Soil Laboratory Data, Field Descriptions and Field Measured Soil Water Limits for Some Soils of the United States

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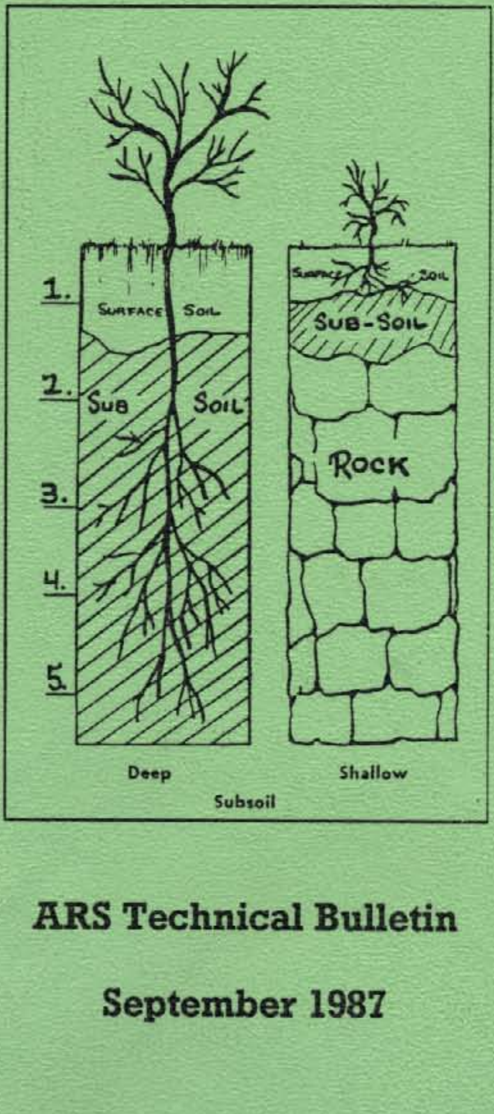

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SOIL LABORATORY DATA, FIELD DESCRIPTIONS AND FIELD MEASURED SOIL WATER LIMITS FOR SOME SOILS OF THE UNITED STATES[1]

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PREFACE

This report was compiled to provide a data base for estimating field-measured soil water limits from soil physical and chemical properties. Appendix A contains laboratory data, pedon descriptions, and field-measured soil water limits of some important agricultural soils from fifteen states. The methods of compiling and analyzing the data base and some equations for estimating the field measured soil water limits have been reported (Ratliff et al. 1983; Cassel et al. 1983).

The soil descriptions prepared specifically for this report were mainly to describe the soil features thought to affect soil water retention. These descriptions were edited to agree with laboratory measurements of soil texture and pH. Eight of the descriptions, which were prepared for other objectives, contain detailed information pertinent to that specific investigation. These descriptions were minimally edited to preserve the original descriptive data.

The soil analyses were made at the National Soil Survey Laboratory, Lincoln, Nebraska. Methods of the analyses are identified by symbols in the column headings of the data tables and are described in Soil Survey Investigations Report No. 1 (USDA 1972, Revised 1984). Appendix A includes examples of data tables and a brief description of the data element in each column of the computer printed data sheets.

The field-measured soil water limits of each soil are shown in graph and table form. These data were contributed by research scientists throughout the United States. The name and location of the contributors are shown at the bottom of each pedon description. Their contribution is gratefully acknowledged.

The soil pedons were classified from 1980 to 1982. Pedons that have one or more properties outside the limits of an established soil series but are otherwise similar are named as a phase, taxadjunct or variant to the named series. The differences are described in the "Remarks" section of the pedon description. Pedons that are not within or near the limits of recognized series are classified to the family level and are identified as "Series Not Designated." In the text, pedons are arranged alphabetically by series name.

ACKNOWLEDGMENTS

The data presented in this report came from scientists in many parts of the United States; therefore, it is not possible to individually recognize each of them. Appreciation is extended to those scientists who assisted in the inventory of existing soil water studies. The cooperation and hospitality of those who provided the field-measured soil water data is gratefully acknowledged. Appreciation is also expressed to the soil scientists and technicians who assisted in describing, sampling, processing and reviewing the soils data.

Special thanks is given to Dr. P. T. Dyke, Economic Research Service, and Oliver Rice, Soil Conservation Service, for their help in the statistical analyses and data interpretation.

Most of the work was done while Dr. Cassel was a visiting scientist at USDA-ARS, Temple, Texas.

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SOIL LABORATORY DATA, FIELD DESCRIPTIONS AND FIELD MEASURED SOIL WATER LIMITS FOR SOME SOILS OF THE UNITED STATES

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INTRODUCTION

Evaluating the capacity of the soil water reservoir requires knowledge of its upper and lower limits in the plant root zone. The most common procedure for estimating the upper limit water content is to extract water from a disturbed or undisturbed soil sample using a soil water extraction apparatus or "pressure chamber" (Richards and Weaver 1943). A matric potential of -0.33 bar is used for moderately coarse- and finer-textured soils; a -0.10 bar potential is used for coarse-textured soils (Jamison and Kroth 1958; Colman 1947). The lower limit water content is estimated using a pressure chamber at a matric potential of -15 bars. The soil water reservoir for a soil profile is estimated by collecting soil samples from the different soil horizons or depths, determining the water content at the upper and lower limits for each horizon, and summing the differences over the entire rooting depth.

Laboratory methods for estimating the soil water reservoir have been criticized (Richards 1960; Gardner 1966; Ritchie 1981). Some argue that plants remove water from the soil at matric potentials <-15 bars. Others say that plants may not remove water to a matric potential of -15 bars. Few have reported field-measured values of the matric potential at the lower limit. For the upper limit, field measurements often do not agree with values estimated using the -0.10 and -0.33 bar pressure apparatus in the laboratory. Estimates of the upper limit made by using the pressure chamber for different depths of a single soil profile may overestimate in situ measurements at some depths, underestimate it at others, and be nearly equal to it at still others (Cassel and Sweeney 1974). In addition, the laboratory method of estimating soil water limits is expensive and time-consuming, requiring a careful collection of undistributed soil cores, an investment in laboratory pressure extraction equipment, and regular monitoring by trained technicians.

Because of the problems in estimating the limits of the soil water reservoir, a joint effort between the Soil Conservation Service (SCS) and the Agricultural Research Service (ARS) was initiated in April 1980. The objective was to assemble a comprehensive data base of field-measured upper and lower soil water limits for a broad range of soils throughout the United States. The purposes of the study were

(a) to provide a data base of field-measured soil water limits, (b) to assess the value of laboratory measurements for estimating the field soil water limits, and (c) to determine if alternative techniques might be used to accurately evaluate the soil water reservoir.

This report summarizes the procedures used in compiling and analyzing the data, compares the laboratory estimates of the soil water limits with field measurements, and reports models for estimating the potential upper and lower water limits of soils based on routinely measured soil physical and chemical properties. Appendix A includes laboratory data, pedon descriptions, and field-measured soil water limits of the soils included in the data base. Much of the discussion presented in this report plus some additional details on the data base and data analysis are discussed in Ratliff et al. (1983).

PROCEDURES

Soil selection process. To develop a data base encompassing a broad range of soils with respect to texture and other chemical and physical properties, both published and unpublished data meeting certain criteria were collected, summarized, and tabulated. Initially a literature review was conducted to locate published data on upper and lower limits measured in situ. After the literature review about 250 questionnaires were sent to state and federal institutions, soil physics or soil water management programs and to researchers who were conducting or had recently conducted research that included field measurements of soil water content under various crops. The questionnaire was designed to identify studies where: (a) the crops had undergone severe water stress, (b) the soil water content had been measured throughout the rooting zone periodically during the stress period, and (c) the water content measurement sites could be precisely located. Applicable data came from 28 respondents who agreed to contribute to the survey.

After identifying the soils to be included in the data base, the sites were visited, the in situ-measured water content data were discussed with the researcher, the soils were described, and soil samples were collected. At one location eight soil sites had previously been described and sampled by individuals experienced in soil classification. These soil samples had been submitted to the same laboratory being used in this study. The resulting analyses were included in the data base. The soil-geomorphic setting, soil classification and some of the data for these eight pedons in Bailey County, Texas, have been previously discussed (for Pedon Nos. S75TX-17-4 through S75TX-17-8, Gile (1979); for

Pedon Nos. S75TX-17-1 through S75TX-17-3, Gile (1981)). In these publications the classification of some pedons is different from their classification in this report.

Eighteen months were required to assemble the data base. During the study, several other sets of water limit data were identified. However, none were used in the analysis because the data and soil properties were either similar to those of soils already included in the data base or the cost of obtaining a single data set from one location was prohibitive.

Methods for defining the soil water limits. The methods used to define the in situ upper and lower limits of the soil water reservoir available to plants was similar to that described by Franzmeier et al. (1973) and Ritchie (1981). Slight modifications were required to accommodate the various experimental approaches used by investigators throughout the United States. Comparing the methods presented below with the above references will show the differences.

To maintain uniformity, we defined the water limits to be investigated before accumulating the data base as (a) drained upper limit (DUL)--the highest field-measured water content of a soil after it had been thoroughly wetted and allowed to drain until drainage became practically negligible; (b) lower limit (LOL)--the lowest field-measured water content of a soil after plants had stopped extracting water and were at or near premature death or became dormant as a result of water stress; and (c) potential extractable soil water (PLEXW)--the difference in water content between DUL and LOL. These parameters--DUL, LOL, and PLEXW--are expressed in percent by volume.

The DUL was derived by analyzing successive measurements of soil water content versus time after the soil had been thoroughly wetted by irrigation or precipitation and allowed to drain. Successive measurements of such a thoroughly wetted soil exhibit a monotonic decrease in soil water with time until the drainage rate becomes negligible. The soil profile was considered to attain a negligible drainage rate and to reach the DUL when the water content decrease was about 0.1 to 0.2 percent water content per day. Some soil sites had been covered with rainfall shelters or plastic sheeting which prevented evaporation losses or precipitation gains of water. Other plots were uncovered and subjected to the above gains and losses. Typically, 2 to 12 days were required for soils to reach the DUL. Some fine-textured soils and soils with restrictive layers required up to 20 days of drainage.

The LOL was derived from successive measurements of soil water content when a field crop was under severe water stress. Water content measurements were continued until the plant died, nearly died, or became dormant. Data from adequately fertilized field plots where plants had reached maximum vegetative growth before undergoing severe water stress were preferentially selected over data from plots inadequately fertilized or early-season stressed. The DUL and LOL were not always measured during the same year. The DUL values generally were made when precipitation or irrigation additions of water were unusually high and the soil profile was thoroughly wetted. Conversely, the LOL values were generally made in unusually dry years or following a prolonged dry period when plant water demands were high. The data shown on the graphs of the "field-measured soil water limits" (Appendix A) are for the year when the LOL measurements were made.

Although extremely useful, there were some inadequacies in the data. The definitions and methods of the selecting the DUL and LOL were designed to identify the limits of the soil water reservoir for drained soil. They do not include water that can be taken up by plants while drainage is occurring (Ritchie 1981). Evaporative losses of soil water from the soil surface or from near soil surface layers of uncovered plots result in an underestimation of DUL. Similarly, soil evaporation causes an underestimation of LOL for layers near the soil surface. Also, there is a rooting depth below which root density is inadequate for complete extraction of available soil water, and thus causing an overestimation of the water content at the LOL.

These conditions were recognized before compiling the data base. The following procedures were used to minimize underestimation of DUL and LOL and overestimation of LOL. All field-measured soil water limits of LOL, DUL, and PLEXW were plotted versus depth for each soil profile (Appendix A). Possible LOL and DUL values near the soil surface that appeared to be affected by soil evaporation and those that appeared to have inadequate root density and hence, incomplete water extraction, were identified by visual inspection and omitted. The values included in the comparison and data analysis are those between the dashed lines on the graphs of the field-measured soil water limits (Appendix A). This method of selection resulted in 401 observations of DUL, LOL and PLEXW where the effects of evaporation and inadequate root ramification were minimal.

Additional soil measurements. At each location, the soil was described and sampled as close as possible to the point at which the soil water content was measured when DUL and LOL were being determined. The soils were described using the terminology of the Soil Survey Manual (USDA 1951) and supplements (1962). The description of plant roots in the pedon description cannot be directly related to the LOL water content since the soils were often described and sampled several years after the LOL measurements were made. About 3 to 5 kg of disturbed soil material and duplicate 5-cm thick and 7-cm diameter undisturbed soil cores were collected at depth increments that coincided with the depth of water measurement and/or soil horizon. All samples were shipped to the National Soil Survey Laboratory, Lincoln, Nebraska, for analysis by procedures described in Soil Survey Investigations Report No. 1 (USDA 1972, Revised 1984).

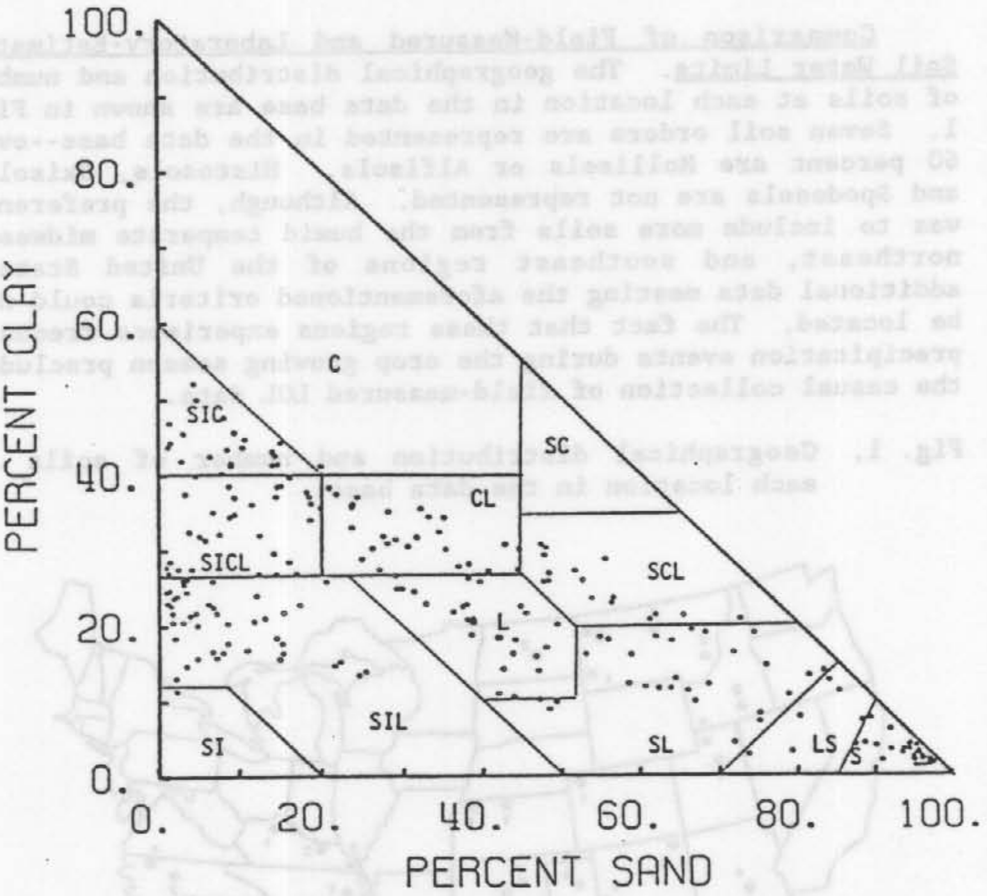
RESULTS AND DISCUSSION

Comparison of Field-Measured and Laboratory-Estimated Soil Water Limits. The geographical distribution and number of soils at each location in the data base are shown in Fig. 1. Seven soil orders are represented in the data base--over 60 percent are Mollisols or Alfisols. Histosols, Oxisols, and Spodosols are not represented. Although, the preference was to include more soils from the humid temperate midwest, northeast, and southeast regions of the United States, additional data meeting the aforementioned criteria could not be located. The fact that these regions experience frequent precipitation events during the crop growing season precludes the casual collection of field-measured LOL data.

Fig. 1. Geographical distribution and number of soils at each location in the data base.

In Fig. 2 is seen the textural distribution of the 401 observations available for comparison of the laboratory-measured -15 bar water limits with the field-measured lower limits. A total of 282 observations of -0.33 bar measurements were available for comparison with the field-measured upper limits. Some samples that had nearly identical textures appear as single points on the graph. The number of samples and the observed range of sand, silt, and clay for each textural class are presented in Table 1. All textural classes were well represented except for sandy clay, silt, and clay.

Fig. 2. Textural distribution of the 401 observations in the data base.



The mean and standard deviation for DUL, LOL, and PLEXW for each textural class are also shown in Table 1. All water content values are expressed as percent by volume. Values of the DUL range from a minimum of 11.8 ± 4.9 for sand to a maximum of 35.0 ± 6.2 for silty clay. The LOL ranged from a minimum of 3.8 ± 2.2 for sand to a maximum of 21.9 ± 1.0 for clay (based on only three observations).

Table 1. Texture and water retention data by textural class for the 401 observations.

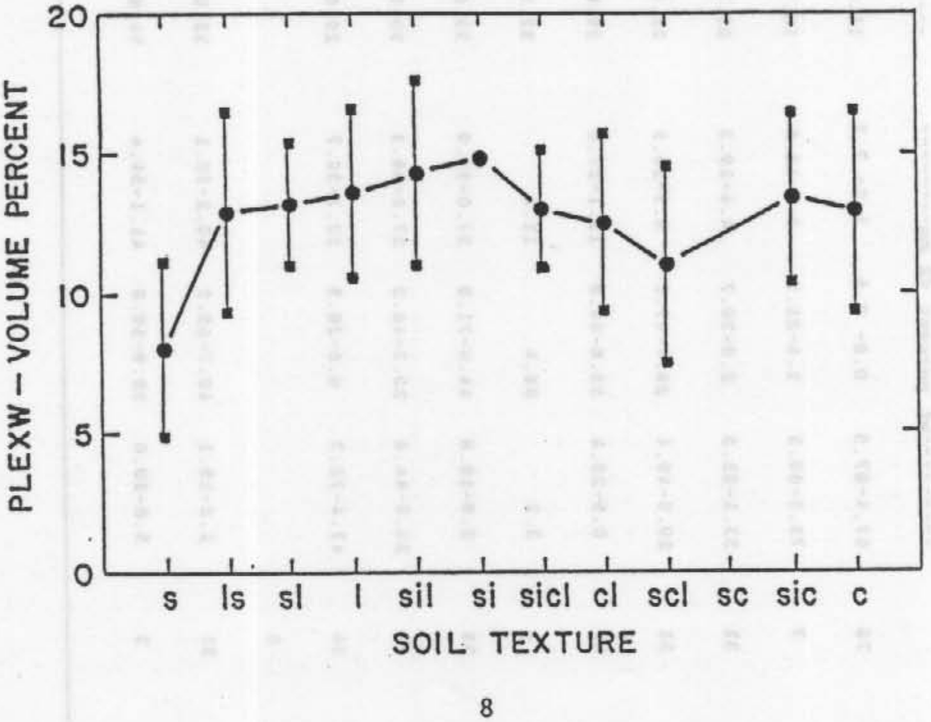
Texture	No. of Samples	Soil Separate			Upper Limit		Lower Limit		PLEXW	WRD
		Sand	Silt	Clay	DUL	-0.33 bar	LOL	-15 bar	(DUL-LOL)	(-0.33 bar - -15 bar)
		---------wt percent <2 mm--------			---------volume percent---------					
s	76	87.4-97.5	0.8- 8.5	1.2- 7.7	11.8 ± 4.9	8.9 ± 2.2	3.8 ± 2.2	3.3 ± 1.3	8.0 ± 3.1	5.6 ± 1.9
ls	7	73.7-88.3	3.4-23.5	2.8-12.6	18.9 ± 6.0	16.0 ± 5.3	5.9 ± 4.0	4.4 ± 2.3	12.9 ± 3.6	11.6 ± 3.3
sl	31	53.1-83.3	2.8-30.7	4.4-19.3	23.7 ± 5.4	21.4 ± 5.5	10.5 ± 5.2	9.9 ± 2.0	13.2 ± 2.2	11.5 ± 3.9
l	51	29.0-49.4	29.7-47.1	8.9-26.9	25.0 ± 5.1	25.2 ± 3.9	11.4 ± 4.5	13.8 ± 4.0	13.6 ± 3.0	11.4 ± 3.3
sil	83	0.9-25.4	53.6-84.8	13.1-27.0	29.0 ± 7.0	31.6 ± 4.1	14.7 ± 5.9	13.0 ± 2.3	14.3 ± 3.3	18.6 ± 3.1
si	1	2.2	86.4	11.4	32.3	36.1	17.5	6.9	14.8	25.4
sicl	53	0.9-18.8	44.0-71.8	27.0-39.9	33.8 ± 3.5	34.9 ± 2.8	20.8 ± 3.4	20.8 ± 2.6	13.0 ± 2.1	14.1 ± 3.6
cl	41	20.0-44.6	25.3-46.2	27.2-38.3	30.9 ± 4.5	33.0 ± 4.4	18.4 ± 4.9	19.2 ± 3.8	12.5 ± 3.2	13.8 ± 4.2
scl	24	47.4-72.7	6.6-26.5	20.7-30.7	29.0 ± 3.6	26.3 ± 3.3	18.0 ± 5.2	15.0 ± 2.7	11.0 ± 3.5	11.3 ± 2.4
sc	0									
sic	31	1.2-15.1	40.7-55.2	40.2-52.1	35.0 ± 6.2	37.3 ± 3.3	21.5 ± 6.8	24.1 ± 5.4	13.4 ± 3.0	13.2 ± 3.4
c	3	5.8-20.0	38.9-39.8	41.1-54.4	34.8 ± 2.9	39.3 ± 1.0	21.9 ± 1.0	27.0 ± 1.0	12.9 ± 3.6	12.3 ± 1.3

The mean and standard deviation for the -0.33 and -15 bar determinations for each textural class are included in Table 1. The -0.33 bar determination overestimated by 2.0 volume percent or more the DULs for silt loam, clay loam, silty clay, and clay; underestimates by 2.0 volume percent or more the DULs for sand, loamy sand, sandy loam, and sandy clay loam; and is within ± 2.0 volume percent for loam and silty clay loam. A better laboratory procedure to estimate the DUL for sand and loamy sand would be -0.10 bar; however, incomplete data for the -0.10 bar value precluded such a comparison. The -15 bar determination overestimates by 1.0 volume percent or more the LOL for loam, silty clay, and clay; underestimates by 1.0 volume percent for more the LOL for loamy sand, silt loam, and sandy clay loam; and estimates within ± 1.0 volume percent the LOL for sand, sandy loam, silty clay loam, and clay loam.

In general, the standard deviations for the -0.33 and -15 bar determinations are less than those for the corresponding DUL and LOL determinations. The higher standard deviations for the field-measured values are thought to be attributable primarily to errors associated with the field measurements of water obtained by different techniques and different personnel.

The mean and standard deviation for PLEXW, which is equal to DUL minus LOL, are also shown in Table 1 and are plotted as a function of soil textural class in Fig. 3.

Fig. 3. Field-measured PLEXW as a function of soil textural class.



The values range from a minimum of 8.0 ± 3.1 for sand to 14.8 for just one observation for the silt. The second highest value is 14.3 ± 3.3 for silt loam. The sand, as expected, has the least PLEXW because the large pores in sandy soils drain easily and rapidly under field conditions; moreover, the particle surface area is low resulting in little adsorbed water at the LOL. The mean PLEXW values for the remaining textural classes are relatively constant with a range of only 11.0 to 14.8 volume percent. The associated standard deviations range from 2.1 to 3.6 volume percent. The values support the concept that plant available water increases with fineness of texture up to silt loam but suggests that the amount of increase is not large.

The water retention difference (WRD) defined in Table 1 as -0.33 bar minus -15 bar, ranges from a minimum of 5.6 ± 1.9 for sand to a maximum of 18.6 ± 3.1 for silt loam. Silt has been omitted from the discussion because only one observation was available. Comparison of WRD with PLEXW reveals that WRD overestimated by 1.0 volume percent or more the observed PLEXW for silt loam, silty clay loam, and clay loam; underestimated by 1.0 volume percent or more PLEXW for sand, loamy sand, sandy loam, and loam; and estimated PLEXW to within ±1.0 volume percent for sandy clay loam, silty clay, and clay. For each of the textural classes except silt loam and silt, the mean WRD was within one standard deviation of the mean PLEXW.

To determine if the field-measured limits were significantly different from the laboratory-estimated limits, a "t" statistic was calculated for the following comparisons for each textural class: DUL versus -0.33 bar; LOL versus -15 bar; and PLEXW versus WRD. Results of these analyses are shown in Table 2. Examination of the table shows that one or more comparisons were significantly different at the 0.10 level, usually at the 0.05 level, for all textural classes except loamy sand and clay loam. However, the PLEXW and WRD values were significantly different only for sand, loam, silt loam, and silty clay loam.

Soils in the data base we assembled were mostly deep and moderately well or better drained. Soils having root restrictive layers were included in the data base, but since root density in the restrictive layers was generally inadequate for complete water removal, the values were excluded from the data reported herein. We also recognize that some of the variation in the field-measured soil water data results from variations in techniques used by the investigators providing the data and from natural within-site soil variations. Assuming the errors due to variation in measuring technique and soil heterogeneity are random, our comparisons between field-measured limits and laboratory-estimated limits should be valid. The results suggest that laboratory-estimates of the soil water limits generally provide good estimates of field-measured soil water limits, but field-measured limits are a more accurate alternative, especially if used to test the accuracy of a water balance model in a specific field.

Table 2. Results of t-test for paired comparison between field-measured and laboratory-estimated soil water limits for each textural class.

Texture	DUL Versus -0.33 bar	LOL Versus -15 bars	PLEXW Versus WRD
s	*	*	*
ls	NS	NS	NS
sl	*	NS	NS
l	NS	*	*
sil	*	*	*
si	--	--	--
sicl	*	NS	*
cl	NS	NS	NS
scl	*	*	NS
sic	**	*	NS
c	NS	*	NS

* and ** indicate significant differences at the 0.05 and 0.10 levels, respectively. NS indicated not significant at the 0.01 level.

A Model for Estimating Extractable Soil Water Limits. As indicated in the results from the comparison of field-measured and laboratory-estimates of extractable water, field-measured limits are usually better than can be obtained using laboratory methods. Therefore, we sought to develop a model from the field data collected in this study that would be applicable to most mineral soils if direct field measurements are not available.

Earlier studies have related laboratory estimated upper and lower limits to various soil properties using regression techniques. Many found that the estimated soil water parameters significantly correlated with one or more soil particle-size classes (Petersen et al. 1968a, 1968b; Gupta and Larson 1979; Salter and Williams 1965; Oosterweld and Chang 1980; Rivers and Shipp 1972). Also correlated with water retention in some cases were organic matter and organic carbon (Gupta and Larson 1979; Hollis et al. 1977; Jamison and Kroth 1958), coarse fragments (Rivers and Shipp 1972; Hanson and Blevins 1979), and bulk density (Petersen et al. 1968a; Gupta and Larson 1979). Two studies use in situ field capacity measurements rather than laboratory measurements (Rivers and Shipp 1972; Cassel and Sweeney 1974).

Using the data base collected in this study, Cassel et al. (1983) used regression analyses to determine correlation of individual soil properties with each extractable soil water limit. Properties with the highest simple correlation with the extractable water limits were selected as possible variables to use in multiple regression equations for estimating the extractable water limits. Four levels of equations were derived. Each level corresponded to a different number of soil properties used as independent variables: two, four, nine, and ten. Separate regression equations for certain textural groupings provided more accurate estimates of the in situ potential extractable water limits.

Although the models developed in the Cassel et al. (1983) paper provided good fit to the soils contained in this report, when the model was used on a much broader base of soil types for prediction throughout the United States in the Erosion Productivity Impact Calculator (EPIC, Williams et al. 1983), the model often gave unreasonable values for the soil water limits. This was especially true for the methods that used the most soil properties.

2a

Because of the difficulty of extrapolation of the models in the Cassel et al. (1983) paper to soils outside the range of soil properties found in this study, we sought a more general set of equations that would apply to broad textural groupings and that would give values in general agreement with this study. Development of the model revealed that several of the samples from eight pedons at rangeland sites that contained some woody vegetation had considerably more variation in the LOL or DUL than the other samples in the study that were taken from cropland. Thus samples from the eight rangeland pedons were removed from the data base for the development of this alternative model for the extractable soil water limits.

For better accuracy in the model, we found that separate equations were needed for various ranges of soil textures. For soil with sand percent greater or equal to 75 percent, the following equations are used to estimate LOL and PLEXW:

$$LOL_m = 18.8 - 0.168 \times Sand \qquad [1]$$

$$Sand \geq 75\%$$

$$PLEXW_m = 42.3 - 0.381 \times Sand \qquad [2]$$

where the subscript m is used with estimated values of the water content limits for mineral soils. In the equations 1 and 2 above and in subsequent equations, sand, silt or clay refer to percent by weight of the <2 mm soil particles and water contents are in volume percent. For sand less than 75 percent, soils are separated into two groups according to their silt content for LOL_m:

$$Sand < 75\%$$

$$LOL_m = 3.62 + 0.444 \times Clay \qquad [3]$$

$$Silt < 70\%$$

$$Sand < 75\%$$

$$LOL_m = 5.0 + 0.0244 \times Clay^2 \qquad [4]$$

$$Silt \geq 70\%$$

For both silt groups,

$$PLEXW_m = 10.79 + 0.05004 \times Silt \qquad Sand < 75\% \qquad [5]$$

For all soil textures,

$$DUL_m = LOL_m + PLEXW_m \qquad [6]$$

Approximating the Influence of Bulk Density, Organic Matter and Rock Fragments on Extractable Soil Water Limits. The field measured limits of extractable soil water reported in this study did not contain samples with large variations in bulk density or organic matter because of the requirement that the samples have adequate root density to remove soil water to the LOL and because the near surface measurements of water content were often lower than LOL because of soil evaporation.

For most deep soils in the study, the water extracted by roots of annual crops decreased at depths greater than about 1.3 m, indicating a lack of complete extraction. However, because some roots reach deeper soil, some water is extracted from there. Thus, the LOL water content for those depths must be estimated in order to calculate PLEXW for use in soil water balance evaluations.

Many soils have relatively high bulk densities within part of the profile which often limits the ability of roots to penetrate uniformly throughout the soil volume. To approximate how bulk density affects the limits of extractable soil water, several literature sources were found that were derived from a large number of pedons where bulk density was measured. Jones (1983) evaluated several published studies related to how soil density affected rooting, and found that soil texture had a significant influence when distinguishing between densities that influenced root growth environments. Soil with higher than a threshold density of a particular texture was penetrated with varying degrees of difficulty.

Rawls et al. (1983) used 2721 samples from various horizons for density and developed a bulk density contour map based on percentages of sand and clay. The measured density data, for the -0.33 bar water content, were adjusted for organic matter using a published formula so that the results were for mineral soil bulk density.

Consider a population of mineral soils of any specific texture combination to have a mean mineral bulk density (D_m) such that DUL, LOL and PLEXW are constant. Further, soils with densities higher than D_m have lower than average PLEXW and higher than average DUL and LOL. Likewise, those with densities lower than D_m will have higher PLEXW and lower DUL and LOL.

Information from literature sources and from this study were used to develop empirical equations to approximate D_m for mineral soils with less than 8 percent organic matter (OM). Bulk densities measured from field samples (D_f) were converted to mineral bulk density (D_{mf}) for this evaluation using the equation

$$D_{mf} = (100 \times D_f - OM \times 0.224)/(100 - OM) \qquad [7]$$

For this evaluation we assume an organic matter density of 0.224 g/cm^3. Further, the average bulk density of soil containing organic matter is assumed to be the mean of the mineral bulk density and organic matter density when weighted with the fraction of each part of the mixture. For best accuracy in estimating D_m from soil texture, the textural ranges were identified that needed separate equations as follows:

$$D_m = 1.709 - 0.01134 \times Clay \qquad Sand > 80\% \qquad [8]$$

$$D_m = 1.118 + 0.00816 \times Sand + Clay \times [0.008340-0.3606/(100-Sand)] \qquad 20\% \leq Sand \leq 80\% \qquad [9]$$

$$D_m = 1.453 - 0.004330 \times Sand \qquad Sand < 20\% \qquad [10]$$

As mentioned earlier, values of DUL, LOL and PLEXW at any given texture should vary with changes in bulk density. Information from the literature was also sought to approximate those relationships.

Voorhees et al. (1975) and Asady et al. (1985) reported data from compaction studies where the soil density for the same soil texture varied considerably. In each case, soil cores were brought into an equilibrium water potential in the -0.1 to -1.0 bar range. In both studies, the water content at pressure potentials near DUL indicated that there was an increase in the water content of approximately 17 volume percent per unit density change (g/cm^3).

How?

Further, assuming that organic matter (OM) increases the DUL by 0.23 volume percent for each one percent of OM, the following equation is used to modify the DUL_m value as calculated in equation 6:

$$DUL_c = DUL_m - 17. \times (D_m - D_f) + 0.23 \times OM_f \qquad [11]$$

where D_f is the measured -0.33 bar water content bulk density, OM_f is the measured OM and DUL_c is the estimated DUL when corrected for OM and density.

No suitable laboratory measured data were available to determine the change in PLEWX for soils with unusually high or low densities or with contrasting OM contents. The following equation was used to approximate how density and OM influence PLEXW:

$$PLEXW_c = PLEXW_m + 3.5 \times (D_m - D_f) + 0.55 \times OM_f \qquad [12]$$

LOL_c follows as

$$LOL_c = DUL_c - PLEXW_c \qquad [13]$$

If measured D_f values are not available for use in equations 11 and 12, default values can be approximated by the equation:

$$D_f \text{ (default)} = [OM \times 0.224 + (100 - OM) \times D_m]/100 \qquad [14]$$

If rock fragments (particles greater than 2 mm diameter) are a significant quantity in soil, there should be a correction made in the estimation of extractable soil water. The rock fragments are usually reported as a weight percentage (RFW). Assuming the density of rock fragments to be 2.65 g/cm^3, the following equation converts weight percent to volume percent (RFV):

$$RFV = 1/[1 + 2.65 \times (100 - RFW/RFW \times D_f)] \qquad [15]$$

The soil volume percentage (SV) excluding rock fragments is

$$SV = 100 - RFV \qquad [16]$$

Assuming the rock fragments hold negligeable water for plant use, the corrected soil water extraction limits are:

$$LOL_e = LOL_c \times SV/100 \qquad [17]$$

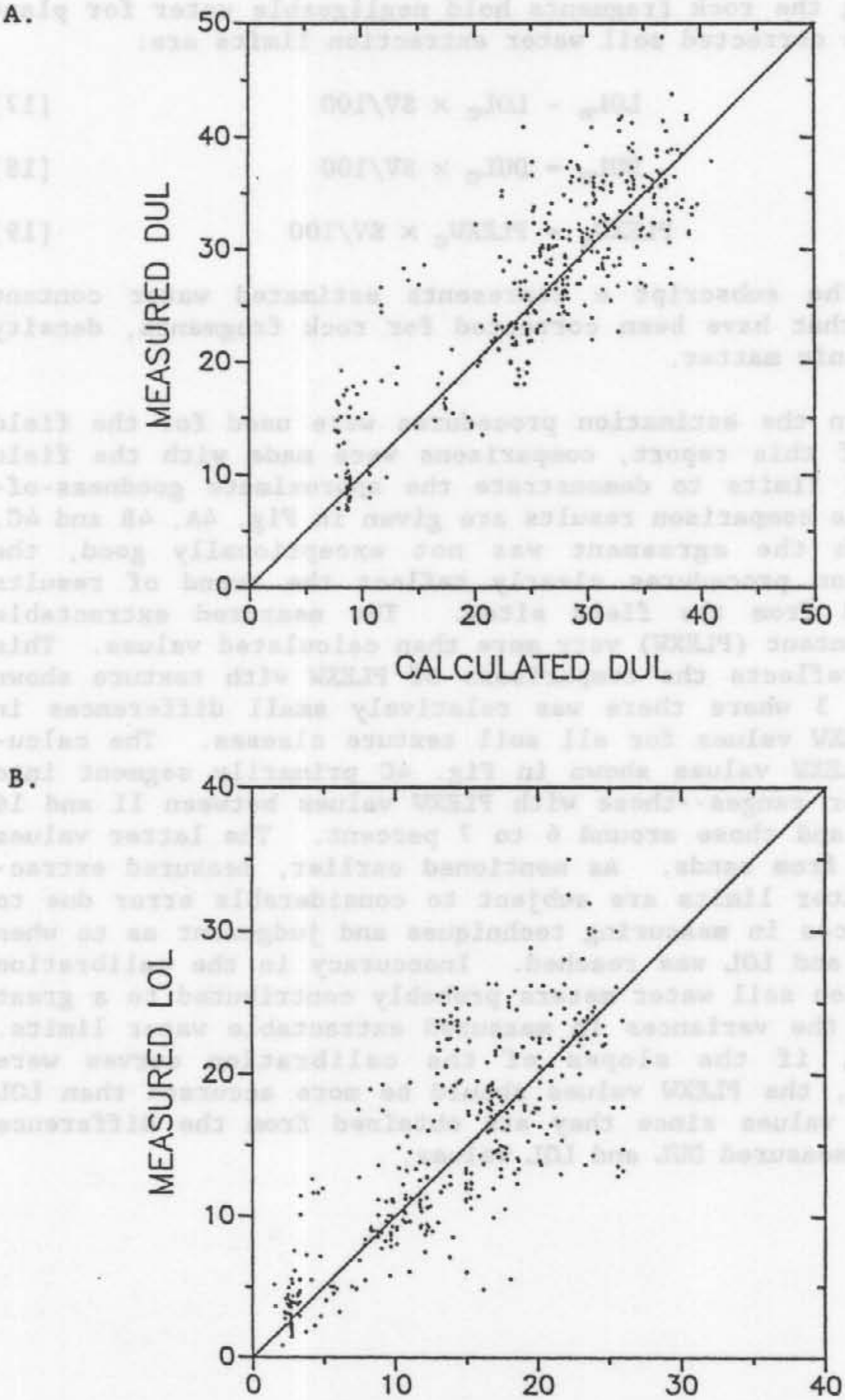
$$DUL_e = DUL_c \times SV/100 \qquad [18]$$

$$PLEXW_e = PLEXW_c \times SV/100 \qquad [19]$$

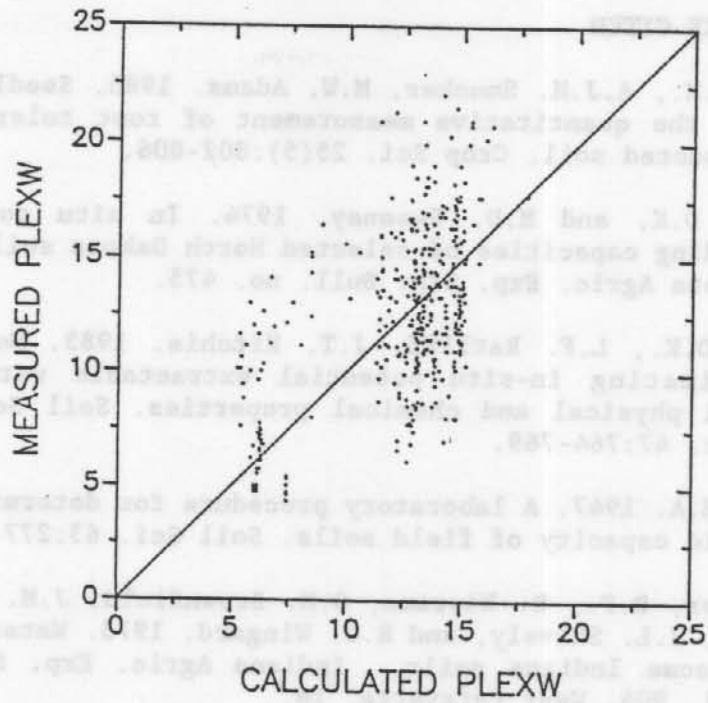
where the subscript e represents estimated water content limits that have been corrected for rock fragments, density and organic matter.

When the estimation procedures were used for the field soils of this report, comparisons were made with the field measured limits to demonstrate the approximate goodness-of-fit. The comparison results are given in Fig. 4A, 4B and 4C. Although the agreement was not exceptionally good, the estimation procedures clearly reflect the trend of results obtained from the field sites. The measured extractable water content (PLEXW) vary more than calculated values. This result reflects the comparisons of PLEXW with texture shown in Fig. 3 where there was relatively small differences in mean PLEXW values for all soil texture classes. The calculated PLEXW values shown in Fig. 4C primarily segment into two major ranges--those with PLEXW values between 11 and 16 percent and those around 6 to 7 percent. The latter values are all from sands. As mentioned earlier, measured extractable water limits are subject to considerable error due to differences in measuring techniques and judgement as to when the DUL and LOL was reached. Inaccuracy in the calibration of neutron soil water meters probably contributed to a great deal of the variances in measured extractable water limits. However, if the slopes of the calibration curves were accurate, the PLEXW values should be more accurate than LOL and DUL values since they are obtained from the difference between measured DUL and LOL values.

Fig. 4. Comparisons of the calculated versus measured values of the limits of water availability for the soils in this study are: A. Drained upper limit (DUL), B. Lower limit (LOL), and C. Plant extractable soil water (PLEXW).



c.



CONCLUSION

The equations to approximate extractable soil water limits expressed in the last section of this paper, are not meant to replace measuring the limits in the field. If it is important to model the water contents of a particular field accurately, measurements in the field are necessary. Based on the results of our study, however, the equations provide as reliable an estimate of the extractable water limits as could be obtained from laboratory measurements. Another possibility for selecting the limits of extractable soil water would be to find the soil in the appendix which most closely resembles the properties of the soils of interest.

This work suggests that soil texture has little influence on PLEXW, except for sands, so that the major factor that varies over many soils of various textures is the value of DUL and LOL. For deep soils and annual crops, the LOL is seldom reached below about 1.3 m apparently because of lack of sufficient uniform rooting below that depth. The results from this study demonstrated that this deep withdrawal characteristic was quite uniform across several contrasting soils, and that practically no water is removed by either upward flow to roots or by root withdrawal below about 2.1 m, at least for annual crops.

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