air porosity, the proportion of the soil volume, including coarse fragments, occupied by air at -5kPa (voids >60 mm), may be estimated from packing density and texture (Hodgson, 1976). A limited test of that approach in the Ottawa area yield mediocre results. The tentative system outlined basically follows the British approach but more emphasis is given to macrostructure, and bulk density rather than packing density is used. The air porosity classes estimated are those used in Britain (Hodgson, 1976); air porosity may also be estimated to the nearest 1%. Testing of the guidelines is limited and not all soil conditions are covered. The guidelines are summarized in Table 7.

<u>Very slightly porous (<5.0% by volume)</u>

1. Massive clayey material with few macrovoids and bulk density of 1.3 $Mg.m^{-3}$ or more, or
2. Clayey material with weak to moderate, medium to coarse blocky or prismatic tightly accommodated peds, few channels and bulk density usually of 1.4 $Mg.m^{-3}$ or more.
3. Loamy material, in which much of the sand fraction is fine or very fine, with bulk density of 1.5 $Mg.m^{3}$ or more, or
4. Cemented sandy material with bulk density of 1.8 $Mg.m^{-3}$ or more; the intergranular spaces are nearly filled.

Slightly porous (5.0-9.9%)

1. Clayey material with bulk density of 1.2 to 1.3 $Mg.m^{-3}$; moderate, medium blocky peds and approximately 1% macrovoids (planar voids ≥0.2 mm and tubular voids ≥0.5 mm), or
2. Loamy material with bulk density of approximately 1.4 $Mg.m^{-3}$, weak to moderate, medium blocky peds and approximately 1% macrovoids, or
3. Fine sand to loamy fine sand with bulk density of more than 1.5 $Mg.m^{-3}$

Moderately porous (10.0-14.9%)

1. Clayey material with bulk density of 1.2 $Mg.m^{-3}$ or less; moderate to strong, fine to medium blocky peds and more than 1% macrovoids, or
2. Loamy material with bulk density of 1.3 $Mg.m^{-3}$ or less; moderate to strong, fine to medium blocky friable peds and approximately 1% macrovoids, or
3. Loamy fine to medium sand with bulk density of 1.5 $Mg.m^{-3}$ or more, and few macrovoids.

Very porous (15.0-20.0%)

1. Clayey material with bulk density of 1.1 $Mg.m^{-3}$ or less, strong, fine, friable peds and more than 1% macrovoids or
2. Loamy material with bulk density of 1.3 $Mg.m^{-3}$ or less; porous, strong, fine peds and more than 1% macrovoids, or
3. Loamy medium sand with bulk density of 1.4 $Mg.m^{-3}$ or more, or
4. Sandy to coarse loamy friable podzolic B horizons with bulk densities of 1.1 $Mg.m^{-3}$ or less.

Extremely porous (>20%)

1. Fine sands with less that 5% silt + clay + organic matter or other amorphous component, or
2. Gravels, medium to coarse sands, loamy coarse sands with little fine material, and fine to medium sands with less than 10% finer material.

Notes on Using Air Capacity Guidelines

1. The particle-size and texture classes are those given in Day (1983).

2. For the many combinations of the texture, bulk density, and structure not mentioned in the guidelines, it is necessary to extrapolate from the examples given.

Table 7. Guidelines for estimating air porosity (0-5 kPa)[1]

VSP <5%

1. Massive, clayey, few macrovoids, bulk density ≥1.3, or
2. Clayey, weak to mod. coarse blocky, few channels, bulk density ≥1.4, or
3. Loamy, bulk density ≥1.5, or
4. Sandy, cemented, intergranular spaces nearly filled, bulk density ≥1.8

SP 5.0-9.9%

1. Clayey, bulk density 1.2-1.3, mod. med. blocky, approx.1% macrovoids, or
2. Loamy, bulk density approx. 1.4, mod. med. blocky. approx.1% macrovoids, or
3. Fine sand to loamy fine sand, bulk density >1.5

MP 10-14.9%

1. Clayey, bulk density ≤1.2, mod.-str. fine-med. blocky, ≥1% macrovids, or
2. Loamy, bulk density ≤1.3, mod.-str. fine-med. blocky, approx. 1% macrovoids, or
3. Loamy fine to med. sand, bulk density ≥1.5, few macrovoids

VP 15-20%

1. Clayey, bulk density ≤1.1, strong fine friable peds, numerous macrovids, or
2. Loamy, bulk density ≤1.3, porous, strong, fine peds, >1% macrovoids, or
3. Loamy. med. sand, bulk density ≥1.4, or
4. Sandy-coarse loamy podzolic B, bulk density ≤1.1

EP >20%

1. Fine sand, <5% (silt + clay +organic matter), or
2. Gravels, med. to coarse sands, fine-med. sands with 40% finer material.

[1] Bulk density values are expressed as $Mg.m^{-3}$

Available Water Capacity

The approach to the estimation of available water capacity (AWC) is similar to that used in Britain (Hodgson, 1976; Hall *et al.*, 1977). It differs in using bulk density rather than packing density as one of the important parameters and it does not distinguish between A horizons and other horizons. Furthermore, the relative lack of measured data in Canada makes it necessary to rely more heavily on estimated values checked by periodic measurements. It remains to be seen whether estimates based on morphology will be as good as those from models relating AWC to texture or to texture and organic matter (De Jong *et al.*, 1983).

Estimates of AWC are based on texture, bulk density, structure and content of amorphous material including humified organic matter; estimates of amorphous material require calibration against measured values. It is useful to consider total porosity estimated from bulk density and an assumed average particle density of 2.65 $Mg.m^{-3}$. For example, suppose that the bulk density of a loamy (20% clay) mineral horizon containing very little amorphous material is 1.5 $Mg.m^{-3}$. Its approximate total porosity, (2.65-1.5)/2.65 x 100% = 43%, can be divided approximately among: water retained at -1500 kPa, available water capacity (-5 to -1500 kPa) and air porosity (0 to -5 kPa).

Water retained by horizons of mixed clay mineralogy at -1500 kPa is approximately 0.4 x % clay on a weight basis. On a volume basis, the approximate -1500 kPa water content of the horizon under discussion would be 0.4 x 20% x 1.5 = 12%. This leaves 31% (43-12) of the soil volume for air porosity and AWC. Amorphous material usually retains approximately 1 g of water or more at -1500 kPa per g of dry material. Thus, for a podzolic B horizon of bulk density 0.8 $Mg.m^{-3}$ containing 15% amorphous material and 5% silicate clay, the approximate 1500 kPa water content (volume basis) would be (0.4 x 5% x 0.8) + (1.0 x 15% x 0.8) = 14%. Air porosity plus AWC of such a horizon would be approximately

$$[((2.6 - 0.8) /2.6) \times 100\%] - 14\% = 55\%.$$

The AWC of each horizon may be estimated in one of the classes defined or to the nearest 1%. The AWC is defined as the volume percent of water retained between -5 and -1500 kPa by undisturbed samples. Estimates based on the guidelines should be checked by comparing the sum of estimated AWC and AP with the difference between total porosity estimated from bulk density and the estimate of water retained at -1500 kPa. If the values are incompatible, estimates of properties should be reassessed. To estimate the AWC of a soil, it is necessary to add AWC for each horizon times the thickness of the horizon to the depth of rooting of the crop to be grown.

The classes are listed:

Very low:	<5% by volume
Low:	5-9.9%
Medium:	10-14.9%
Moderately High:	15-19.9%
High:	20-24.9%
Very High:	≥25%

The tentative guidelines for estimating AWC, summarized in Table 8, are a listing of some of the soil morphological properties that are associated with each of the classes. Judgment is required in extrapolating these guidelines to other soil conditions and more measured water retention data are required for a wide range of soils. In estimating AWC of sandy soils, it is essential to evaluate the dominant size classes of the sand fraction. If very fine sand is dominant, AWC is usually very high; if medium sand is dominant, it may be very low.

<u>Very low, <5%</u>

1. Extremely gravelly or bouldery sandy loam to loam, or
2. Very gravelly loamy sand or sand containing little fine or very fine sand and less than 5% finer material, or
3. Medium to coarse sands with less than 5% finer material.

<u>Low, 5-9.9%</u>

1. Medium to coarse sands with 5-10% material finer than sand and loamy medium to coarse sands with ≤5% amorphous material, or
2. Very gravelly sandy loam.

<u>Medium, 10-14.9%</u>

1. Loamy medium to fine sands with bulk densities of 1.5 $Mg.m^{-3}$ or more, or
2. Clays with bulk densities of 1.5 to 1.7 $Mg.m^{-3}$.

<u>Moderately high, 15-19.9%</u>

1. Fine sands with approximately 5-10% silt + clay and ≤2% amorphous material, or,
2. Sandy loams with bulk densities of 1.7 $Mg.m^{-3}$ or more, or
3. Loams with bulk densities of 1.6 $Mg.m^{-3}$, or more, or
4. Clays with bulk densities of approximately 1.4 $Mg.m^{-3}$

<u>High, 20-24.9%</u>

1. Loamy fine sands with less than 10% amorphous material, or
2. Fine sandy loams and loams with bulk densities of 1.4 to 1.5 $Mg.m^{-3}$, or
3. Clay loams with bulk densities of approximately 1.4 $Mg.m^{-3}$, or
4. Clays with bulk densities of approximately 1.2 $Mg.m^{-3}$ and <5% amorphous material.

Table 8. Guidelines for estimating available water capacity (5-1500 kPa) [1].

VL <5%

1. Ext. gravelly sl-l, or
2. Very gravelly is or s, little finer material, or
3. Med.-coarse s,<5% finer material.

L 5-9.9%

1. Med.-coarse s, 5-10% finer than sand; loamy med.-coarse s ≤5% amorphous, or
2. Very gravelly sl.

M 10-14.9%

1. Loamy med.-fine s, bulk density ≥1.5, or
2. Clays, bulk density 1.5-1.7

MH 15-19.9%

1. Fine sand, 5-10% si + c and <2% amorphous, or
2. Sandy loam, bulk density ≥1.7, or
3. Loam, bulk density ≥1.6, or
4. Clay, bulk density approx 1.4

H 20-24.9%

1. Loamy fs, <10% amorphous, or
2. Fine sl and l, bulk density 1.4-1.5, or
3. Clay loam, bulk density approx 1.4, or
4. Clay, bulk density 1.2, <5% amorphous

VH >25%

1. Loamy vfs or vf-fsl, bulk density ≤1.5, or
2. Loam-cl, bulk density ≤1.3, or
3. Fine s-c, bulk density <1.0, >10% amorphous.

[1] Bulk density values are expressed as Mg.m^{-3}, 'amorphous' means amorphous material including organic matter, Fe-Al-Si-organic complexes, etc.

Very high, >25%

1. Loamy very fine sands or very fine-fine sandy loams with bulk densities of 1.5 $Mg.m^{-3}$ or less, or
2. Loams and clay loams with bulk densities of 1.3 $Mg.m^{-3}$ or less, or
3. Fine sands to clays with bulk densities less than 1.0 and more than 10% amorphous material.

An example follows of the application of these guidelines to a soil described briefly:

Horizon	Depth	
Ap	0-20	Fine sandy loam with bulk density of 1.4 $Mg.m^{-3}$ and friable fragments smaller than 3 cm.
Bm	20-50	Loam, bulk density of 1.3 $Mg.m^{-3}$, moderate, medium blocky, friable peds.
BC	50-70	Loam, bulk density 1.7 $Mg.m^{-3}$ massive, firm, very few macrovoids.
Ck	70-120	Moderately calcareous loam, bulk density of 1.8 $Mg.m^{-3}$, massive, firm, no macrovoids.

To calculate the AWC of the soil, the steps are:

1. Assess whether the roots of the crop to be grown would exploit each of the horizons.
2. Assign an AWC class to each horizon that would be exploited by roots.
3. Calculate AWC of the soil by adding (means of AWC class of horizon x depth of horizon) of each horizon exploited by roots.

Suppose that observations in similar soils showed that very few corn roots penetrated into the BC horizon. Only the Ap and the B horizons are considered in calculating AWC for corn on that soil.

The Ap horizon is assigned to the high AWC class (fine sandy loam, bulk density of 1.4 $Mg.m^{-3}$). The Bm horizon fits in the very high AWC class (loam with bulk density of 1.3 $Mg.m^{-3}$). The numerical values assigned for AWC's are: Ap, 22.5% (middle of high class range) and Bm, 28%.

Thus AWC of the soil for corn is (0.225 x 20 + 0.28 x 30) 12.9 cm or 129 mm. This value is approximately half the value obtained by applying current procedures that assume availability of water to a depth of 120 cm (Shields and Sly, 1984). The AWC classes of the BC and Ck horizons would be medium but this is not relevant for corn growth if the assumptions are correct.

DESCRIBING MACROSTRUCTURE

In dealing with this topic, we are aware that there is no unique, best way of proceeding in describing soil macrostructure. The operations involved, the time spent and the degree of detail of the information recorded should depend both on the purposes for which the description is made and on the skill and experience of the observer. This discussion is intended to encourage the many soil scientists and users of soil who are unfamiliar with structure as characterized by soil survey to realize that anyone can learn rapidly to describe soil macrostructure for his purposes and that few other important attributes of soil can be assessed so easily. For pedologists concerned with the study and mapping of soils as a part of natural science, and as a basis for a wide range of interpretations, we hope to point out some guidelines that will lead to better and more uniform descriptions of soil macrostructure. Field workshops on macrostructure are an additional requirement for achieving satisfactory uniformity of description.

Steps in Describing Soil Macrostructure

Four basic steps are involved: deciding why macrostructure is to be described; choosing a site or sites at which to describe the soil, deciding upon the operations to follow in describing macrostructure, proceeding according to plan to describe and record macrostructure. Each of these steps is considered.

Purpose for Describing Macrostructure

Deciding why macrostructure should be described is an important step because it influences decisions on where and how. The majority of descriptions in Canada are done by soil surveyors for the purpose of characterizing soils in an area being mapped. Most surveyors accept the view expressed years ago by Kellogg (1937) that soil structure is important. The role of the soil surveyor is to describe soil macrostructure well; the tacit assumption is made that someone will use this important information. Thus nearly all soil survey reports in Canada include descriptions of the pedality (but not the porosity) of "typical" examples of pedons representing major series. The advent of CanSIS more than a decade ago tended to encourage the description of porosity because space is provided on the forms for describing one kind of void. It tended, however, to decrease the completeness of descriptions of pedality because it is convenient to code only one grade, size and shape of ped per horizon unless pedality is compound. This is not a serious practical problem because, in fact, soil macrostructure information is rarely used for any applied purpose. It appears that this fact was recognized by the Ontario Soil Survey as Ontario soil surveyors no longer describe soil macrostructure routinely. Thus, even in the case of the major producer of soil macrostructure descriptions, there is a great need to reconsider the purpose.

Agronomists and farmers might wish to describe soil macrostructure because it is an important soil property in determining root growth, aeration and drainage. For such purposes, the "tentative simple scheme" outlined in this bulletin should be adequate. Such a scheme could be learned in brief field workshops and used in assessing the effects on macrostructure of different crops, tillage treatments, amendments, etc.

Drainage specialists should be interested in soil macrostructure because it is a major factor related to capacity of the soil to transmit water (McKeague and Topp, 1986). The "tentative simple scheme" outlined and the K_{sat} guidelines could be applied usefully to drainage planning. Complete descriptions of pedality and porosity are not essential for such a purpose.

Soil scientists such as physicists, and specialists such as land assessors may have different purposes for describing soil macrostructure. Obtaining useful information begins with specifying the purpose.

Choosing the site

This is one of the most important steps in soil characterization. Soils on a field scale are variable in many properties including macro-morphology (Wang *et al.*, 1985a). Describing soil morphology at a single site chosen for convenience in an old road cut or at the edge of a field is unlikely to provide reliable information relevant to the field. The choice of site depends on the purpose as already discussed. A general rule is that the site should be away from roads, abandoned farmsteads, and other locations likely to have aberrant soil properties, unless the purpose is to study the change of morphology due to roads, etc.

Examples are given of possible steps to follow in choosing sites for specified purposes.

1. Preparing a description of a modal pedon of a series and indicating the degree of variability of morphology of pedons of that series in a soil survey project area.
   a. The morphology of pedons of the series in question would be described through the course of the survey. Preferably, many of the descriptions would be made along stratified random transects (Wang, 1982), hence avoiding bias.
   b. The descriptions would be analyzed and the most commonly-occurring (modal) morphological features and the range of those features would be recorded.
   c. Delineations thought to have the modal pedon as the dominant soil would be numbered and one would be selected at random.
   d. The soil would be checked within that delineation to ensure that it satisfied the modal requirements. If so, it would be described in detail. If not, another of the delineations mentioned in 'C' would be selected at random.
   e. The morphology of the modal pedon and the range of properties within approximately one standard deviation would be recorded.

2. Determining whether poor crop growth in a field might be due to poor soil structure.

   a. Examine and record soil morphology, rooting depth and crop growth at each of ten or so equally-spaced points along a random transect through the field.
   b. Analyze the information to assess how structure is related to root and above ground growth of the crop.

c. Formulate conclusions or plan further testing if necessary.

Deciding on Operations to Follow

The kind and degree of detail of description of morphology required depends upon the purpose of the work. For example, in the case of describing the morphology of a modal pedon of a series, a complete description of macrostructure is necessary. It should include semi-quantitative information on the size, shape and arrangement of both voids and peds. A large soil pit to a depth of 1.5 to 2 m would be necessary, and at least half a day would be required to describe structure thoroughly.

If, on the other hand, the requirement is to assess the physical condition of the surface as a seedbed for grass the required operations would be much different. Obviously the focus would be on the surface layer to a depth of 5 or 10 cm at randomly-selected points across the field. The distinctness, size, shape and arrangement of peds or fragments and voids in this layer in addition to the consistence of peds or fragments should be described. Estimates should be made of bulk density, vertical K_{sat}, and air capacity. A judgment would be made on whether tillage was needed to provide a suitable seedbed. Desirable qualities of the surface would be strong, fine granular structure with abundant voids, friable peds, low to moderate bulk density (1.0-1.4 $Mg.m^{-3}$ depending on texture), high K_{sat} and air capacity of 10% or more. Some other structural conditions would also be suitable and judgment would be required.

Describing and Recording Macrostructure

After a plan has been made of the operations required to describe soil macrostructure to meet the purpose, the final step is to follow the plan and record the required elements of structure and the estimates based upon macrostructure. The material that follows is an attempt to outline how to do this final step for both the simple scheme outlined previously and for detailed descriptions. It is assumed that a site or several sites have been selected according to the guidelines stated previously.

Simple System

1. Dig a soil pit, or have one dug, to the required depth. Preselect two walls of the pit that will be exposed best to the light and avoid standing or shovelling soil on the surface adjacent to those walls. In general the pit should extend 20 to 30 cm below the lowest layer to be described. Much can be deduced about soil structure and consistence while digging the pit. The relative firmness of layers, the degree to which shovelsful of soil remain intact or fall apart into aggregates, and the frequency of major fissures and tubular voids can be observed while digging.

2. Pick one or preferably two walls of the pit so as to break the soil along natural

surfaces of weakness, if any. The wall should be picked from top to bottom moving from left to right in the case of right-handed pedologists. A stiff knife or other such tool may be used.

3. After picking the profile, examine it for major features such as vertical cracks, distinct peds bounded by planar voids, layers of different structure, texture, color, etc. Note these features and their depths or frequency of occurrence.

4. Examine in detail the soil within the obvious layers or horizons to ensure that they are more-or-less homogeneous with depth. If some are not, identify a boundary that best separates the initially-observed layer into two distinct layers.

5. Mark the layers or horizons to the depth of interest using nails and string, or other convenient materials.

6. Observe the soil surface, after cutting the vegetation if necessary, in an area 30 cm x 30 cm or larger adjacent to a picked wall of the pit. Record whether the surface soil appears to be sealed or loose; if loose, note the size range of fragments. Record also the width, frequency and pattern of any cracks and the frequency and sizes of tubular voids open at the surface. The approximate percentage of the area occupied by tubular voids can be estimated by referring to Fig.1.

7. Describe each horizon in sufficient detail to permit assignment of it to one of the 14 subclasses defined. This requires two steps: (i) breaking out a clod of soil approximately 10 cm x 10 cm or larger through the thickness of the horizon, applying force with the hands to determine whether and how readily it separates along surfaces of weakness into peds and noting the distinctness, size and shape of peds, and (ii) cutting laterally through approximately the middle of the horizon, cleaning the surface, and estimating the area of tubular voids using Fig.1. Assign each horizon to a structure subclass.

8. Review the overall structure of the soil in relation to the notes recorded and the subclass assigned and correct any discrepancies.

9. Estimate for each horizon or layer properties such as vertical and horizontal K_{sat}, air porosity, etc. required in the plan according to the guidelines given previously. Hand texturing is a prerequisite to estimates of most other properties.

10. Assess the overall properties of the sequence of horizons or layers in the sample of the pedon examined in relation to the purposes of the work. For example, if the aim is to estimate the capacity of the soil to store water available to a particular crop, and if the roots of that crop stop at a compact layer at a depth of 20 cm, the available water capacity of only the 0-20 cm layer should be estimated.

Detailed System

The steps listed may be used at a particular site selected according to the guidelines stated. To achieve the purposes of the work it may be necessary to describe one or several pedons.

1. Dig a pit to a depth 20 or 30 cm below the deepest horizon to be described. The control section upon which classification of mineral soils is based in Canada extends to a depth of 2 m or less depending on the depth of the solum (Canada Soil Survey Committee, 1978). Thus, for detailed descriptions of pedons sampled to characterize soils in map units, soil pits may have to be dug to a depth of approximately 225 cm. In such cases, it is necessary to consider the stability of the material and to take precautions to avoid cave-in of the soil and premature burial of the pedologist. For some purposes, it is desirable to describe the soil at depths of several meters. If deep road-cuts or stream banks are not available, coring equipment may be used, if available, to obtain relatively undisturbed samples. The lateral dimensions of an adequate pit depend on several factors. If the pedon has cyclic horizonation, the length of the trench should exceed half the cycle as a minimum. If the pit is approximately 2 m deep, its length should be 2 m or more and the width approximately 70 cm to allow room for digging and sampling. Machine digging is necessary for adequate pits in stony or compacted deep soils.

2. Pick one or more faces of the pit exposed to the light as described for the 'simple system' so as to expose soil structure. While picking, note vertical cracks, distinct peds, layers of different texture or composition and other major morphological features.

3. Examine in detail the obvious layers or horizons to ensure that they are reasonably homogeneous with depth; if not, decide on the required boundaries. Mark the layers or horizons as described for the simple system.

4. Observe the soil surface adjacent to a picked wall of the pit as indicated for the simple system. The area observed should be at least 30 cm by 30 cm and at least twice the width of any polygons separated by major cracks. Note the width, pattern and continuity of any cracks, the sizes and frequencies of any tubular voids, (use Fig.1), the coherence of the surface material (if it is loose, note the sizes and shapes of fragments), and the roughness of the surface. If it is not clear whether cracks, tubular voids or other macrovoids penetrate well into the soil, pour a 0.1% methylene blue solution into the void (or into a metal frame 10 x 10 cm or so driven into the surface) and excavate the soil carefully so as to observe blue-dyed walls of voids.

5. Study pedality, if any, of the top horizon, first by observing shapes and sizes of peds and of any visible planar voids between them in the picked wall of the pit. Then break

out a large clod as described for the simple system and apply force with the hands to pull the clod apart. Note the force required to break the clod and the sizes and shapes of peds or fragments that are separated. If the clod breaks readily and almost entirely into units of similar sizes and shapes, they are probably peds, and the distinctness of pedality is strong. Examine several possible peds as follows: i) Apply gentle force to see if the peds separate into smaller peds; if so note their sizes and shapes, and check to see if they divide still further along apparent natural planes of weakness, ii) Break several apparent peds and observe the freshly-broken surface and the apparently natural surface of the ped. Usually, natural surfaces are different from broken surfaces in color, apparent smoothness or other properties. After thorough examination, describe voids and peds according to the detailed semi-quantitative system outlined.

It is important to describe compound peds using the convention that the largest peds are primary peds that part successively into secondary, tertiary, etc. peds. The consistence of peds and the relative wetness of the soil when it is described should be noted: wet (>-1 kPa), very moist (-1 to -30 kPa); moist (-30 to -1500 kPa); dry (<-1500 kPa). Ideally, water content can be measured directly using TDR (Topp *et al.* 1984). The horizon may disintegrate readily into aggregates or primary particles 0.5 mm or less in diameter. In such cases, it may be impossible to determine in the field whether the small units are peds or fragments and the soil should be described as apedal. Descriptions of the consistence of such a horizon (very friable or friable) and estimates of its porosity and bulk density would indicate its good physical condition for plant growth. The notion that apedal (or structureless) soils are poor soils leads some pedologists to assign granular structure to friable horizons in which peds can not be seen.

6. Proceed systematically downward observing both the vertical section and a horizontal section cut through the middle of each horizon and also clods isolated from the wall of the pit. Record the information on voids and peds, if any. Note also the degree of continuity of voids from the horizon above. Observation of rooting patterns may be useful in detecting the pattern and continuity of voids especially in horizons of firm consistence. Record consistence of peds, if any, and estimate properties associated with structure such as K_{sat}, air porosity, etc. as required, according to the guidelines.

7. Assess the entire structure profile noting the continuity of macro-voids, the degree to which peds, if any, are aligned or offset, the pattern of roots and the occurrence of any discontinuities or compact layers they may indicate. Check the semi-quantitative assessment of structure of each horizon, and the estimates of related properties in the light of this overview. Reexamine horizons and modify descriptions if necessary.

8. Ensure that the description is clearly recorded in a format that will be comprehensible

years later. Coding forms currently in use are not suitable. For example, the CanSIS forms allow for description of only one kind of void and one kind of ped per horizon. Suitable forms could be developed if this descriptive system is refined and accepted for general use.

EXAMPLES OF INTERPRETATIONS BASED ON MACROSTRUCTURE

Assessing the Influence of Land Use on Soil Physical Condition

Soil structure degradation associated in some cases with poor growth of corn *(Zea mays*, L.) is a matter of concern on clay soils in the Great Lakes-St. Lawrence Lowlands. The extent of degradation has been assessed by a wide range of methods some of which are time-consuming (Coote and Ramsay, 1983). Wang *et al.* (1985a) tested the hypothesis that differences in structure associated with degrees of compaction by heavy machinery or with other factors could be seen and that they would be related to K_{sat} (vertical) values of the affected horizons. Preliminary work showed that the most severely affected horizon was the lower part of the Ap (approximately 10-25 cm) and, in some cases to a lesser degree, the underlying B horizon to a depth of 40 cm or so. Structure of these horizons was assessed rapidly more-or-less according to the simple system outlined here and vertical K_{sat} was estimated according to the guidelines at several points along transects through adjacent fields of corn and hay. The soil in all cases was an Orthic Humic Gleysol of clay loam to heavy clay surface texture. Fields were selected to include those used for corn for periods ranging from one to more than 15 years consecutively, and others in hay for various periods.

Macrostructure of the Ap2 horizons ranged from subclass IB in some of the long-term cornfields to VIIB in some hayfields. Associated estimates of K_{sat} class ranged from L2 to H2 respectively. Measurements of K_{sat} with an air-entry permeameter at approximately ¼ of the points described indicated that the K_{sat} class of the Ap2 horizon was estimated correctly in more than half of 33 cases and within one of the measured class in all bu one case. Macrostructure of the Ap2 horizon and the associated K_{sat} estimates were variable within cornfields. For example, in one of the worst fields, macrostructure of the Ap2 ranged from IB to VA and the associated K_{sat} estimates ranged from L2 to M3.

The corn crop was obviously affected by soil structure. In a new field (first year after hay), the roots were abundant in the uppermost 40 cm or so of soil and growth was even and excellent. In the worst long-term corn fields, on the other hand, roots turned laterally at the top of the Ap2 horizon and some of them proceeded downward through cracks. Above ground growth was patchy and poor with common bare patches associated apparently with ponding of water.

Observation of macrostructure requiring approximately 10 minutes at a site and an hour or two in a field was adequate to assess the extent of influence of land use on soil physical condition. Such an assessment by means of field measurements of penetration resistance, oxygen diffusion rate, etc. accompanied by sampling in order to measure bulk density, water retention, etc. would require at least ten times the person hours. Though "quantitative" data are desirable, the latter type of assessment of structure degradation is feasible only at a few research sites. Furthermore, estimates of K_{sat} (K_v and K_h), bulk density, etc. can be expressed semi-quantitatively and subjected to statistical manipulations. It is important to bear in mind the fact that the so-called "hard" data of measurement of properties such as bulk density are estimates based on many assumptions, one of which is that the core samples are truly undisturbed.

Assessing Soil Air-Water Properties

A preliminary test of guidelines similar to those put forward in this report showed a reasonable degree of success in estimating basic air-water properties of a soil from observation of macromorphology (Bullock and McKeague, 1984). The properties estimated and the degree of conformity of estimates to measured values are summarized.

K_{sat} estimates were within one class of the measured class, similar to results of a previous testing (McKeague *et al.*, 1982).

Available Water Capacity. Estimates were within 2% of the measured value (cores) except for one horizon (of 6 compared). For that horizon, the measured value was 23% and the estimate 14%.

Air Capacity. Estimates for 5 of the 7 horizons were within 3% of the measured values, which ranged from 1 to 26%. The other two were off by 6%, one being high and the other low. Further testing would be required to ensure that the measured values were superior as they were based on data for cores of only 100 cm^3.

Packing density (Hodgson, 1976) was estimated correctly for 6 of the 7 horizons. This implies reasonable estimates of bulk density and clay content as packing density is defined as bulk density ($g.cm^{-3}$) + 0.009 clay%.

These preliminary results and others since 1984 are promising enough to indicate the desirability of further checking of estimates of air water properties against measured values, and refinement of guidelines for estimates as required. It is important to keep in mind the fact that soil survey organizations differ greatly in procedures used for determining important soil parameters such as available water capacity (McKeague *et al.*, 1984). Application of British and Canadian procedures, for example, would result in estimates of 350 mm and 110 mm respectively for Piperville very fine sandy loam. The large difference is due to the difference in the retention range over which water is considered to be available (-5 to -1500 kPa, Britain; -33 to -1500 kPa, Canada). According to West German criteria, the available water capacity of the Piperville soil would be more than 350 mm because some capillary water would move from the water table to the root zone. The point is that values assigned for available water capacity, etc. based upon measured values are no better than the assumptions made. Thus even crude estimates of such properties based upon direct examination of the soil may be better than those based on measurement of properties of a few samples and application of standard criteria. This is particularly true of soils in which a compact layer near the surface prevents the penetration of roots. Measurement of water retention of cores taken to a depth of 120 cm and application of the standard assumption that roots withdraw water to a depth of 120 cm, would result in vastly overestimating the water available to plants whose roots penetrate only to a depth of 20 cm.

The above reasoning applies to the common practice in soil survey organizations of extrapolating hard data for one or two modal pedons of a series to large areas of land in which that series is dominant. This results in very poor estimates of some soil properties because land use has a major influence on properties such as air capacity and available water capacity in the upper 30 cm or so. A better approach would be to estimate these properties at the site from soil morphology. Hard data for some pedons could be extrapolated to pedons of the same series under the same land use. This would serve as a rough check on estimates based directly on morphology.

CONCLUSIONS

The essential message of this report is that useful and consistent descriptions of soil structure can be made subject to a few conditions:

1. The individual making the description must have some training in the concepts and terminology involved. This could be achieved in a course of a few days including some practical instruction in the field. Soils graduates would need only to rearrange some concepts and participate in occasional field workshops.

2. The individual making the description must have a purpose clearly in mind. The kind of description required depends upon the purpose.

3. In most cases, estimates of soil properties important to the purpose should be made on the basis of the description following available guidelines. For example, if structure is being described to aid in assessment of drainability of the soil, vertical and horizontal K_{sat} of the horizons should be estimated.

4. Estimates should be checked as often as possible by measurement. If hulk density is being estimated to assess compaction, take core or clod samples periodically, measure bulk density and check estimates. Revise guidelines if necessary.

5. Check structure descriptions and estimates based upon them by comparisons with independent descriptions and estimates of colleagues. If you do not agree, make measurements, if possible, to resolve the problem.

Increased skill in describing and assessing soil structure will result from consistent efforts to describe the soil objectively, applying guidelines to estimate soil properties relevant to the purpose, checking estimates by direct measurements, or by keeping records of soil performance, and improving guidelines for estimates based on experience and testing. The fact must be recognized that there is no other practical route toward making useful assessments of soil properties in relation to potential for various uses of land in a vast country such as Canada. Even if all soils specialists in the country worked full time for the next century in measuring bulk density, air capacity, available water capacity, K_{sat}, etc. of pedons representing soil series under different systems of land use, there would be an inadequate hard data base to permit reliable extrapolation to soils of all areas. The only practical approach is to estimate soil properties from morphology, to check estimates by careful measurements at a few sites, and to improve guidelines for estimates.

For experienced pedologists, another basic message is that porosity is at least as important a part of soil structure as pedality. We have been trained to describe peds but not voids. It requires some effort to focus on macrovoids in describing soil structure. In swelling soils, of course, the width of major planar voids at the time of description will depend on the state of wetness of the soil. Useful information on shrinkage can be derived from measuring the widths and frequencies of planar macrovoids, and the water content in each horizon. Potentially, planar void width can be estimated at other water contents. Tubular voids are less influenced by shrinking and swelling.

The systems outlined for describing macrostructure and the guidelines suggested for estimating properties such as K_{sat}, available water capacity, etc. are intended as points of departure on a route toward improved systems and guidelines. We hope that this bulletin will stimulate many pedologists and users of soil to look again at soil structure, try the suggestions here and propose improvements in them.

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REFERENCES

Brewer, R. 1964. Fabric and Mineral analysis of soils. Wiley. 470 pp.

Bullock, P. and McKeague, J.A. 1984. Estimating air-water properties of a clay soil. In Comptes Rendu du Collogue, Fonctionnement Hydrique Comportement des Sols. AFES, 4 rue Redon, 78370 Plaisir, France.

Canada Soil Survey Committee. 1978. The Canadian system of soil classification. Can. Dep. Agric. Publ. 1946, Supply and Services, Canada, Ottawa.

Coote, D.R. and Ramsey, J.F. 1983. Quantification of the effects of over 35 years of intensive cultivation on four soils. Can. J. Soil Sci. 63:1-14.

Day, J.H. (Editor). 1983. Manual for describing soils in the field. LRRI 82-52. Agr. Can. Ottawa.

DeJong, R., Campbell C.A. and Nicholaichuk W. 1983. Water retention equations and their relationship to soil organic matter and particle size distribution for disturbed samples. Can. J. Soil Sci. 63:291-302.

Hall, D.G.M., Reeve, J.J., Thomasson, A.J. and Wright, V.F. 1977. Water retention, porosity and density of field soils. Soil Survey Technical Monograph No. 9. Harpenden, England.

Hodgson, J.M. ed. 1976. Soil survey field handbook. Tech. Monograph No. 5. Soil Survey of England and Wales. Harpenden.

Joel, A.H., Mitchell, J., Edmunds, F.H. and Moss H.C. 1936. Soil survey of Saskatchewan. Soil Survey Rept. No. 10, Univ. of Saskatchewan, Saskatoon.

Johnson, W.M., McClelland, J.E., McCaleb, S.B., Ulrich, R., Harper, W.G. and Hutchings, T.B. 1960. Classification and description of soil pores. Soil Sci. 89, 319-321.

Jongerius, A. 1959. The morphological soil structure classification of the Dutch soil survey institute. Rijksfaculteit Landbouw Wetenschappen Mededelingen, 24:206-213.

Kellogg, C.E. 1937. Soil survey manual. U.S.D.A. Misc. Publ. No. 274, Washington, D.C.

McKeague, J.A., Eilers, R.G., Thomasson, A.J., Reeve, M.J., Bouma, J., Grossman, R.B., Favrot, J.C., Renger, M. and Strebel, O., 1984. Tentative assessment of soil survey approaches to the characterization and interpretation of air-water properties of soils. Geoderma 34: 69-100.

McKeague, J.A. and Topp, G.C. 1986. Pitfalls in interpretation of soil drainage from soil survey information. Can. J. Soil Sci. (in press).

McKeague, J.A. and Wang C. 1982. Soil structure: concepts, description and interpretation. LRRI 82-15. Agr. Can., Ottawa (out of print).

McKeague, J.A., Wang, C. and Topp, G.C. 1982. Estimating saturated hydraulic conductivity from soil morphology. Soil Sci. Sec. Am. J. 46: 1239-1244.

Peerlkamp, P.K. 1959. A visual method of soil structure evaluation. Rijksfaculteit Landbouw Wetenschappen Mededelingen, 24:216-221.

Soane, B.D., Dickson, J.W. and Campbell, D.J. 1982. Compaction by agricultural vehicle: A review III. Incidence and control of compaction in crop production. Soil and Tillage Research 2:3-36.

Soil Survey Staff, 1951. Soil survey manual. U.S.D.A. Handbook No. 18.

Soil Survey Staff, 1981 draft. Revised U.S. Soil survey manual draft. U.S.D.A. Washington, D.C.

Topp, G.C. and Binns, M.R. 1976. Field measurement of hydraulic conductivity with a modified air-entry permeameter. Can. J. Soil Sci. 56:139-147.

Topp, G.C. Davis, J.L., Bailey, W.G. and Zebchuk, W.D. 1984. The measurement of soil water content using a portable TDR hand probe. Can. J. Soil Sci. 64:313-321.

Topp, G.C. and Sattlecker S., 1983. A rapid measurement of horizontal and vertical components of saturated hydraulic conductivity. Can. Agri. Eng. 25:193-197.

Topp, G.C., Zebchuk, W.D. and Dumanski, J. 1980. The variation of *in situ* measured soil water properties within soil map units. Can. J. Soil Sci. 60, 497-510.

Wang, C. 1982. Application of transect method to soil survey problems. LRRI 82-02. Agr. Can. Ottawa.

Wang, C., McKeague, J.A. and Switzer-Howse, K.D. 1985a. Saturated hydraulic conductivity as an indicator of structural degradation in clayey soils of the Ottawa area, Canada. Soil Tillage Res. 5:19-31.

Wang, C., McKeague, J.A. and Topp, G.C. 1985b. Comparison of estimated and measured horizontal K_{sat} values. Can. J. Soil Sci. 65 (in press).

Wyatt, F.A., Bowser, W.E. and Odynsky, W., 1939. Soil survey of Lethbridge and Pincher Creek sheets. Bull. No. 32, Univ. of Alberta, College of Agriculture, Edmonton