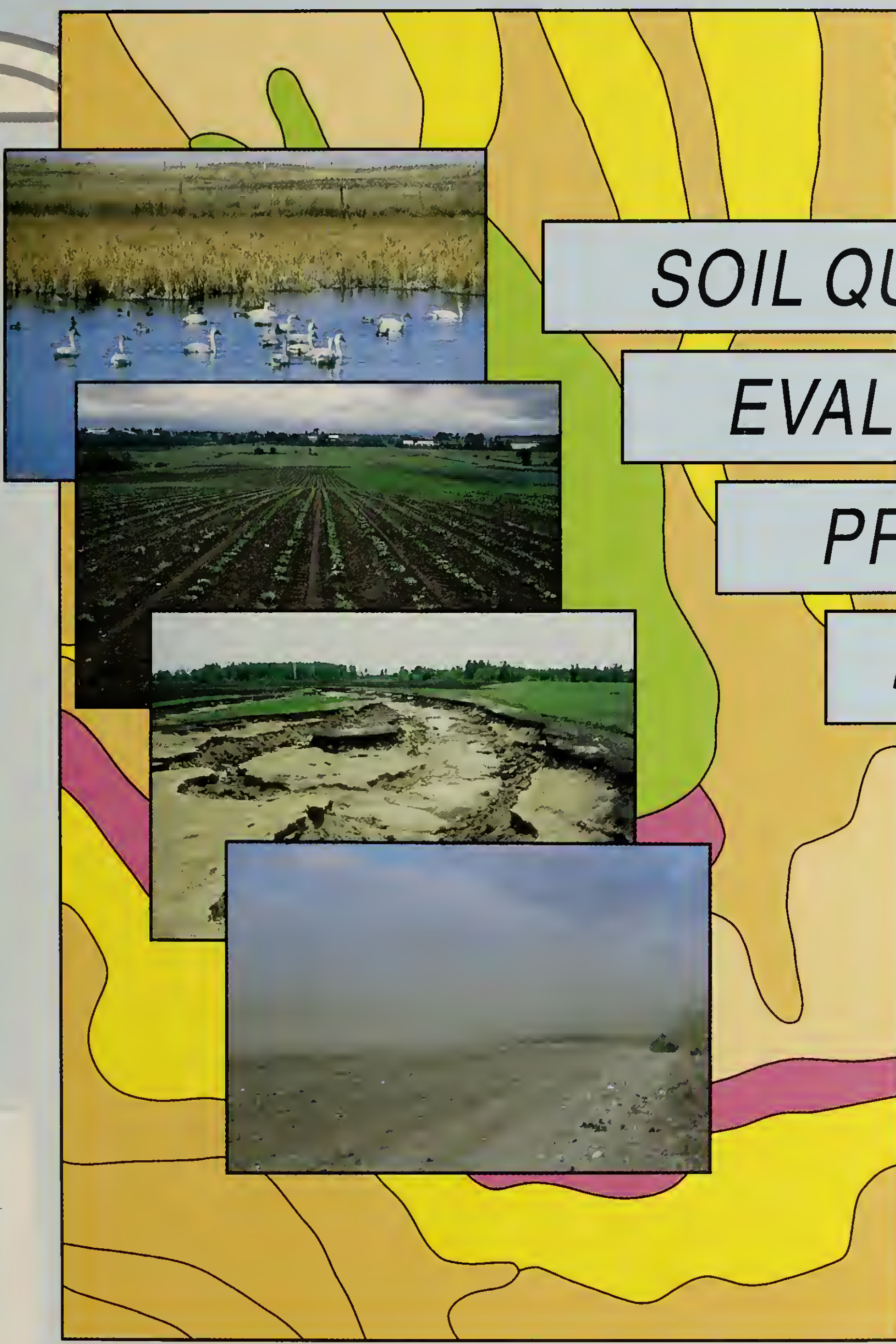
THE NON-LIMITING WATER RANGE (NLWR): AN APPROACH for ASSESSING SOIL STRUCTURE



SOIL QUALITY EVALUATION PROGRAM

Report 2

for a sustainable agriculture
pour une agriculture durable

Agriculture Canada

Research Branch
Direction générale de la recherche

Canada

Non-limiting water range (NLWR): an approach for assessing soil structure

Soil quality evaluation program
technical report 2

G.C. Topp, Y.T. Galganov,
K.C. Wires and J.L.B. Culley

Land Resource Division,
Centre for Land and Biological Resources Research,
Agriculture and Agri-Food Canada,
Research Branch, Ottawa

Funding for this program was provided
through the National Soil Conservation Program,
under Federal-Provincial Agreements on Soil and Water
Conservation and Development in Alberta, Saskatchewan,
Manitoba, Ontario, New Brunswick, Nova Scotia
and Prince Edward Island.

Research Branch
Agriculture and Agri-Food Canada
1994

This publication may be cited as G.C. Topp, Y.T. Galganov, K.C. Wires and J.L.B. Culley. 1994. Non-limiting water range (NLWR): an approach for assessing soil structure. Soil Quality Evaluation Program Technical Report 2. Centre for Land and Biological Resources Research, Agriculture and Agri-Food Canada, Ottawa, ON. 36 pp.

Centre for Land and Biological Resources Research Contribution No. 94-41

Copies of this publication are available from:

Centre for Land and Biological Resources Research
Research Branch
Agriculture and Agri-Food Canada
OTTAWA, ON K1A 0C6

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The Non-Limiting Water Range (NLWR) has been measured for eight Canadian soils using a combination of both field and laboratory methods. Infiltration and redistribution in the field, monitored with TDR and tensiometers, gave the upper part of the desorption curve. A friction sleeve penetrometer determined cone resistance of soil cores equilibrated to matric potentials between 0 and -1500 kPa. The intent was to assess the NLWR as an indicator of soil physical quality. When viewed relative to available water capacity, the NLWR was found to indicate trends in soil physical condition showing that long term or intense cultivation regimes have contributed to a decline in soil structural quality. Over 90% of the soil horizons tested developed > 2 MPa penetrometer resistance above matric potentials of -1500 kPa. Less than 50% of the horizons showed inadequate aeration porosity. Many field crops were able to extract water to well below the water content having 2 MPa penetration resistance. In some cases the crops extracted water to below -1500 kPa. NLWR values were reported from cores only as there were some instances of unexplained discrepancies between field and laboratory water content measurements at -10 kPa. The NLWR is a useful integrator parameter and its wide-spread use will depend both on additional assessments of the limiting values for both aeration and soil strength in relation to plant response and also on being able to estimate the NLWR limits from other more readily available soil parameters.

INTRODUCTION

Soil physical quality affects the soil's ability to function for the production of food and fibre, and also as a porous medium for the partitioning of water and gaseous exchange and for environmental buffering. This report considers the physical conditions within the upper plant root zone or solum. This knowingly excludes those very important physical conditions at the immediate soil surface. Soil surface phenomena are extremely important to the functioning of the processes within the solum but there are other studies, such as those dealing with wind and water erosion which address some of the effects of soil physical conditions at the soil surface. No other study in this soil quality evaluation program has addressed the physical conditions within the solum. Thus the focus in this study has been the rooting zone conditions. This study was addressed in two components. "Soil compaction susceptibility and compaction risk assessment for corn production in the Regional Municipality of Haldimand-Norfolk" by McBride et al. (1993) addresses the soil degradation conditions associated with compaction both from pedogenic and anthropogenic causes. The current report identifies soil physical conditions which limit availability of water and/or air and root growth within the soil.

This research was aimed at developing or adapting procedures to assess selected aspects of the structural condition of agricultural soils. The suitability of physical rooting conditions in a soil is a function of complex interactions involving soil strength and the supply of air and water to plant roots. An attempt has been made to integrate these complex interactions into a single parameter, the Non-Limiting Water Range (NLWR) (Letey, 1985). Between the soil-water content boundaries defining the NLWR is included those water contents where the efficacy of the plant root system to extract water is not limited by; (1) a lack of aeration for root respiration, (2) excessive mechanical resistance to root growth, or (3) water too tightly sorbed by the soil matrix. Methods are described which were used to determine the NLWR for the upper profile of soils from various locations across Canada. The results of using these methods on a variety of soils, each subjected to varying levels of intensity of cultivation and management, serve to illustrate the potentials and the limitations of the NLWR parameter as an indicator of soil structural quality. To take account of differences from soil to soil the NLWR was compared to the conventional available water capacity (AWC) of the same soil. Some limitations of the NLWR concept have been identified at both ends of the water availability range. The soil strength or 2 MPa penetration resistance was chosen as the limit which restricts root elongation and the uptake of water. Setting a limit for water uptake in relation to root elongation implies the assumption that soil that is dry enough to restrict root growth also will not allow enough water to move in the soil to meet growth requirements. Penetration resistance was the factor which most often reduced the NLWR relative to the available water capacity for these soils. The conditions where the aeration was the limiting factor was observed for only about 25% of the cases studied. There are some conditions where 10% air-filled porosity may not be sufficient for adequate aeration.

The NLWR is a soil parameter based on static measurements. It is, however, aimed at integrating a number of dynamic processes in order to get a single parameter for assessing the limitations which soil conditions inflict on plant growth. There are many hazards involved in reducing a number of complex interactions to a single parameter. Thus much attention must be given to the selection and testing of the limits for the NLWR and this report identifies where some of this attention should be directed. The time frames influencing soil water content can change in a few hours or gradually over days. NLWR assessments are made on the shorter time scale whereas the net effect on plant growth or crop yield takes effect only over several months. Thus one must be careful drawing conclusions about assessing the performance of a static parameter in relation to processes which operate on separate time scales. Even with these limitations, however, NLWR provides a means of identifying the influence some agricultural soil management systems have on soil physical quality. Ranking soil management systems, by their influence, allows the opportunity to identify options for mitigating physical degradation of the soil.

Very little is known in absolute terms about Non-Limiting Water Range or other aspects of the physical quality of agricultural soils in Canada. Most commonly soil compaction is associated with soil physical degradation (Science Council of Canada, 1986). Soil compaction would have the effect of narrowing the NLWR by reducing the plant-available water from the soil, by increasing the water content at which the limiting threshold penetration resistance is reached, and by decreasing the macro- or aeration porosity. It has been estimated that 50 to 70 percent of the fine-textured soils of southwestern Ontario have been adversely affected by soil compaction, with 3/4 of this affected land area rated as moderately compacted and 1/4 as severely compacted (Can-Ag Enterprises, 1988). The crop yield reduction of 10% attributed to soil compaction in central Canada costs over $120 million annually (Science Council of Canada, 1986).

In view of this deficiency in basic knowledge of soil physical quality, the following broad objectives were adopted for this study:

- To develop procedures to measure aspects of the soil physical quality of agricultural soils and the current state of these physical qualities.

- To assess the influence of current agricultural land management practices (traffic, tillage and cropping patterns) on these physical qualities.

On the basis of these general objectives an advisory committee was assembled to develop more specific experimental protocols which could be adopted for the project. The result was the two-pronged approach, involving; (a) the soil compaction susceptibility and soil compaction risk study reported earlier by McBride et al. (1993) and (b) development of ways to measure and assess the NLWR as a parameter/indicator of soil structural quality. This report presents the degree of achievement of the objectives for the NLWR.

MEASUREMENTS FOR THE DETERMINATION OF NON-LIMITING WATER RANGE (NLWR)

The determination of NLWR of the soil included both field and laboratory measurement. The upper part of the soil-water desorption curve was determined from field measurements and the full range to -1500 kPa was measured in the laboratory on intact soil cores. The limiting conditions for aeration were estimated from the shape of the upper part of the desorption curve from both the field and laboratory measurements over the range 0 to -10 kPa. The strength of the soil at specific matric potentials was measured as a penetrometer resistance in the soil cores. The data were assembled as profiles of water content as a function of depth at the various thresholds or limits chosen for consideration. Details of each measurement and analysis phase are presented in more detail below.

The Soil Sites and Treatments

The sites at which measurements were made were chosen on the basis that they were already well-documented research or farm sites on which there was additional information on the performance of the soils for crop production. We also attempted to investigate a wide range of cultivation practices and history in order to assess, in some sense, the sensitivity of the NLWR to differing cultivation and management practices. A total of eight locations reflecting different climatic regions across Canada were chosen for this study, as described briefly in Table 1. It was not possible to standardize the treatments as other on-going research would have been disrupted and the time required to establish plot treatments would have been longer than the duration of this project.

Infiltration of Water in the Field

In general, three infiltration rings were installed as replicates in each field treatment/management system. The replicates were separated from each other by approximately 4 m. Following completion of the field tests, intact soil cores were taken from the same pedon at depths 10, 20 and 30 cm for laboratory analysis. The exception was the grassed site at Clinton where it was found that the A horizon extended to below 25 cm and that the normal pedological sequence of horizons may have been disturbed.

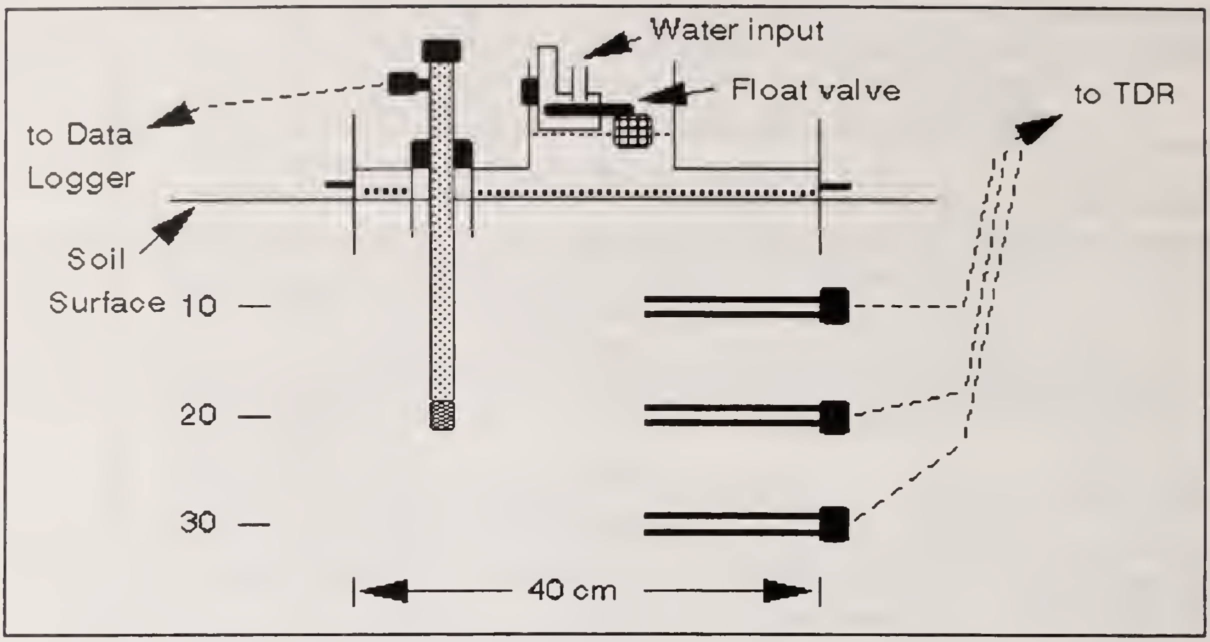
The soil was initially wetted to a condition of field-saturation by infiltration into a 40 cm diameter cylinder from an applied head of 10 cm until increases in water content and potential were no longer recorded at the 30 cm depth Fig. 1. The infiltration cylinder was constructed from 26 gauge (1 mm) cold-rolled steel. At 5 cm from the bottom a 1.2 cm cross-section ring was welded on the inside of the infiltration cylinder to provided a sealing bead at the soil surface when the cylinder was driven to the 5 cm depth. The ring serving as this sealing bead was made from "half-round" steel rod rolled into a 40 cm diameter ring with the flat side of the "half-round" as the outer side of the ring to be welded inside the cylinder. To distribute the infiltrating water and dissipate its erosive energy, a perforated metal sheet with 1.5 mm holes giving approximately 30% opening/70% coverage was suspended 5 mm above the soil surface . The infiltration ring was capped 5 mm above the water distribution plate by a sheet of the 26 gauge (1 mm) steel. A rectangular chamber 10 x 20 cm was attached in the central area of the infiltration ring where removal of the bottom provided the region for input of water for infiltration. The height of the chamber was chosen to allow the application of the infiltration head, which in our case was 10 cm. The level of the water was controlled by float valve as is used for control on livestock watering troughs. The supply of water to the float valve was from a 20 litre bottle whose weight was being recorded by a digital bathroom scale connected to a 21X data-logger (Campbell Scientific) giving a continuous record of the infiltration rate.

Tensiometry and TDR Measurement of Water Content

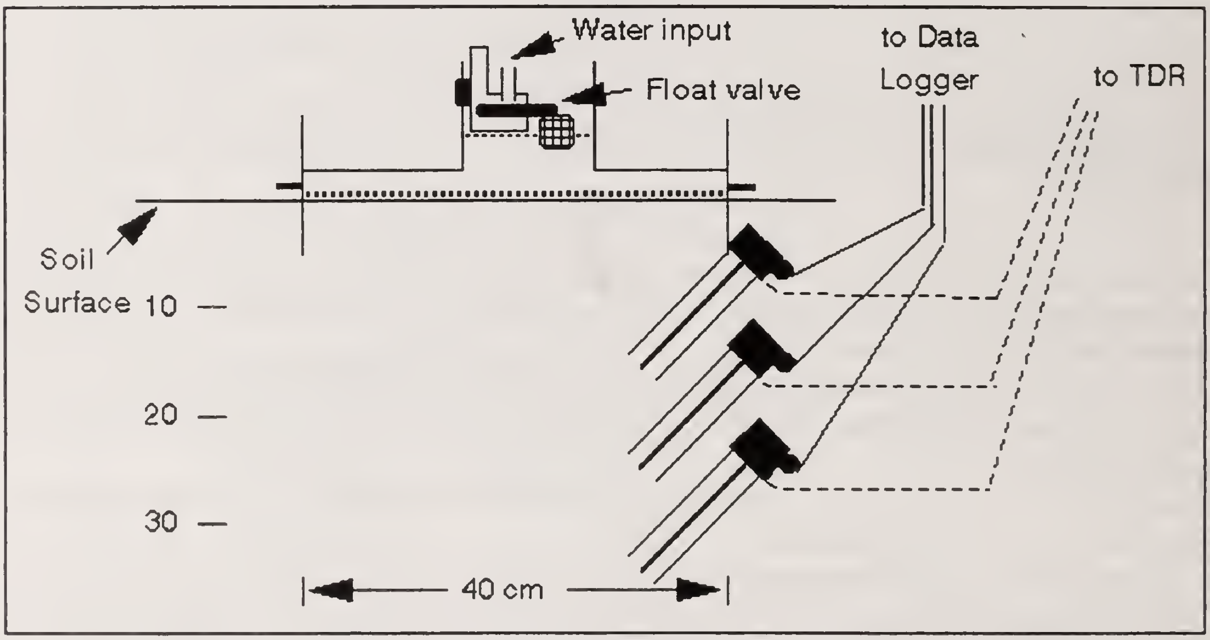
In the field the upper part of the soil water desorption curve was measured at depths of 10, 20 and 30 cm using both tensiometers to record the soil matric potential and time-domain reflectometry (TDR) to determine the volumetric water content, as shown schematically in Fig. 1. The tensiometers and the TDR probes were installed before any wetting of the soil had taken place. The method of installation and type of tensiometers differed in each of the two field seasons as a result of advances in equipment design.

Table 1: Site, soil, crop, rotation and cultivation practices where Non-Limiting Water Range was determined. * indicates the time in the rotation sequence when field measurements and sampling were done.

SITE LOCATION	SOIL & TEXTURE	CROP/ROTATION	CULTIVATION
Lethbridge Res. Stn., Alta.	Lethbridge clay loam	wheat	conv. since 1912
		fallow/wheat*	conv. since 1912
		native grass	nil
Termuende Res. Stn., U. of S., near Lanigan, Sask.	Oxbow loam	wheat	conv. since 1910
		wheat	conv. since 1977
		native grass	nil
Indian Head Exp. Farm, Sask.	Indian Head heavy clay	continuous wheat	fertilized, zero-till
		fallow/wheat*/ wheat	fertilized, zero-till
		fallow/wheat*/ wheat/3-hay	non-fertilized, zero-till
Leonard Rance Farm, Brunkild, Man.	Osborne clay	wheat	conventional
		wheat	zero-till
		native grass	nil
Don Lobb Farm, Clinton, Ont. #1	Brady sandy loam	corn*/soybean	conventional
		corn*/soybean	minimum-till
Don Lobb Farm, Clinton, Ont. #2	Huron clay loam	corn*/soybean	conventional
		corn*/soybean	minimum-till
Elora, Ont.	Conestogo/ London loam	corn	conventional
		corn	minimum-till
		brome grass	hay
Harrington Farm, P.E.I.	Charlottetown sandy loam	potatoes	conventional
		potatoes	zero-till
		sod	nil



(a)



(b)

Figure 1: Schematic diagram of the field set-up for infiltration and redistribution of water, where (a) was used in 1991 and (b) in 1992.

In 1991, six ceramic tensiometer cups, 2 cm diam. by 5 cm length, with "O"-ring seals to varying length extension tubes were installed vertically within the 40 cm diameter cylinder. Pilot holes were drilled with a 1.9 cm diam. spiral wood auger bit powered by a portable electric drill. Soil in very dry and crumbly condition was prewetted with a spray bottle to prevent collapse of the pilot hole. The prewetted tensiometer was carefully pushed into the drilled pilot hole to the predetermined depth. Direct infiltration down the tensiometer tube from the soil surface was prevented by 4 cm diam. collars around each tensiometer inserted 4 cm into the soil. The tensiometer potentials were recorded from Sens-Sym pressure transducers connected to each tensiometer using a 21X data-logger (Campbell Scientific).

The measurement of the soil water content was by the method of Time Domain Reflectometry (TDR) (Topp, 1993). The probes used in 1991 were parallel pair using 150 mm long x 5 mm diameter rods at 40 mm spacing. In two diametrically opposite locations, 20 cm (W) x 30 cm (deep) x 50 cm (long) pits were excavated in the soil to allow installation of the TDR probes from the outer edge of the 40 cm diameter infiltration cylinder. The probes were inserted on a horizontal plane at depths of 10, 20 and 30 cm in each of the two pits. The probes were installed above but slightly offset from each other. During installation a plastic sheet was placed at the pit face, prior to backfilling to prevent infiltrating water from entering directly into the soil pits. The TDR measured water content was determined by visual interpretation of the TDR pulse travel time directly from the display of a model 1502C cable tester (Tektronix Inc.).

In 1992, the tensiometers were incorporated as part of the TDR probes. The difficulties arising from breakage of ceramic tensiometer cups and problems caused by leaks around the vertically-oriented tensiometers resulted in a redesign of the tensiometers. Cylindrical porous stainless steel cups (8 mm diam x 30 mm) were used for the tensiometer sensitive region of the central prong of a triple pronged TDR transmission line. A 6 cm length of rod was silver soldered to the closed end of each cup and a 10 cm length of tubing to the open end of the porous cup. This combination of rod, porous cup and tube became the body of the tensiometer and also served as the centre-rod of a 15 cm long TDR probe (Fig. 1(b)). The open end of the tensiometer tube was sealed into the base of a 7.6 cm cylindrical PVC block which served as a mount for the pressure transducer and the other parts of the TDR probe. The central cavity in the PVC block was closed by a special cap which could be removed for filling the tensiometer with water but could also be closed and sealed without introducing excessive pressure, thereby allowing the use of extremely sensitive transducers. The transducer was mounted on the side of the PVC cylinder. A metallic ring attached to the base of the PVC cylinder served for mounting the two ground prongs of the TDR probe. The electrical connection for the TDR measurement was made to the ring and the top of the tensiometer tube. The outer or ground prongs of each TDR probe were 5 mm diameter rods threaded into the metallic ring. The other end of each rod was tapered for easier insertion into the soil. The installation of these combination TDR-Tensiometer probes was made at 45°. The installation at 45° allowed measurement to be made beneath the surface of infiltration but without disturbing that surface or the infiltration. In addition, the angled installation allowed easier removal of air bubbles from the tensiometer tube. A pilot hole was drilled for the centre prong using a 6 mm drill bit and portable battery-powered drill. A sliding hammer was affixed to the TDR/tensiometer and used to insert the triple pronged probe. The pilot hole served to guide the centre prong and removed sufficient soil to prevent over consolidation in the region used for matric potential determination.

The water content was read using a model 6050XI TRASE (Soilmoisture Equipment Corp.) instrument on manual prompt after the appropriate cable connection was made. The data were stored in the TRASE instrument memory and dumped to diskette on a daily basis.

The Water Redistribution Phase and Core Sampling

After the tensiometer and TDR measurements at the 30 cm depth had reached a maximum during infiltration and were constant for 30 min, the supply of infiltration water was shut off and the water contents and tensiometer potentials were recorded periodically during the ensuing time period of 24 to 48 h. We aimed for a 48 h period of water redistribution following the cessation of infiltration. The scheduling of the experimental measurements and the occurrence of rainfall sometimes resulted in shorter redistribution periods. At the end of this redistribution time period the infiltration cylinder, the tensiometers and the TDR probes were removed carefully from the soil. Intact soil cores (7.6 cm diam. by 7.6 cm high) were taken vertically at 10, 20 and 30 cm depths from soil which had been wetted during the infiltration but which was not disturbed by the TDR or tensiometer probes. The cores were sealed in plastic bags for transport to the laboratory.

Friction Sleeve Penetration and Soil-Water Desorption from Cores

In the laboratory the soil-water desorption curves were measured according to the procedure described by Topp et al. (1993). This procedure included saturation of the cores by immersion in water for one day followed by desorption on glass bead and aluminum oxide tension media to give the upper portion of the desorption curve (0 to -33 kPa). The lower part of the curve was determined with a pressure plate apparatus using the intact cores. The seven selected matric potentials were -0.35, -6, -10, -33, -100, -400, -1500 kPa. When the soil had reached equilibrium at each of the potentials the penetrometer resistance was measured in each core using the friction sleeve penetrometer as described by Bradford (1986). Fig. 2 shows a schematic representation of this procedure where the shaft behind the penetrometer tip contacts a load cell whose output voltage was recorded using a 21X data-logger (Campbell Scientific). The shaft of the penetrometer was free to move within a sleeve tubing attached to the frame which moved downward at the rate of 20 mm/min to engage the penetrometer tip with the soil. The penetrometer tip was a 60° cone of diameter 3.6 mm. A vertical displacement transducer connected also to the data-logger recorded the depth of the penetrometer within the soil. Depth and load cell readings were taken after each mm displacement. A total of 14 penetrations were made within each core, duplicates at each of the 7 matric potentials. The first 7 penetrations were made over the top 30 mm depth. One such measurement was made in the centre of the core and the remaining 6 were half way between the centre and edge of the core (19 mm from centre) and every 60° around. The remaining 7 penetrations were measured similarly from 30 to 60 mm deep, except that the core was rotated 30° to give an offset from the earlier holes from previous penetrations. This allowed each penetration to be separated from a neighbouring penetration or the cylinder wall by 19 mm in the horizontal direction. From a series of trial measurements at lateral separations of 1 cm from each other, the interference of adjacent readings could not be separated from variability of the penetrometer resistance values. Thus it was assumed without additional evaluation that a separation of 19 mm was sufficient to minimize lateral interferences. This separation is not as high as the criterion recommended by Bradford (1986).

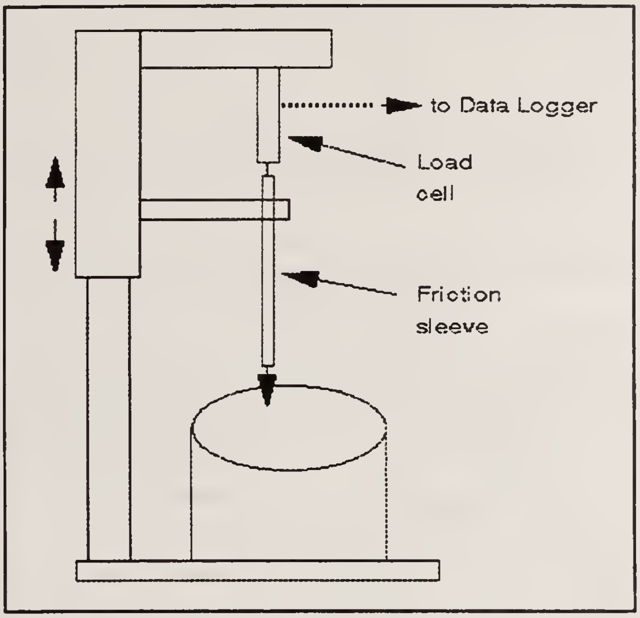
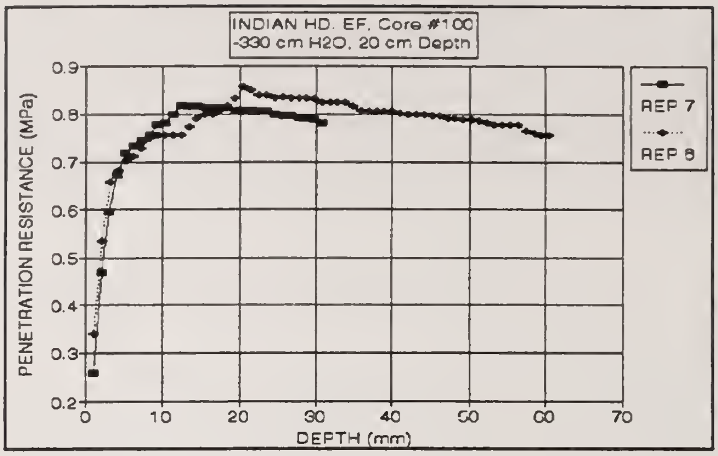


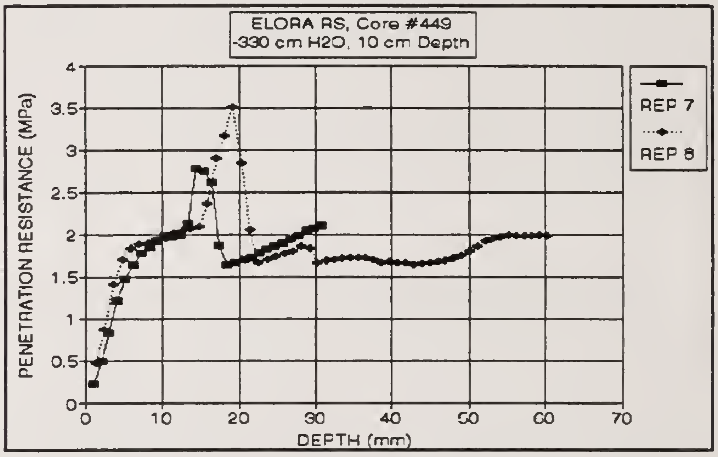
Figure 2: The friction sleeve penetrometer, shown schematically, for measurement of penetration resistance in soil cores. The load cell and LVD transducers were read by a 21X datalogger (Campbell Scientific) to record penetration resistance as a function of depth.

The penetrometer resistance values were plotted as a function of depth (Fig. 3). A "representative" value was visually approximated from the measurements recorded over the depth of 10 to 30 mm or 40 to 60 mm as shown in Fig. 3. It is worth noting from Fig. 3 that at least 10 mm penetration was required to establish a pattern for the resistance profile. The "representative" value was chosen to give or represent the penetration resistance of the core at the given matric potential. Some judgement was required to exclude non-representative penetration values caused by such factors as disturbance at the soil surface, stones, cracks, worm holes, etc. Examples of more difficult patterns are given as Figs 3(b) and 3(c). After all penetrometer measurements were completed at -1500 kPa the volume of the soil at this matric potential was estimated by recording the volume of glass spheres (100 μm diam.), having a known packing density, required to fill the spaces around the soil in the cylinder. Then the soil was oven dried at 105°C and weighed for determination of the bulk density as originally sampled and at -1500 kPa.

(a)



(b)



(c)

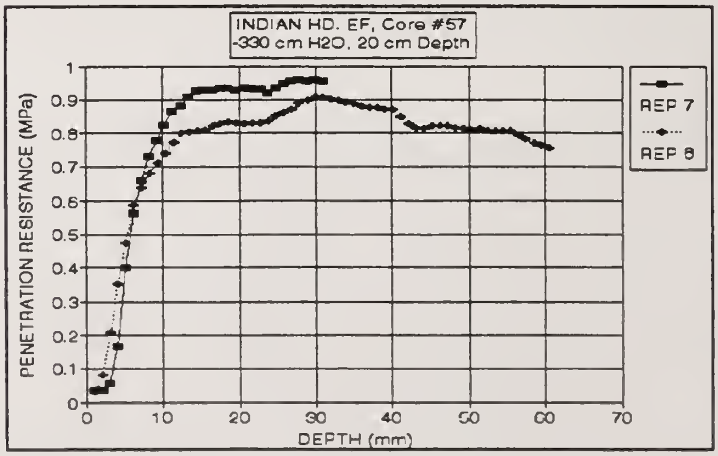


Figure 3: Examples of penetration resistance in soil cores, plotted as a function of depth.

Data Handling and Analyses

A comparison between field and laboratory desorption data was desired to ascertain the validity of using laboratory data to represent field conditions. The laboratory measurements included only desorption so that comparison with the field data were with those from the water redistribution or desorption phase after the infiltration ceased. The tensiometer data retrieved from the data-logger files were only those that were simultaneous with the measurement of the TDR water content data. The combination of the selected tensiometer data and the corresponding TDR data were used to plot soil water desorption curves from the field measurements. The times of measurement for each replicate were not coincident and at some times the tensiometer readings were changing quite rapidly. Thus we decided to use time running averages where the number of data points in the average was equal to the number of replicates (6 in most cases). These averaged data were used for comparison with those obtained from soil cores. Data were rejected where anomalies were identified, such as, tensiometer leakage, non-wetting or lack of response from tensiometers. Few of the TDR data were identified as anomalous.

In the laboratory, the masses of the soil cores at each of the 7 applied matric potentials were converted to volumetric water contents. The bulk density used in making the conversion from mass basis to volume basis was that measured at -1500 kPa at the end of the experiment. These data were compared with those obtained directly in the field for the range of potentials which were measured in the field experiment.

The friction sleeve penetrometer data were analyzed in a sequence of steps. Each series of penetration resistance values was plotted against depth (Fig. 3). A "representative" value was chosen for the applicable depth range. "Non-representative" values were those which were anomalously high (Fig. 3(b)) or low. Some difficulty was experienced in choosing a "representative" value in cases where the penetrometer resistances was a sloping function of depth (Fig. 3(c)). In the cases of depth-dependent penetration resistance as in Fig. 3(c) a representative value was obtained by taking a mean over the applicable depth range, i.e a single "representative" value for rep. 7 and another for rep. 8 from Fig. 3(a) and similarly for Figs 3(b) and 3(c). From this process, duplicate sets of seven penetrometer resistance values were obtained for each core.

Each set of 7 data points was plotted as a function of soil-water potential expressed as -pF and fitted by regression using a third degree polynomial (Fig. 4). This curve was used to find the potential or pF where the penetrometer resistance exceeded the limiting value selected (2 MPa for this experiment) which restricts root elongation and water uptake. The resulting pF value was then used on the desorption curve for each core to find the corresponding water content in the soil core below which the penetrometer resistance would exceed this limiting value. The 6 values (2 from each core) were averaged to give a mean value.

All resulting data were grouped by depth and means of triplicate values were taken for estimation of the various limits for NLWR determinations. The limits chosen were the water content values of cores in the following conditions:

(1) @ saturation (porosity),

(2) @ aeration limit (porosity - 0.1),
(3) @ -10 kPa,
(4) @ 2 MPa penetration resistance and
(5) @ -1500 kPa.

Means for replicates at each potential were used to calculate NLWR. The greater of (4) or (5) was subtracted from the lesser of (2) or (3) to give NLWR, as presented below. The more traditional plant available water capacity of the soil (AWC) was calculated as the difference between (3) and (5). AWC represents the upper limit for NLWR. In addition to mean values, the individual values for core and field data are presented below to illustrate specific behaviour patterns in some of the soils.

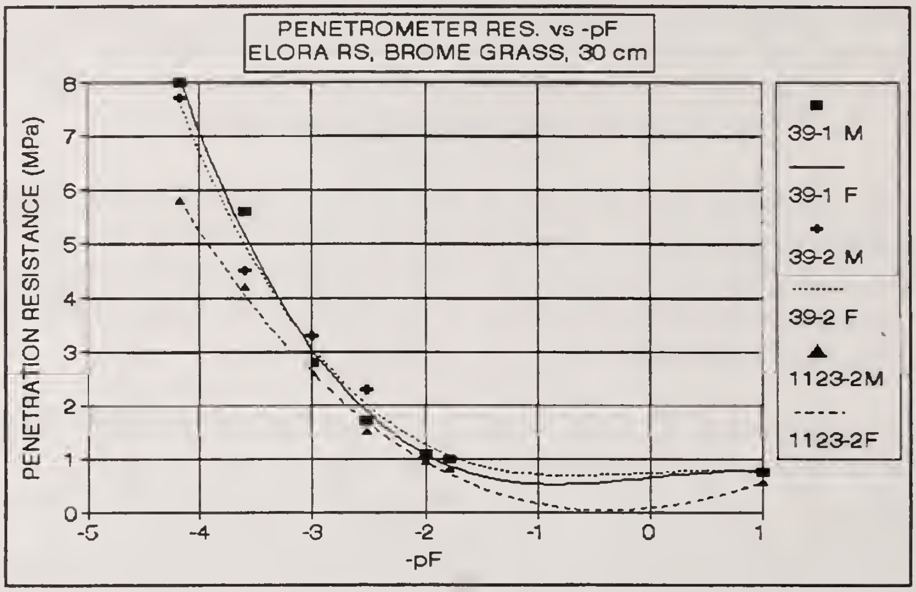


Figure 4: Penetration resistance in soil cores as a function of pF. Points are measured data and the lines are from regressions fitted to the data using a third degree polynomial.

RESULTS AND DISCUSSION

Defining the Limits for the Non-Limiting Water Range

Two factors are considered to affect the upper limit of soil-water available to growing plant roots. Under inadequate aeration, plant roots cease taking in water because of disruption of the usual biochemical processes. In soils which have very rapid internal drainage or high hydraulic conductivity, soil-water may be "lost" from access by plant roots as a result of drainage from the soil root zone under the influence of gravity. At a matric potential of -10 kPa, the hydraulic conductivity of most soils is low enough that gravity drainage is very small and the water remains available to plant roots (Cassel and Nielsen, 1986). Soil in this condition is often described as "at field capacity". Thus, we considered water retained below -10 kPa as potentially available for plant uptake (Fig. 5). At the upper end, aeration may pose a more significant limitation.

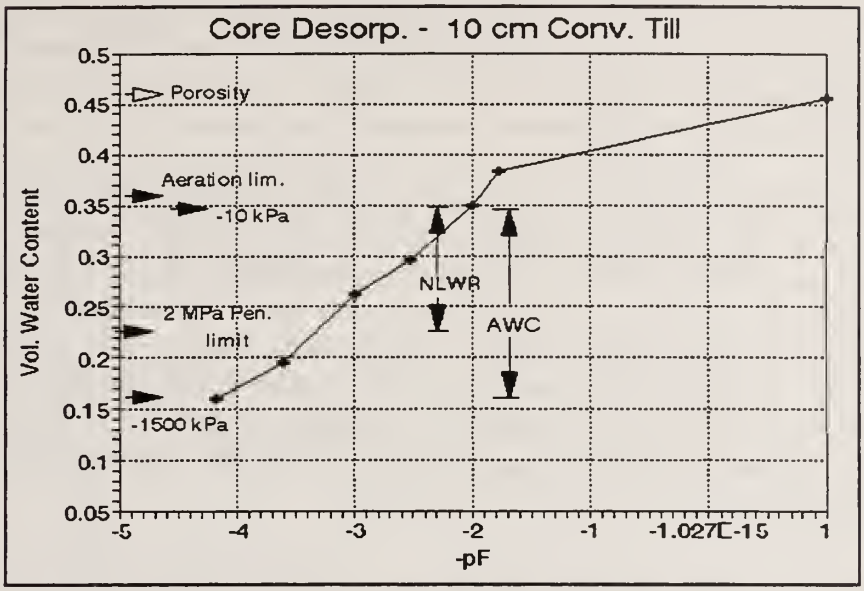


Figure 5: A desorption curve for a sandy soil showing how the limits of the Non-Limiting Water Range (NLWR) have been defined, along with the conventional AWC.

The simplest criterion for aeration status is to prescribe an aeration porosity or the fraction of the total volume that is air-filled. An aeration porosity of 0.1 has often been taken as sufficient to maintain aerobic conditions (Snyder, 1994; Glinski and Stepniewski, 1985). Lacking a practical alternative, we adopted the criterion that air-filled pore space should equal or exceed 0.1 or aeration limitations were deemed to be present in the soil. Thus, the upper limit of the NLWR was the lower water content at either -10 kPa or 0.1 air-filled porosity (Fig. 5).

The lower limit of available water is assumed to be controlled by either of two factors. The water within the soil matrix may be so tightly sorbed as to be not available rapidly enough to supply the plant requirements. This has been adopted by convention to be at -1500 kPa and often identified as the permanent wilting point. Alternatively, the availability of water from the soil matrix may be restricted when the soil becomes so hard that roots will cease to penetrate the soil matrix. Cone penetrometer resistance is used to simulate the impedance encountered by growing roots. A cone resistance of 2 MPa is recognized as the upper limit of penetration pressure exerted by roots of most field crops (Greacen, 1986). We have selected the lower limit of the NLWR as the greater of water content at -1500 kPa potential or at 2 MPa penetration resistance (Fig. 5).

Overall comparison of NLWR vs. Available Water Capacity (AWC)

Table 2 presents the water content data from which the NLWR and AWC were calculated and presented in Figs. 6 - 13. Table 3 gives a summary showing the percentage reduction in plant available water if NLWR were used in place of AWC. In almost all cases NLWR is less than the traditional AWC. For these soils, the high penetrometer resistance provides evidence that soil strength has probably restricted root growth more than has lack of aeration. Only 34% of the horizons showed inadequate aeration porosity, whereas over 90% of the horizons showed >2 MPa penetrometer resistance at potentials above -1500 kPa.

In Table 3, the cultivation treatments have been arranged from the most intensive or longer term across the top of the table to the least intensive at the bottom. Considering each soil separately, there is generally a trend toward increasing percentages or NLWR approaching the magnitude of AWC as the intensity of cultivation decreases. For examples, 66, 71, 73 for Lethbridge; 56, 80, 77 for Termuende; 39, 61, 71 for Clinton (sandy); etc. A major exception is the Charlottetown soil showing a reverse trend 52, 36, 22. Equally surprising is the Huron clay at Clinton which was measured as having no NLWR, i.e. no water is readily available to plants. This would indicate that plants are almost always at risk of experiencing some stress either from a lack of aeration or excessive soil strength.

Although intensive cultivation appears to be associated with reducing NLWR, cultivation of some soils can enhance the available water in the tilled layer as shown for the conventionally tilled sandy soils at Clinton and Charlottetown, 15 years of conventional tillage at Termuende and conventional tillage at Brunkild. By contrast, however the cultivation and associated compaction during cultivation decreased the available water in the layer immediately below the cultivation as shown particularly for the Termuende, Brunkild and sandy Clinton soils. The great improvement in NLWR at the 20 cm depth following 15 years of no till in the sandy #1 Clinton soil is attributed to earthworm activity and less compressive effects due to a reduction in agricultural equipment traffic.

A surprising finding from this study (Figs. 6-13) was how consistently was the lower limit of NLWR determined by soil strength. In only 5% of the soil layers was -1500 kPa reached before the soil strength exceeded the 2 MPa penetration limit chosen here as the limit for root growth. In general, the clayey soils from prairie Canada exhibited less strength than the coarser textured soils. In some of the sandy soils, strengths in excess of 2 MPa were measured in cores at a matric potential of -100 kPa, whereas in the clayey soils from Brunkild and Indian Head, penetration resistances >2 MPa were not measured until the soil was below -400 kPa. Thus the increase in penetration resistance during drying of the soils has resulted in a large reduction in the NLWR compared to the AWC.

Table 2: Water content values used for calculating NLWR and AWC. * indicates aeration is limiting in the layer. NLWR and AWC (in mm) is calculated as a product of the volumetric water content and the appropriate depth increment (DPH INC) in mm.

TREAT-MENT	DPH cm	DPH INC	CORE SATN	AER. LIM	2 MPa PEN LM	-1500 kPA	-10 kPa CORE	-10 kPa FIELD	NLWR mm	AWC mm	AER LIM
LETHBRIDGE, ALBERTA, Lethbridge clay loam											
CONT. WHEAT	10	150	0.396	0.296	0.224	0.188	0.299	0.252	10.8	16.7	*
	20	100	0.420	0.320	0.196	0.169	0.301	0.270	10.5	13.2	
	30	150	0.425	0.325	0.209	0.147	0.300	0.255	13.7	23.0	
Total 0-40		400							35.0	52.8	
WHEAT FALLOW	10	150	0.391	0.291	0.231	0.185	0.296	0.317	9.0	16.7	*
	20	100	0.420	0.320	0.211	0.180	0.302	0.331	9.1	12.2	
	30	150	0.411	0.311	0.185	0.164	0.291	0.308	15.9	19.1	
Total 0-40		400							34.0	47.9	
NATIVE GRASS	10	150	0.517	0.417		0.210	0.311	0.292	15.2	15.2	
	20	100	0.409	0.309	0.247	0.180	0.318	0.325	7.1	13.0	
	30	150	0.483	0.383	0.215	0.160	0.310	0.313	15.6	23.9	
Total 0-40		400							37.9	52.0	
TERMUENDE, SASKATCHEWAN, Oxbow loam											
TILLED FROM 1910	10	150	0.465	0.365	0.230	0.167	0.331	~0.22	15.2	24.6	
	20	100	0.409	0.309	0.215	0.144	0.292	0.292	7.7	14.8	
	30	150	0.420	0.320	0.205	0.137	0.284	~0.19	11.9	22.1	
Total 0-40		400							34.7	61.5	
TILLED FROM 1977	10	150	0.500	0.400	0.181	0.185	0.355	0.300	26.1	28.5	
	20	100	0.414	0.314	0.189	0.129	0.277	0.273	8.8	14.8	
	30	150	0.419	0.319	0.160	0.127	0.281	0.259	18.2	23.1	
Total 0-40		400							53.1	66.4	
NATIVE GRASS	10	150	0.483	0.383	0.211	0.179	0.348	0.315	20.6	25.4	
	20	100	0.472	0.372	0.196	0.163	0.310	~0.31	11.4	16.7	
	30	150	0.470	0.370	0.233	0.193	0.327	0.340	14.1	20.1	
Total 0-40		400							46.1	60.2	

Table 2: (cont'd.): Water content values used for calculating NLWR and AWC. * indicates aeration is limiting in the layer. NLWR and AWC (in mm) is calculated as a product of the volumetric water content and the appropriate depth increment (DPH INC) in mm.

TREAT-MENT	DPH cm	DPH INC	CORE SATN	AER. LIM	2 MPa PEN LM	-1500 kPA	-10 kPa CORE	-10 kPa FIELD	NLWR mm	AWC mm	AIR LIM
INDIAN HEAD, SASKATCHEWAN, Indian Head heavy clay											
FALLOW WHEAT WHEAT +3 HAY	10	150	0.550	0.450	0.379	0.328	0.483	0.335	10.7	23.3	*
	20	100	0.571	0.471	0.352	0.329	0.446	0.364	9.4	11.7	
	30	150	0.582	0.482	0.386	0.316	0.454	0.377	10.2	20.7	
Total 0-40		400							30.3	55.7	
CONT. WHEAT	10	150	0.667	0.567	0.390	0.363	0.522	0.358	19.8	23.9	
	20	100	0.590	0.490	0.386	0.349	0.464	0.367	9.8	11.5	
	30	150	0.549	0.449	0.332	0.331	0.427	0.360	14.3	14.4	
Total 0-40		400							43.9	49.8	
FALLOW WHEAT WHEAT	10	150	0.639	0.539	0.410	0.376	0.535	0.365	18.8	23.9	
	20	100	0.634	0.534	0.399	0.370	0.513	0.350	11.4	14.3	
	30	150	0.604	0.504	0.393	0.361	0.483	0.375	13.5	14.3	
Total 0-40		400							43.7	56.5	
BRUNKILD, MANITOBA, Osborne clay											
CONV. TILL	10	150	0.658	0.558	0.387	0.351	0.524	~0.39	20.6	26.0	
	20	100	0.609	0.509	0.410	0.383	0.532	~0.42	9.9	14.9	*
	30	150	0.602	0.502	0.363	0.355	0.530		20.9	26.3	*
Total 0-40		400							51.3	67.1	
NO TILL	10	150	0.569	0.469	0.401	0.338	0.501	0.414	10.2	24.5	*
	20	100	0.613	0.513	0.403	0.368	0.516	0.525	11.0	14.8	*
	30	150	0.603	0.503	0.378	0.372	0.523	N/A	18.8	22.7	*
Total 0-40		400							40.0	61.9	
NATIVE GRASS											
	20	100	0.634	0.534	0.341	0.329	0.479	0.386	13.8	15.0	
	30	150	0.631	0.531	0.380	0.327	0.490	0.385	16.5	24.5	
Total 0-40		400							30.3	39.5	

Table 2: (cont'd.): Water content values used for calculating NLWR and AWC. * indicates aeration is limiting in the layer. NLWR and AWC (in mm) is calculated as a product of the volumetric water content and the appropriate depth increment (DPH INC) in mm.

CLINTON, ONTARIO #1, Brady sandy loam

TREAT-MENT	DPH cm	DPH INC	CORE SATN	AER. LIM	2 MPa PEN LM	-1500 kPA	-10 kPa CORE	-10 kPa FIELD	NLWR mm	AWC mm	AER LIM
CONV. TILL	10	150	0.452	0.352	0.175	0.153	0.329		23.1	26.4	
	20	100	0.382	0.282	0.215	0.108	0.271		5.6	16.3	
	30	150	0.345	0.245	0.242	0.063	0.272		0.5	31.4	*
Total 0-40		400							29.2	74.1	
NO TILL 15 y	10	150	0.459	0.359	0.233	0.179	0.349		17.4	25.5	
	20	100	0.484	0.384		0.178	0.310		13.2	13.2	
	30	150	0.311	0.211	0.169	0.070	0.202		5.0	19.8	
Total 0-40		400							35.6	58.5	
LAWN GRASS	10	150	0.479	0.378	0.236	0.179	0.382		21.5	30.5	*
	20	100	0.499	0.399	0.253	0.211	0.396		14.3	18.5	
	30	150	0.509	0.409	0.282	0.226	0.400		17.7	26.1	
Total 0-40		400							53.5	75.1	

CLINTON, ONTARIO, #2, Huron clay loam

TREAT-MENT	DPH cm	DPH INC	CORE SATN	AER. LIM	2 MPa PEN LM	-1500 kPA	-10 kPa CORE	-10 kPa FIELD	NLWR mm	AWC mm	AER LIM
CONV. TILL	10	150	0.478	0.378	0.408	0.215	0.429	0.350	0.0	32.1	*
	20	100	0.486	0.384	0.379	0.211	0.428	0.350	0.7	21.7	*
	30	150	0.428	0.328	0.350	0.288	0.371	0.350	0.0	12.5	*
Total 0-40		400							0.7	66.3	
NO TILL 15 y	10	150	0.451	0.351	0.366	0.266	0.376	0.320	0.0	16.5	*
	20	100	0.415	0.315	0.347	0.246	0.356	0.350	0.0	11.0	*
	30	150	0.474	0.378	0.424	0.331	0.440	0.340	0.0	16.4	*
Total 0-40		400							0.0	43.9	

Table 2: (cont'd.): Water content values used for calculating NLWR and AWC. * indicates aeration is limiting in the layer. NLWR and AWC (in mm) is calculated as a product of the volumetric water content and the appropriate depth increment (DPH INC) in mm.

ELORA, ONTARIO, Conestogo/London loam

TREAT-MENT	DPH cm	DPH INC	CORE SATN	AER. LIM	2 MPa PEN LM	-1500 kPA	-10 kPa CORE	-10 kPa FIELD	NLWR mm	AWC mm	AER LIM
BROME GRASS	10	150	0.480	0.380	0.325	0.180	0.396	0.355	8.3	31.1	*
	20	100	0.492	0.392	0.313	0.175	0.375	0.325	6.2	20.0	
	30	150	0.431	0.331	0.280	0.150	0.352	0.320	7.7	30.3	*
Total 0-40		400							22.1	81.4	
CONV. TILL CORN	10	150	0.523	0.423	0.406	0.228	0.464	0.360	2.6	35.4	*
	20	100	0.517	0.417	0.380	0.224	0.425	0.365	3.7	20.1	*
	30	150	0.540	0.440	0.344	0.211	0.415	0.360	10.7	30.6	
Total 0-40		400							16.9	86.1	
MIN. TILL CORN	10	150	0.457	0.357	0.361	0.224	0.382	0.348	0.0	23.7	*
	20	100	0.462	0.362	0.310	0.228	0.366	0.345	5.2	13.7	*
	30	150	0.388	0.288	0.254	0.179	0.318	0.290	5.1	20.9	*
Total 0-40		400							10.3	58.3	

HARRINGTON FARM, P.E.I., Charlottetown sandy loam

TREAT-MENT	DPH cm	DPH INC	CORE SATN	AER. LIM	2 MPa PEN LM	-1500 kPA	-10 kPa CORE	-10 kPa FIELD	NLWR mm	AWC mm	AER LIM
CONV. TILL	10	150	0.519	0.419	0.233	0.180	0.366	0.318	20.0	27.9	
	20	100	0.508	0.408	0.294	0.147	0.379	0.320	8.5	23.2	
	30	150	0.508	0.408	0.239	0.143	0.321	0.312	12.3	26.7	
Total 0-40		400							40.8	77.8	
NO TILL	10	150	0.501	0.401	0.299	0.183	0.366	0.300	9.2	26.6	
	20	100	0.508	0.408	0.275	0.141	0.353	0.290	7.8	21.2	
	30	150	0.454	0.354	0.225	0.110	0.295	0.277	10.5	27.8	
Total 0-40		400							27.5	75.5	
GRASS SOD	10	150	0.503	0.403	0.357	0.156	0.376	0.309	2.9	33.0	
	20	100	0.477	0.377	0.330	0.157	0.350	0.300	2.9	19.3	
	30	150	0.508	0.408	0.272	0.167	0.362	0.272	13.5	29.3	
Total 0-40		400							18.4	81.6	

The analyses presented thus far have been based on the results from the soil cores as determined in the laboratory. It was our hope that the field measurements could be used for establishing the upper part of the desorption curves for specifying the aeration conditions. As will be presented later we did not always get good agreement between field and laboratory results for the desorption curves. We did not have an adequate understanding of the causes for the observed discrepancies between the results from the field and those from the laboratory. Since the conditions for measurements on the soil cores were similar over the whole range of conditions studied we consider the laboratory measurements the better option for making comparison spanning the whole range of the soil water release curve. To ensure that the impact of the soil structural conditions were assessed we made a great effort to measure the soil water desorption data on intact cores. This allowed consistent treatment over the range of matric potentials from 0 to -1500 kPa and also provided a consistent medium on which to measure the penetration resistance. There were data also available from the field experiments over the upper matric potential range which allowed for direct comparisons of the soil behaviour.

From the data collected in the field, the initial water content before experimentation and the final water content prior to collection of the core samples are presented (Figs. 6 - 13). The field experiments at most sites were initiated late in the growing season of 1991 or 1992. Thus the initial conditions reported represent a field dry condition in most cases. The intent of the field experiment was to add sufficient water by infiltration to achieve conditions approaching field saturation which would drain to "field capacity". The matric potential which was measured at the termination of each field experiment was at or slightly above -10 kPa. Where necessary we have extrapolated to give an estimate of the water content at -10 kPa in the field (Table 2 and Figs. 6 -13). In some cases (Clinton sandy site) the soil did not approach a matric potential of -10 kPa because rainfall occurred and rewet the soil during the experiment.

The initial water content profiles, as measured before addition of any water, show that the crops and plants growing at most of the sites had extracted water below the lower limit of the non-limiting range identified from the soil cores. At the four sites in prairie Canada (Figs. 6, 7, 8 and 9, light-dashed profiles) the water content of the field sites was reduced to well below the -1500 kPa water content as determined from the cores. At the eastern Canada sites the plants had extracted water well beyond the NLWR lower limit but not often below -1500 kPa. This raises questions about the adequacy of the penetration resistance limit of the NLWR being set at 2 MPa. The penetrating ability by different plants is species dependent. More attention should be given to quantifying an effective lower limit for plant uptake of water from soil.

It should be emphasized that the NLWR is a range of water content where conditions are most favourable for root growth and water uptake. The onset of limitations is gradual and the effects are manifested by progressive reductions in growth and performance of the plant. Thus the extraction of water below the NLWR is possible without invalidating the concept. The roots may have proliferated the soil earlier in the growing season or in a previous season when the water content was higher and the rooting resistance was lower. Under lower evaporative demand at the end of the growing season the water may have been extracted from the soil around the roots in sufficient quantity without significant reliance on root growth. The roots may also be growing

Table 3: The percentages of the usual Available Water Capacity (AWC) which is available to plants in the Non-Limiting Water Range (NLWR).

A	Lethbridge AB Loamy		Termuende SK Loamy		Clinton ON Lobb #1, Sandy		Clinton ON Lobb #2, Clayey	
depth	treatment	%	treatment	%	treatment	%	treatment	%
10	cont.	65	conv.	62	conv.	88	conv.	0
20	wheat	80	till	52	till	34	till	3
30	for 80y	60	for 81y	54		1		0
0-40		60		56		39		1
10	wheat	54	conv.	92	no	88	no	0
20	fallow	75	till	59	till	100	till	0
30	for 80y	83	for 15y	79	for 15y	25	for 15y	0
0-40		71		80		61		0
10	native	100	native	81	grass	70		
20	grass	55	grass	78		77		
30		65		78		88		
0-40		73		77		71		

B	Brunkild MB Clayey		Indian Head SK Clayey		Elora ON Loamy		C'town PE Sandy	
depth	treatment	%	treatment	%	treatment	%	treatment	%
10	conv.	79	cont.	62	conv.	7	conv.	72
20	till	60	wheat	52	till	18	till	37
30	wheat	79		54	corn	35		46
0-40		76		56		20		52
10	no	42	fallow	79	min.	0	no	34
20	till	74	wheat	80	till	38	till	37
30	wheat	83	wheat	74	corn	25		38
0-40		64		77		18		36
10	native	na	fallow	46	brome	27	grass	9
20	grass	92	wheat	80	grass	31	sod	10
30		68	wheat	49		25		46
0-40		77	3 hay	54		27		22

among soil peds in zones of lower strength which are not accessible to the penetrometer used for our measurements (Grant et al., 1985). On the other hand, the penetration resistance limit of 2 MPa may be too low or this method of setting the limit may not be appropriate for estimating the conditions which the root encounters. Our results indicate more work is required to determine the effective soil strength which acts as a lower limit of water availability.

At all four sites in the prairies (Figs. 6 - 9), some of the treatments had an initial water content below the -1500 kPa measured value. It is possible for plants to extract water below the wilting point of soil but the amount of water taken from below -1500 kPa was larger than expected, amounting to 16.5 mm in the long term treatment at Termuende and 41 mm under continuous wheat at Indian Head from 40 cm depth of soil. It is well accepted that particular plant species are better able to extract water below -1500 kPa but are undergoing some stress at the time. The impact of such plant stress is dependent both on the plant type and on the stage of growth at which the stress is encountered. A water shortage stress in a ripening crop at the end of the season has much less effect on crop yield than at the grain filling stage. Wheat crops grown on a medium-textured soil in southwestern Saskatchewan were capable of extracting water well below -1500 kPa (Cutforth et al., 1991).

Field versus Laboratory Measurements during Desorption

The estimate of the water content at -10 kPa from the field measurements provide interesting insight into the wetting behaviour of these soils. The water content condition, represented by the heavy dashed profiles in Figs. 6 - 13, was achieved in the field by drainage following controlled infiltration with a 10 cm head of water. The infiltration was allowed to proceed until maximum water content and potential had been achieved at the 30 cm depth, usually less than 3 h were required. The drainage period was chosen to give an approximation to field capacity. In the laboratory, the soil cores were immersion wetted for 16 h and drained in several steps to -10 kPa (Topp et al., 1993). In spite of these differences in rate of change of conditions we considered it valid to compare the upper portions of the field- and laboratory-measured desorption curves. In some of the soils and some of the treatments there is good agreement between field-measured and laboratory-measured water content profiles at -10 kPa (Fig. 6, 7 and 12). In a majority of the cases there was not good agreement. Those for which agreement was acceptable, i.e. probably within experimental uncertainties, were Lethbridge, fallow/wheat and native grass (Fig. 6); Termuende, tilled since 1977 and native grass (Fig. 7) and Elora minimum till corn and brome grass (Fig.12). In some of the soils the "field capacity" measured was close to and even lower than the water content at which the penetrometer resistance exceeded 2 MPa in the corresponding soil core (Figs. 7, 8 and 9). In fact, for Indian Head clay the measured "field capacity" was as low or lower than the -1500 kPa water content measured in the cores (Fig. 8). In all cases where the "field capacity" was anomalously low compared to the equivalent from the cores, the highest water content achieved in the field was considerably lower than the water content of the saturated cores.

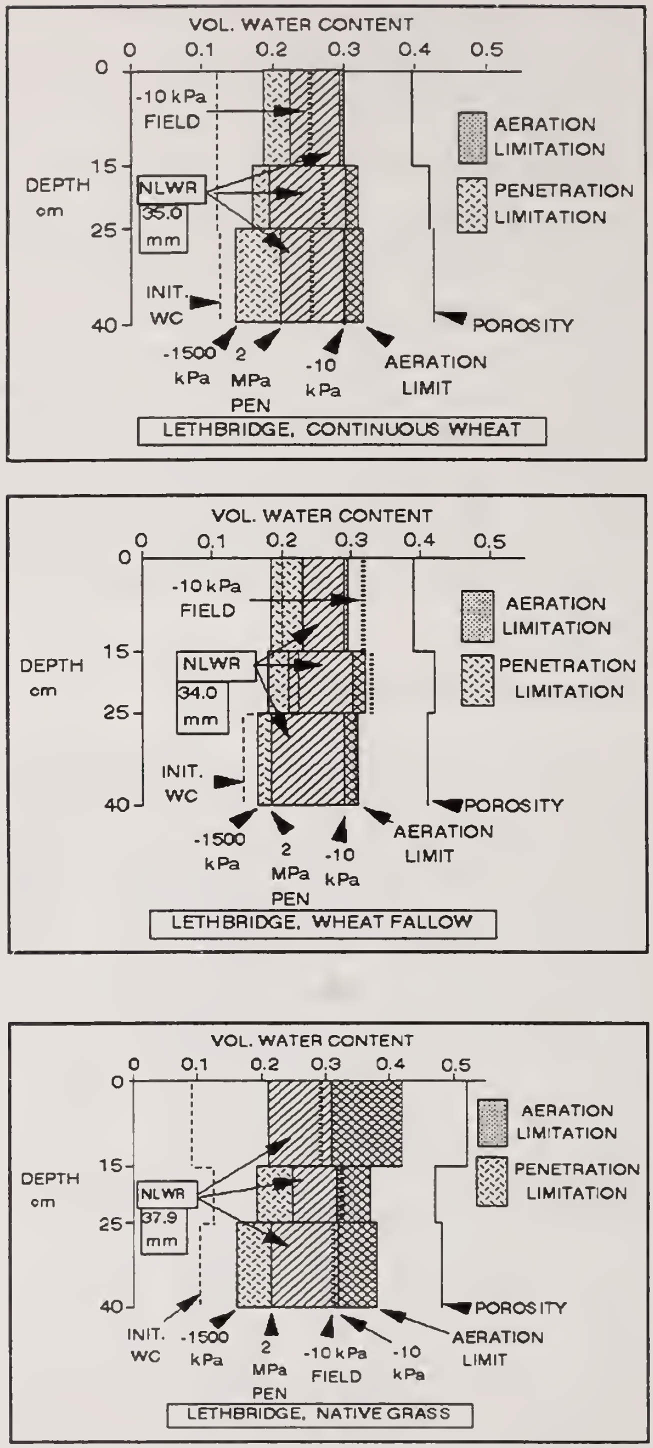


Figure 6: Water content profiles for the soils at Lethbridge Research Station, Lethbridge clay loam showing how the NLWR is related to the various profiles. The legend for the rectangle patterns refers to types of limitations which decrease NLWR, if present. The cross-hatched areas represent excess aeration porosity.

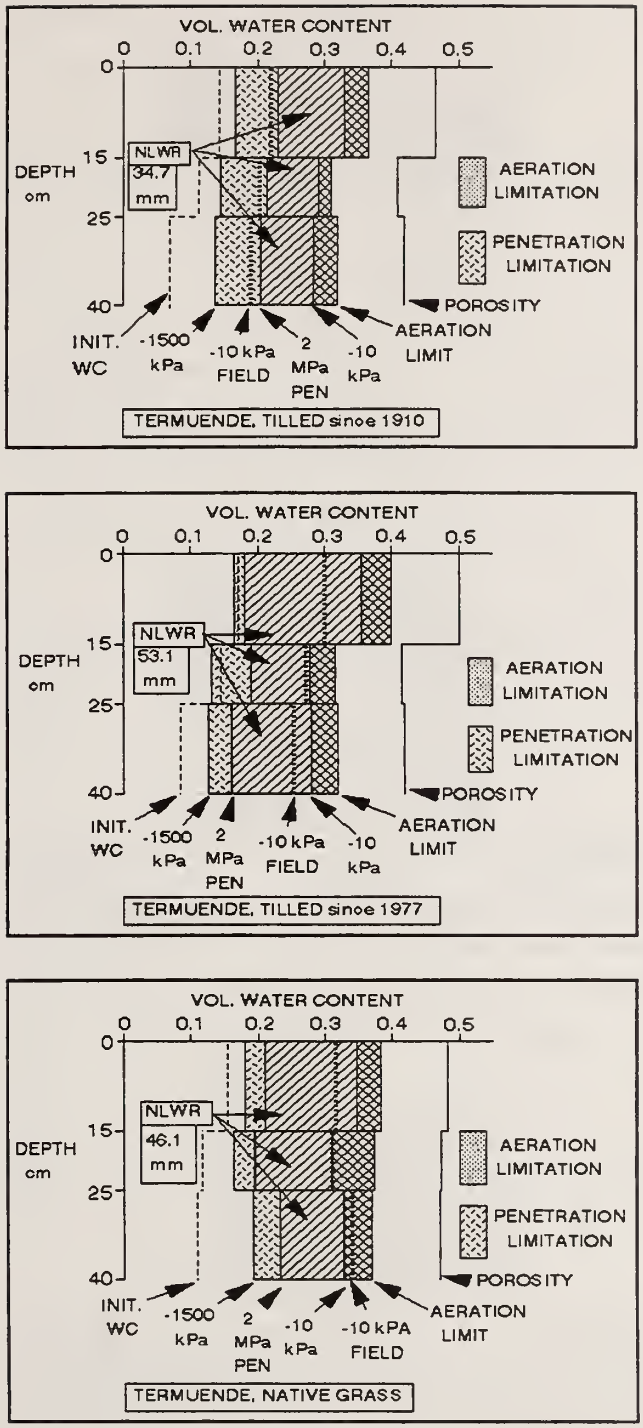


Figure 7: Water content profiles for the soils at Termuende Research Station, Oxbow loam showing how the NLWR is related to the various profiles. The legend for the rectangle patterns refers to types of limitations which decrease NLWR, if present. The cross-hatched areas represent excess aeration porosity.

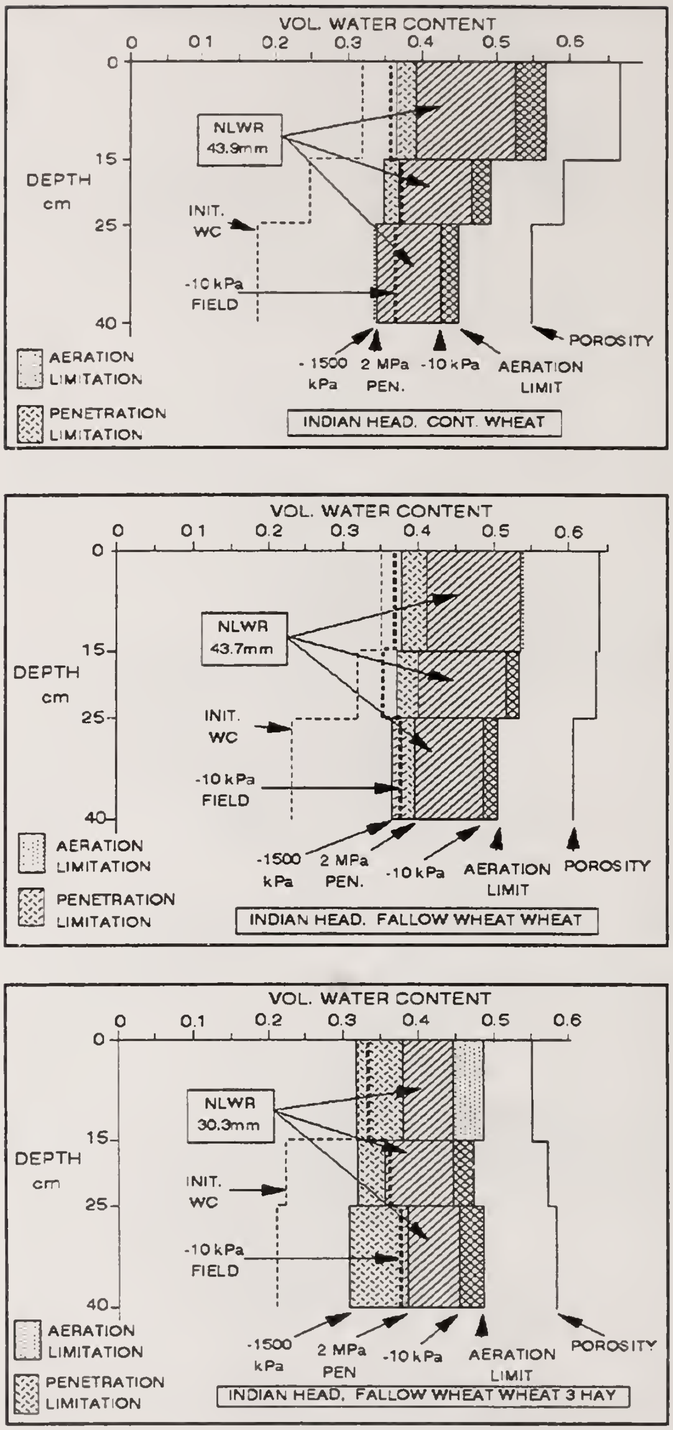


Figure 8: Water content profiles for the soils at Indian Head Experimental Farm, Indian Head heavy clay, showing how the NLWR is related to the various profiles. The legend for the rectangle patterns refers to types of limitations which decrease NLWR, if present. The cross-hatched areas represent excess aeration porosity.

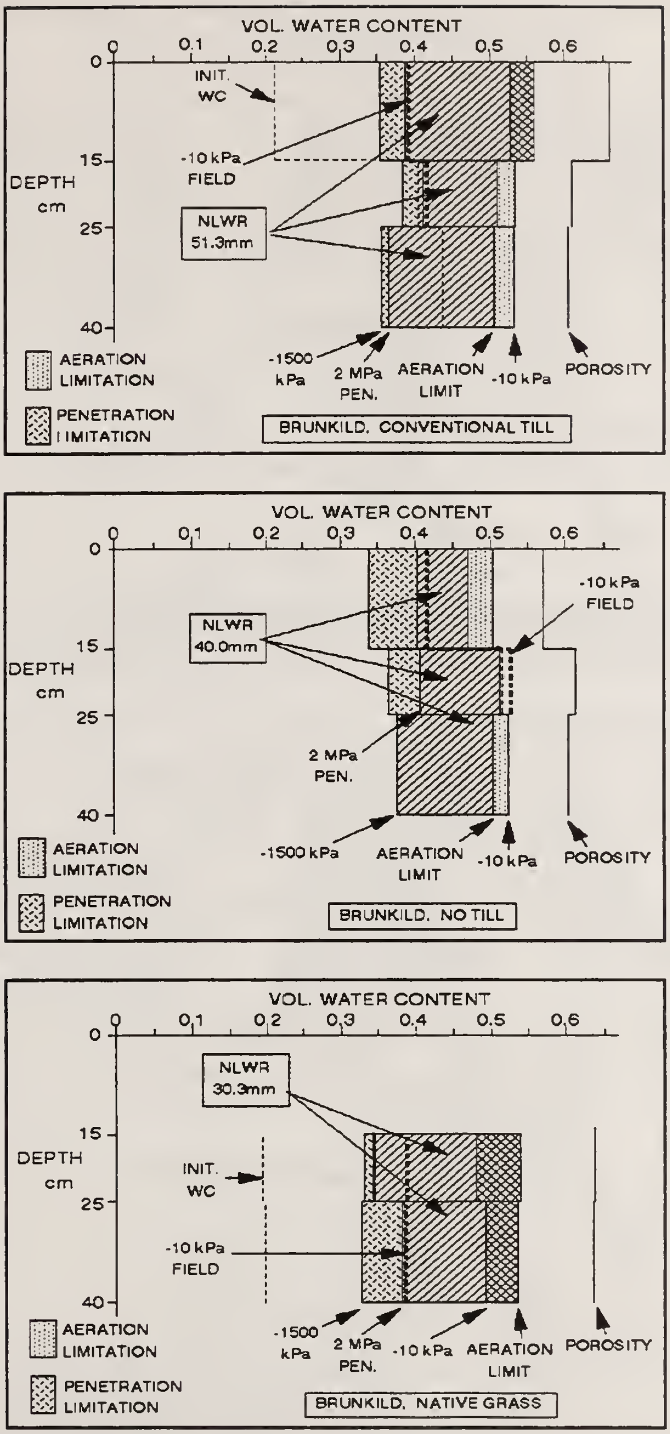


Figure 9: Water content profiles for the soils at Leonard Rance's Farm at Brunkild, on Osborne clay, showing how the NLWR is related to the various profiles. The legend for the rectangle patterns refers to types of limitations which decrease NLWR, if present. The cross-hatched areas represent excess aeration porosity.

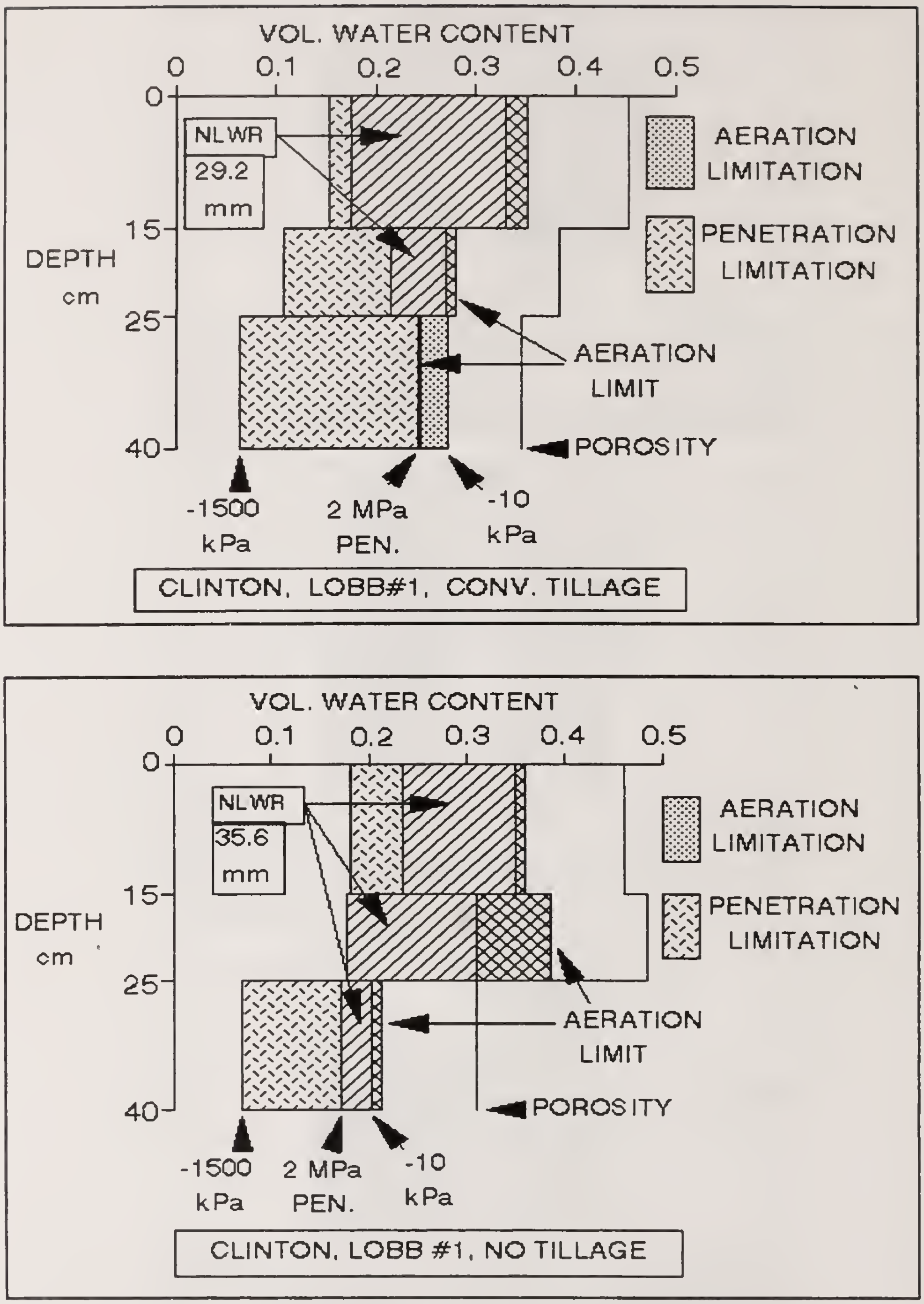
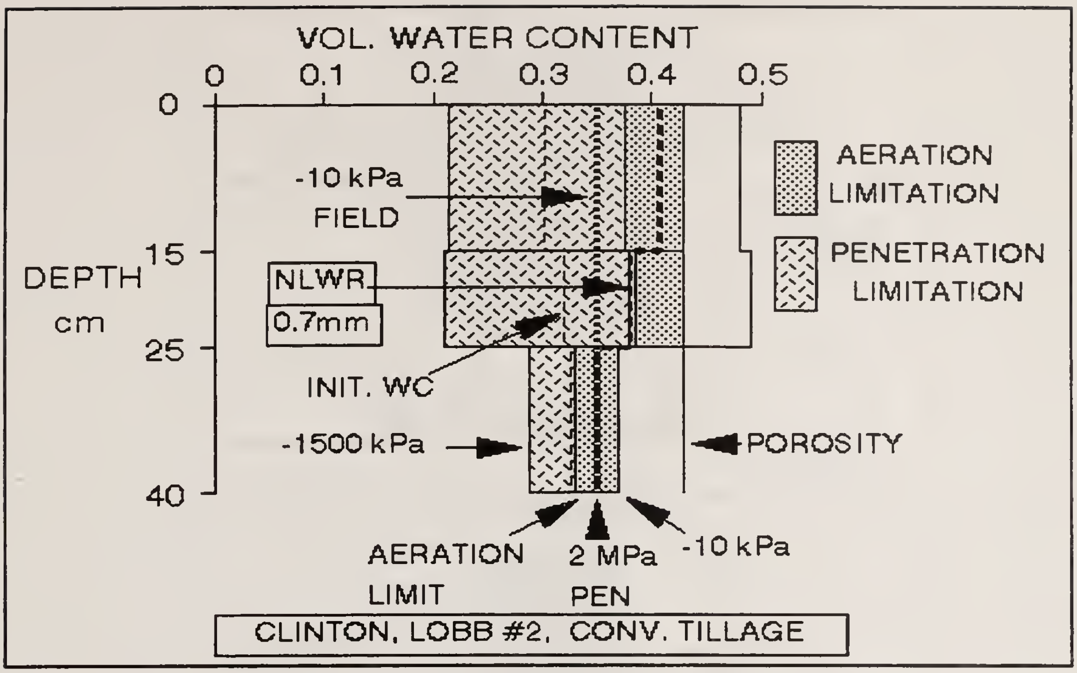


Figure 10: Water content profiles for the soils at Don Lobb's Farm at Clinton, site #1, on Brady sandy loam, showing how the NLWR is related to the various profiles. The legend for the rectangle patterns refers to types of limitations which decrease NLWR, if present. The cross-hatched areas represent excess aeration porosity. The field-measured profiles for initial water content and at -10kPa are missing here because of rainfall during the field measurements.



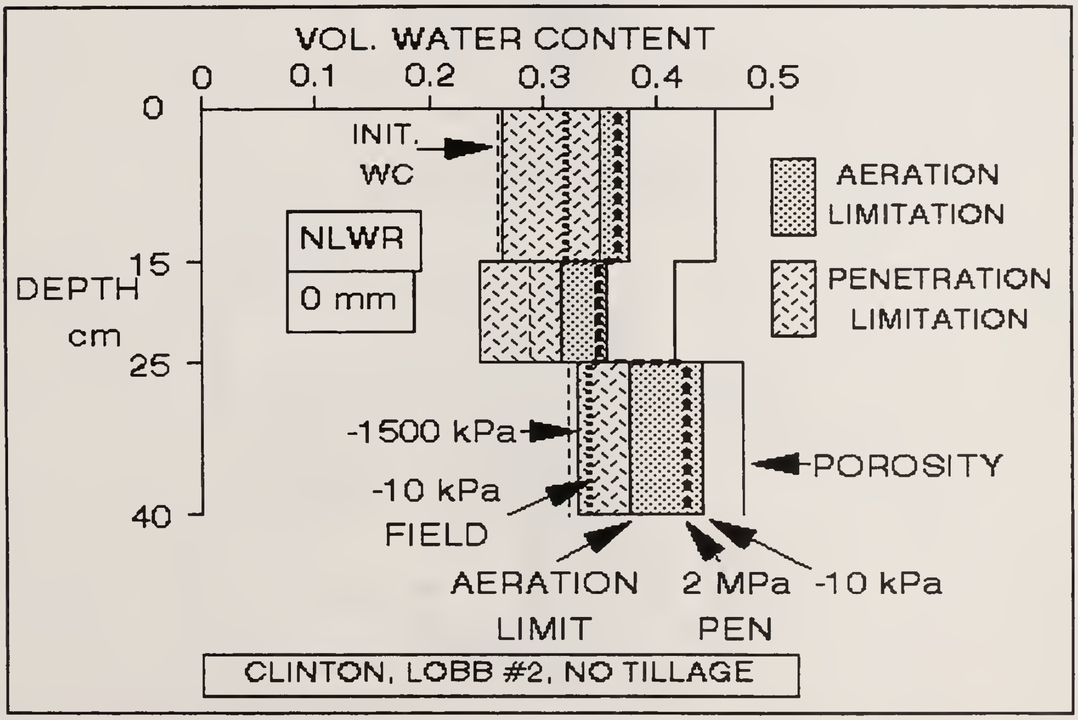


Figure 11: Water content profiles for the soils at Don Lobb's Farm at Clinton, site #2, on Huron clay loam, showing how the NLWR is related to the various profiles. The legend for the rectangle patterns refers to types of limitations which decrease NLWR, if present. The cross-hatched areas represent excess aeration porosity.

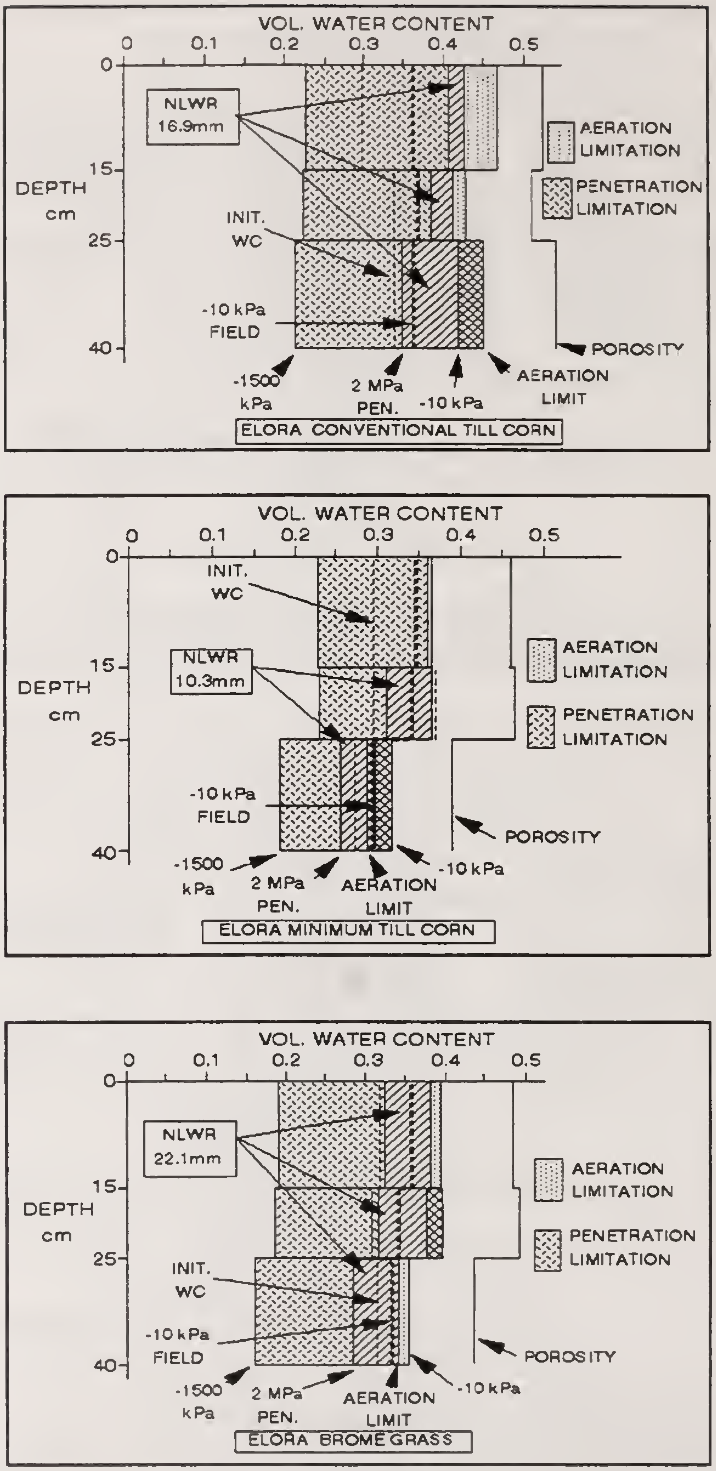


Figure 12: Water content profiles for the soils at Elora Research Station, Conestogo/London loam, showing how the NLWR is related to the various profiles. The legend for the rectangle patterns refers to types of limitations which decrease NLWR, if present. The cross-hatched areas represent excess aeration porosity.

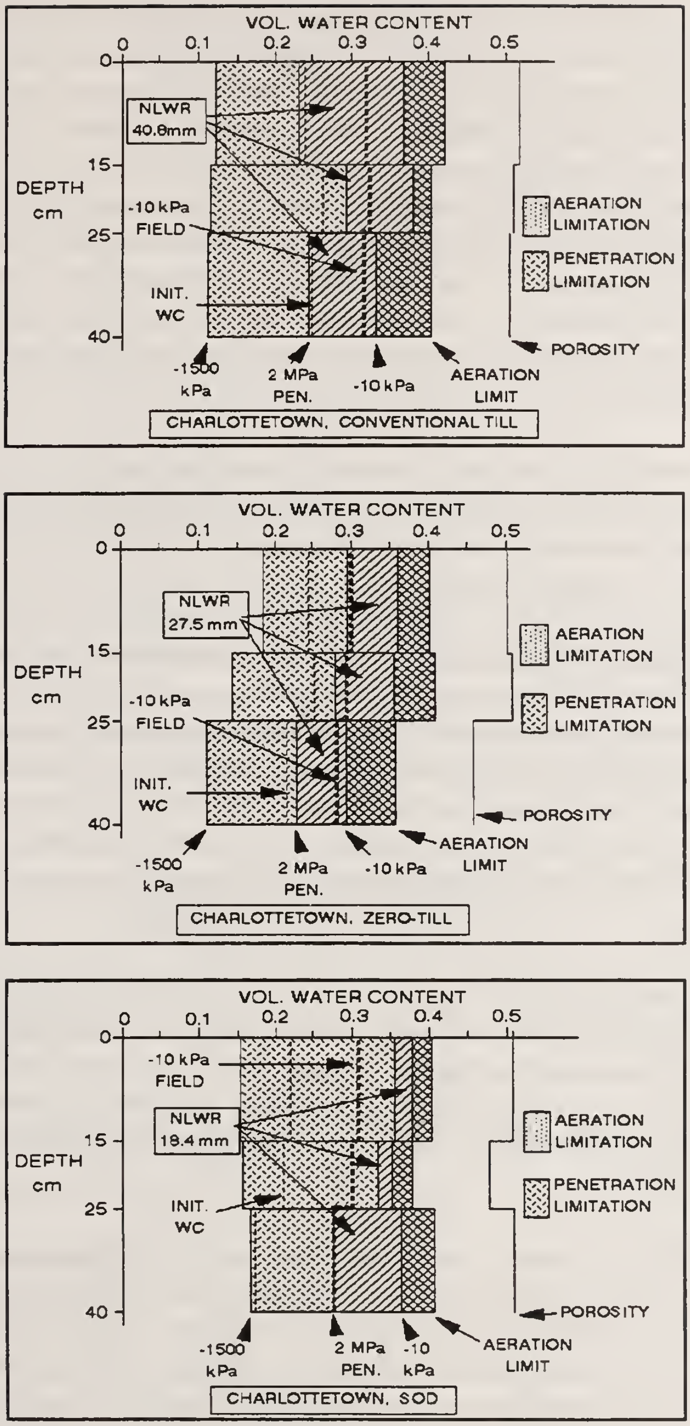


Figure 13: Water content profiles for the soils at Harrington Farm, Charlottetown sandy loam, showing how the NLWR is related to the various profiles. The legend for the rectangle patterns refers to types of limitations which decrease NLWR, if present. The cross-hatched areas represent excess aeration porosity.

Thus we have good agreement (Fig. 14) and poor agreement (Fig. 15) between the field-measured and the laboratory-measured desorption curves. An explanation for such discrepancies is desired. Some possibilities include non-wettability or delayed wettability of the soil, by-pass flow with occlusion of some soil zones and experimental measurement problems. The good agreement between field and laboratory desorption curves in some soils we take as very strong indication that our experimental approaches were soundly chosen and carried out effectively. It would be difficult to expect the field measured desorption curve to result in higher water contents than in the laboratory. We believe that the field measurements reflect reliably the field soil state. The discrepancy between field and laboratory results reflect the drying history of the soil since its last prolonged wetting. In some regions this may have a seasonal frequency and at others it may be a more frequent event. How does soil wetting history affect soil water availability?

Some degree of non-wettability of soil is a possibility needing more investigation. Dinel et al. (1990, 1992) have shown that the dominance of naturally-occurring lipids confers non-wettability to the soil. The long-term cultivation and intense management of some of the soils in this study may have contributed to a transformation of the organic matter so that hydrophobic organic molecules are conferring some degree of non-wettability to the soil. Wallis et al. (1991) have determined that a surprisingly high proportion of the New Zealand soils studied were "sub-critically" non-wetting. A similar non-wetting behaviour would give the differences between field- and laboratory-measured water contents at -10 kPa as was found in our study. The longer wetting time used in the laboratory compared to the infiltration time in the field would tend to overcome the "sub-critical" non-wetting and contribute to differing initial conditions for the start of desorption in laboratory and field. More research is required to ascertain whether there is any validity to the possible role of non-wettability in causing the discrepancy between field and laboratory measurements.

The occurrence of by-pass flow in structured soil is possible when infiltration takes place under a positive head as in our experiments and where macro voids, such as, cracks and biopores occur at the soil surface. The conditions favouring by-pass flow would tend to be more prevalent in the clayey soils. As the discrepancies between field and laboratory desorption curves did not appear to be more evident for the clayey soils, we believe that by-pass flow is not the only cause of the observed discrepancies.

The presence or formation of a crust or impeding layer during infiltration could prevent wetting of the soil below such a layer. In such instances, the soil water potential would remain negative (Hillel and Gardner, 1969, 1970). In those cases where heavy dashed lines are given (Figs. 6 - 13), the tensiometers registered ≥0 during infiltration or before draining commenced. Thus we do not believe that restricted infiltration contributed significantly to these discrepancies.

The Aeration Limit - Is It Adequate?

In this study we have accepted the arbitrary and somewhat conventional limit for adequate aeration as an air-filled porosity of ≥10%. This resulted in the clayey soils of Brunkild and Clinton and the loam soil of Elora showing frequent aeration stress (Table 2, Figs. 9, 11 and 12).

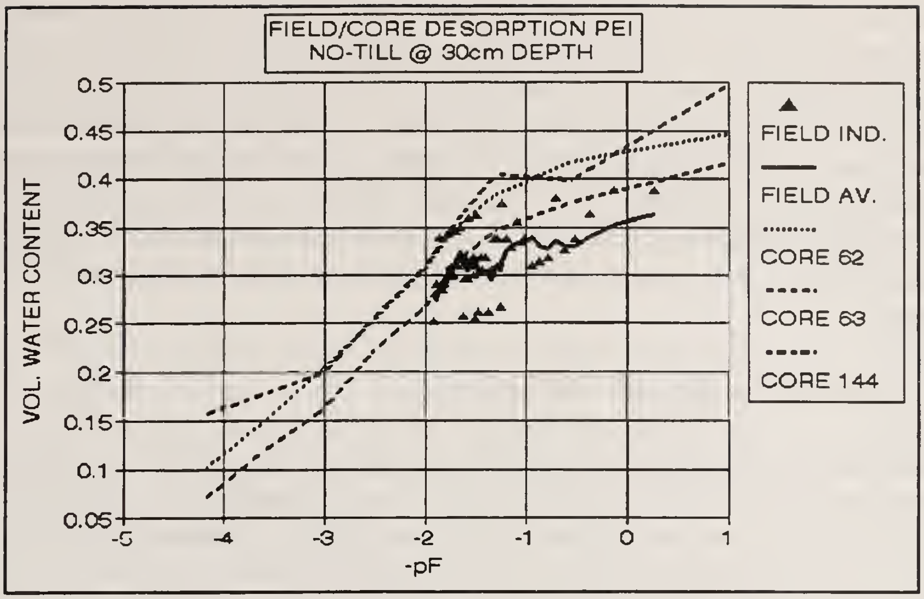


Figure 14: An example of desorption curve where agreement between field and core measurements was quite acceptable.The dotted and dashed lines join the data points from cores. These data are not displayed to minimize clutter on the graph. "FIELD AV" is a 6-point running average of individual field measured data points.

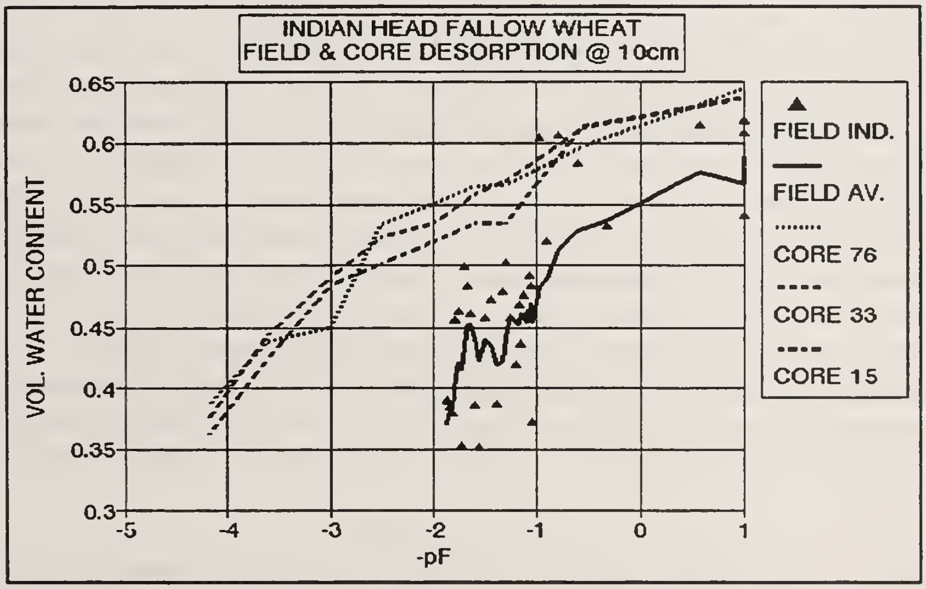


Figure 15: An example of desorption curves where discrepancies between field and core measurements were greater than expected from experimental or soil variation factors. The data presentation is the same as used for Fig. 14.

Cook (1994), Snyder (1994) and Glinski and Stepniewski (1985) propose other possible criteria for the limits on aeration based on the dynamics of oxygen supply within the solum. Cook (1994) allowed for a depth dependent consumption rate of oxygen and took into account the factors affecting the diffusion rate of oxygen. This more realistic approach would result in a requirement for increasing air-filled porosity, with depth, as the limit for adequate aeration. This approach is intuitively more acceptable than the use of static air-filled porosity limits. It does require a higher degree of soil characterisation to provide for the calculation of oxygen diffusion. These additional soil parameters were not determined for these soils but they could be considered for future analyses.

The Clinton Clayey Site - A Special Mention

The data obtained from the clayey soil at Clinton indicate that crops growing at this location will always be experiencing some stress based on the criteria used in this study. The 2 MPa penetration resistance limit was at or above the water content which provided 10% air-filled porosity (Fig. 11). The practice of no-till for 15 years has also contributed to a decreased available water capacity compared to the conventionally tilled location. Under both conventional tillage and no-till, this soil regularly produces corn and soybeans in rotation. A more detailed assessment of the NLWR concept, particularly for this soil and others at the Clinton farm, is currently part of a Ph.D. study at the University of Guelph (A. da Silva, 1993, pers. communication).

On NLWR as a Soil Structural Quality Parameter

To have a quantifiable single indicator parameter, such as NLWR, for soil structural quality is a worthwhile goal. The quantification of soil structure has been indirectly related to crop response. The advantage of NLWR is that it attempts to relate soil limitations directly to crop response factors. A major limitation and challenge is to assure that a static parameter, such as NLWR, can be an effective surrogate for the complex and dynamic processes which affect soil structure. In this study we have identified some of the potentials for and limitations to the effective application of NLWR. The limitations to use of a single air-filled porosity value at all depths in the soil should be assessed using oxygen diffusion analyses and probable oxygen consumption rates. In many instances, growing crops were observed to have extracted water successfully from soil which would exhibit higher strength than 2 MPa penetration resistance. In addition, some crops extracted considerable water from below -1500 kPa. These findings limit the possibilities for "universal" application of the NLWR, without explicit qualifications being applied.

We have proposed that the NLWR can be applied for comparative purposes of treatments within a single soil after NLWR has been normalized against AWC (Table 3). The reasoning behind this approach assumes that AWC is related more to the basic soil constituents while the NLWR is a function of the constituents but also of the structure which may be altered by the management of the soil.

NLWR Parameter Estimates from Other Soil Data.

The application of the NLWR concept as an indicator of soil structural quality depends on one being able to estimate the NLWR from readily available soil data. This limited study indicates the possibility for using the NLWR to indicate changing soil quality within a particular soil. Yet there remains a need for continued testing of the NLWR concept to determine the conditions governing its use for various soil and cropping situations. Here we address the possibility of estimating the limits of the NLWR from existing data or measurements.

If the aeration limit is adopted based on a set air-filled pore space then the upper limit of NLWR can be estimated from soil bulk density and soil-water desorption data as was done for this study. In many of the more detailed soil studies and surveys being undertaken, both the bulk density and the -10 kPa water content are determined from core desorption measurements or directly in situ. Thus the upper limit of the NLWR is a feasible estimate. There is some question now whether air-filled pore space of 10% is adequate, as discussed above.

Estimates of soil strength pertaining to root growth should emulate the soil deformation caused by the root. Soil deformation around cone penetrometers is a reasonable approximation to that around roots. The usual parameters (cohesion and angle of internal friction) used to characterize soil strength are not easily nor directly related to cone penetrometer resistance. The strong dependence of soil strength on water content or matric potential further complicates the possibility of estimating the soil strength at which root growth is restricted. In addition, there are few examples where basic soil properties have been related to soil strength as a function of water content or potential. Koppi and Douglas (1991) show a relationship between shear strength (the combined effect of cohesion and friction) and clay content for water contents "close to field capacity". The increasing concern about soil strength and stability of soil structure will lead to improved measurement and estimation procedures over those which are available now. "Permanent wilting point", the usual lower limit of availability of water (-1500 kPa) is a more readily obtained parameter, both because it has been often a part of many laboratory routine procedures but also because a number of models are available to estimate such values from the soil constituents (clay, sand and organic matter) and bulk density. As estimates of soil strength from basic soil parameters are inadequate approximations for water availability, the estimates of permanent wilting point serves as the lower limit of available water until better models relating soil strength, water potential and root growth have been developed and evaluated.

CONCLUSIONS

1. Intense long-term cultivation has resulted in a decreased NLWR:AWC ratio, indicating that NLWR, even in its current definition, is a useful index of soil structural conditions. The approach of normalizing NLWR as a ratio of AWC allowed comparisons of treatments within a particular soil.

2. Soil strength, in excess of 2 MPa penetration resistance, was approximately four times as often the cause of decreased NLWR than was aeration, assumed adequate at 10% air-filled pore space.

3. The low water contents measured before the field experiments showed that plants had extracted water to well below that where the soil strength exceeded 2 MPa penetration resistance. In some of the cases from prairie Canada, the initial water contents were also below -1500 kPa, the conventional "permanent wilting point". The lower limit for water availability, either from soil water sorption or from soil strength, needs to be assessed and validated against crop response in the field.

4. The aeration limit (10% air-filled porosity) is believed to be too small for adequate aeration at depth. This criterion warrants added consideration in relation to oxygen dynamics.

5. The unaccountable differences between field and laboratory measured water content at -10 kPa have suggested that other factors, as yet unidentified, are affecting the dynamics of the soil-water. This highlights the need for better ways to measure or estimate the NLWR. What measurement options can give results which reflect the reality encountered by the growing plant?

The NLWR concept has proved to be useful for assessing soil structure but it must be applied with appropriate regard for its limitations. This study shows that agricultural land subjected to management practices which include frequent cultivation are undergoing a decline in soil structural quality. This decline has resulted in a soil/plant environment in which stress on the plant root system has restricted the water uptake and possibly crop yield. The wide spread use of the NLWR as an indicator of soil structural quality will depend on more reliable estimates of the limits to the range and improving methods for their determination.

ACKNOWLEDGEMENTS

The assistance of Mark McGovern, Bruce Compton and Jean-Marc LeClerc has been absolutely vital to the NLWR method development and data collection. Co-op work term students, Peter Chesney, Cora Henderson and Tim Teefy, were often responsible for keeping things going and maintaining a sense of appropriate urgency with humour.

The scientific collaborators who provided access to the farms or research sites played an invaluable role in facilitating this study. Mentioning some of those persons will leave out others but the importance of the personal assistance warrants specific mention of some of the people. Leonard Rance, on whose farm was our first field site, and Walter Michalyna saw the breaking-in of the procedures and assisted with follow-up sampling. In Saskatoon, Don Acton and Glenn Padbury provided us with a truck and the use of facilities at the Land Resource Unit there. These services allowed us to use Saskatoon as our focal point for the part of the study in the prairies. Mark Cutts was helpful in introducing us to the Oxbow soil and the Termuende site. Many at the Lethbridge station were of assistance to us and we mention Chi Chang and Greg Tavis whom we constantly pestered with our needs. Guy Lafond turned on the truly western hospitality from himself, his family and the Indian Head Experimental Farm and probably wonders why we did not stay longer. Don Lobb welcomed us to his farm where more scientific data has been collected than on any other land in Ontario. Don and his wife also provided us shelter, food and warmth when we should have known enough to "come in out of the rain". Ed Perfect introduced us to the Lobb research and help us choose our sites so that we came back for a second site. Similarly, Ed and others at Guelph made it possible for our work at the Elora Research Station. Our field program ended in Charlottetown, where Martin Carter provided the opportunity and encouragement to use his plots and Delmar Holmstrom assisted with his characteristic optimistic enthusiasm.

REFERENCES

Bradford, J.M. 1986. Penetrability. Pages 463-478 in A. Klute, Ed. Methods of soil analysis. Part 1. Physical and mineralogical methods. Agronomy No. 9. American Society of Agronomy, Madison, WI.

Can-Ag Enterprises. 1988. Assessment of soil compaction and structural degradation in the lowland clay soils. A report prepared for Agriculture Canada under the Soil and Water Environmental Enhancement Program (Technology Evaluation and Development sub-program). 117 pp.

Cassel, D.K. and D.R. Nielsen. 1986. Field capacity and available water capacity. Pages 901-926 in A. Klute, Ed. Methods of soil analysis. Part 1. Physical and mineralogical methods. Agronomy No. 9. American Society of Agronomy, Madison, WI.

Cook, F.J. 1994. One-dimensional oxygen diffusion into soil with exponential respiration: Analytical and numerical solutions. Soil Sci. (In Press).

Cutforth, H.W., P.G. Jefferson, and C. A. Campbell. 1991. Lower limit of available water for three plant species grown on a medium-textured soil in southwestern Saskatchewan. Can. J. Soil Sci. 71:247-252.

Dinel, H., M. Levesque and P. Jambu. 1992. Effects of long-chain aliphatic compounds on the germination and initial growth of corn, radish and spinach seedlings, and on hydrological properties of a sandy growth medium. Can. J. Soil Sci. 92:107-112.

Dinel,. H., M. Schnitzer and G. Mehuys. 1990. Soil lipids: Origin, nature, content, decomposition and their effect on soil physical properties. Pages 397-429 in J.M. Bollag and G. Stotzky, Eds. Soil biochemistry. Marcel Dekker, New York.

Glinski, J. and W. Stepniewski. 1985. Soil aeration and its role for plants. CRC Press, Boca Raton, FL. 229pp.

Greacen, E.L. 1986. Root response to soil mechanical properties. Trans. 13th Congress Intern. Soc. Soil Sci., Hamburg, Germany. 5:20-47.

Hillel, D. and W.R. Gardner. 1969. Steady infiltration into crust-topped profiles. Soil Sci. 108:137-142.

Hillel, D. and W.R. Gardner. 1970. Measurement of unsaturated conductivity and diffusivity by infiltration through an impeding layer. Soil Sci. 109:149-153.

Koppi, A.J. and J.T. Douglas. 1991. A rapid, inexpensive and quantitative procedure for assessing soil structure with respect to cropping. Soil Use Manage. 7:52-56.

Letey, J. 1985. Relationship between soil physical properties and crop production. Adv. Soil Sci. 1:277-294. B.A. Stewart, Ed. Springer Verlag, New York.

McBride, R.A., Ed. 1993. Soil compaction susceptibility and compaction risk assessment for corn production in the Regional Municipality of Haldimand-Norfolk. Vol. I and II.

Science Council of Canada. 1986. A growing concern: soil degradation in Canada. Ottawa, ON. 24pp.

Snyder, V. 1994. Plant stresses associated with soil structure. In Proc. plant stresses in the environment, Caribbean and Pacific Basin Advisory Groups, Kona, Hawaii (In Press).

Topp, G.C. 1993. Soil water content. Pages 541-557 in M.R. Carter, Ed. Soil sampling and methods of analysis. Lewis Publishers of CRC Press Inc., Boca Raton, FL., USA.

Topp, G.C., Y.T. Galganov, B.C. Ball and M.R. Carter. 1993. Soil water desorption curves. Pages 569-579 in M.R. Carter, Ed. Soil sampling and methods of analysis, Lewis Publishers of CRC Press Inc., Boca Raton, FL, USA.

Wallis, M.G., D.R. Scotter and D.J. Horne. 1991. An evaluation of the intrinsic sorptivity water repellency index on a range of New Zealand soils. Aust. J. Soil Res. 29:353-362.