Changes in Soil Water Retention Curves Due to Tillage and Natural Reconsolidation

L. R. Ahuja,* F. Fiedler, G. H. Dunn, J. G. Benjamin, and A. Garrison

ABSTRACT

Changes in soil water retention of the surface soil brought about by tillage can significantly alter the amount of rain water that infiltrates into the root zone and is available for plant growth. Soil tillage generally increases porosity and changes the pore-size distribution, leading to changes in the soil water retention curve and hydraulic conductivities. The objective of this study was to investigate some simple ways of estimating the soil water retention curve of a tilled soil from that of an untilled soil, knowing the change in soil porosity or bulk density due to tillage. The study of literature and empirical analysis of the available data indicated: (i) under field conditions the tillage did not significantly change the air-entry value of the soil; (ii) tillage increased the absolute value of the slope of the log-log relationship below the air-entry value; and (iii) the changes due to tillage in the retention curve occurred only in the larger pore-size range, approximately between the air-entry pressure head value and 10 times the air-entry value. Assuming these observations hold in general, two simple methods of estimating the water retention curve of a tilled soil from that of its untilled condition are proposed. The first method is a simple imposition of the Brooks and Corey function between the air-entry value and 10 times this value. The second method assumes that the change in soil water content at a given pressure head in the above range of pressure heads was inversely proportional to the value of the pressure head. The tests on four pairs of measured water retention curves on three different soils showed that these methods provided good approximations.

Agricultural management practices, such as tillage, have a large effect on soil hydraulic properties and the processes of infiltration, runoff, water storage, soil temperature, and chemical transport. Soil tillage generally decreases soil bulk density and increases soil porosity by loosening up the soil. These changes are large with the initial primary tillage (e.g., moldboard plowing), but are moderated by the secondary tillage (e.g., disking). The magnitude of these changes varies with the nature of the soil, tillage method, and soil water content. The change in these properties is not permanent; they tend to revert over time to values close to those of the soil before tillage.

The increase in total soil porosity expectedly changes the pore-size distribution of the soil, and hence, the soil water content–pressure head relationship, here called the soil water retention curve. It has been shown that most of the increase in porosity is associated with the increase in number or volume fraction of the larger pores. Lindstrom and Onstad (1984) observed that the increase in porosity by conventional tillage was mostly in the range of pores corresponding with greater than −60 cm pressure head. Results of Hamblin and Tennant (1981) were similar, but there was also some decrease in smaller size pores. Results of Mapa et al. (1986) indicated that the changes in soil water retention (decrease in soil water contents) after tillage were mainly at soil water pressure heads greater than −300 cm.

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The porosity increases caused by tillage gradually degrade due to natural reconsolidation during cycles of wetting and drying (Cassel, 1983; Onstad et al., 1984; Rousseva et al., 1988). During wetting by a natural rainfall or irrigation, the soil is reconsolidated by three mechanisms: (i) raindrop impact; (ii) the effective stress in the soil approaching zero, which causes the soil matrix to collapse under its own weight, thus reducing the size and number of macropores; and (iii) the dynamic forces of water moving through the pores (adsorption and momentum), which tend to condense the matrix. During redistribution or drainage following infiltration, the increasing negative pore-water pressures increase the effective stress on the matrix, which further brings the soil particles together. Most of the reconsolidation occurs during the first wetting and drying cycle, and progressively less in the succeeding cycles (Mapa et al., 1986). The soil approaches the bulk density prior to tillage asymptotically.

During wetting, the tilled soil may also be subject to changes in pore-size distribution and the water-retention characteristics due to slaking and dispersion of soil aggregates (Kemper and Koch, 1966; Shamberg, 1992). At the soil surface, this process is enhanced by the raindrop impact, which often results in the development of a surface crust (Keren, 1989; Bradford and Huang, 1992). The crusting–sealing is an ubiquitous phenomenon that greatly reduces infiltration. Several investigations have addressed how the saturated hydraulic conductivity of the soil surface changes as a result of crusting (McIntyre, 1958; Mannering, 1967; Ahuja and Schwartendruber, 1992). Not much work has been done on how the water retention curve for the crusted layer changes, although some theoretical concepts have been proposed on how this characteristic may be estimated from bulk density changes for modeling purposes (Mualem and Assouline, 1992). Our study does not address the changes in soil water retention curve due to slaking, dispersion, and crusting. This study is focused on the changes in the soil matrix and water retention due to loosening by tillage. Specifically, the objective of this study was to investigate and try to quantify the differences in the water retention curve of a soil measured immediately after tillage vs. measured before tillage. For simplicity, we chose to represent the soil water retention curve with the Brooks and Corey (1964) function.

THEORY

Brooks and Corey Representation of Soil Water Retention Curve

The Brooks and Corey (1964) equation may be written as:

$$\frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} = \left(\frac{h}{h_e}\right)^{\lambda} \qquad h < h_e \qquad [1]$$

$$= 1 \qquad h \geq h_e \qquad [2]$$

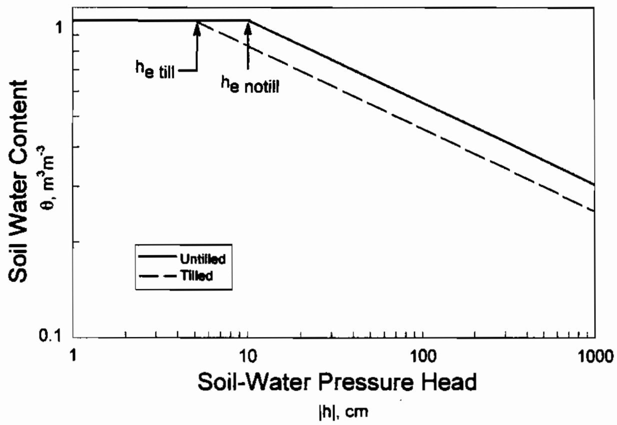

Fig. 1a. Schematic and reduced log-log soil water retention curves for untilled and tilled soil conditions based on the extended similar-media concept. θ is the volumetric soil water content and θ_s is the saturated value.

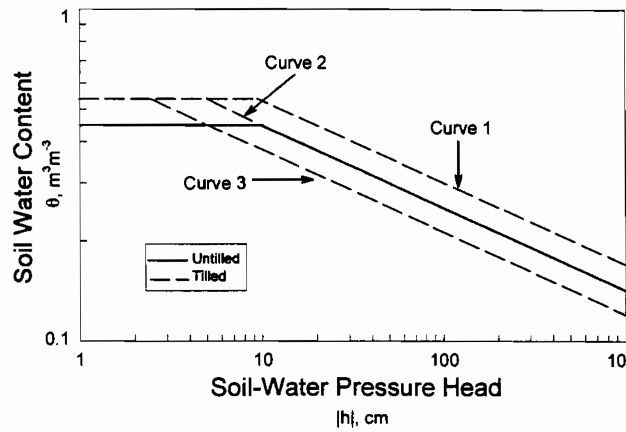

Fig. 1b. Schematic but unreduced log-log soil water retention curves for untilled and tilled soil conditions based on the extended similar-media concept. Curves 1, 2, and 3 are the three possible options for the tilled condition.

where θ is the volumetric soil water content, θ_s is the saturated value of θ (θ_s = total porosity), θ_r is the so-called residual water content (a fitting parameter), h is the negative soil water pressure head, h_e is the air-entry pressure head during desorption or the water-entry value during absorption, and λ is the pore-size distribution index. The h_e is hypothesized to represent the largest continuous soil pore in the matrix. Ahuja and Hebson (1992) have suggested a modification of Eq. [2] as:

$$\frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} = 1 - Ah \qquad h \geq h_e \qquad [3]$$

where A is a constant slope of the water retention curve between saturation and h_e. Equation [3] seems to describe the field data or undisturbed soil-core data better than Eq. [2]. Equation [1] indicates a log-log linear relationship between $(\theta - \theta_r)/(\theta_s - \theta_r)$ and $|h|$ or between θ and $|h|$ with slope λ, for all $h < h_e$.

Similar-Media Scaling Concept

The extended similar-media scaling concept (Warrick et al., 1977; Simmons et al., 1979) provides a simple way to relate the $\theta(h)$ relationship of a soil in tilled condition to that under an untilled condition or a reconsolidated condition. At any given value of the reduced soil water content $(\theta - \theta_r)/(\theta_s - \theta_r)$, the pressure head h_{till} of tilled soil is related to h_{notill} as:

$$h_{till} = h_{notill}/\alpha \qquad [4]$$

where α is a scaling factor that is assumed to remain constant for all $(\theta - \theta_r)/(\theta_s - \theta_r)$ values of the two $\theta(h)$ relationships. Combining Eq. [4] with Eq. [1] gives:

$$\frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} = \left(\frac{h_{till}}{h_{e\,till}}\right)^{\lambda} = \left(\frac{h_{notill}/\alpha}{h_{e\,till}}\right)^{\lambda} = \left(\frac{h_{notill}}{h_{e\,notill}}\right)^{\lambda} \qquad h < h_e \qquad [5]$$

Equation [5] indicates that the tilled soil condition differs from the untilled soil condition only with air-entry value h_e, the $h_{e\,till} = h_{e\,notill}/\alpha$, and the slope of the log-log linear relation (λ) stays the same. Equation [2] will also remain the same, except that the value of h_e changes for each condition. In Eq. [3], the constant "A" for tilled condition will be equal to A_{notill}/α, in order to satisfy the scaling requirement of Eq. [4]. In Fig. 1a, we illustrate the relationship of Eq. [5], [2], and [1] between the tilled and untilled soil conditions on a log-log scale, assuming $\theta_r = 0$. In Fig. 1b, the plot log θ vs. log $|h|$ rather than log $(\theta - \theta_r)/(\theta_s - \theta_r)$ vs. log $|h|$ illustrates the three different forms the $\theta(h)$ the tilled soil condition may take with respect to $\theta(h)$ of the untilled soil condition. Curve 2 is based on the assumption of the validity of the extended similar-media scaling (slope λ remains the same), as well as the observed fact that below a certain value of h, the curves for the tilled and untilled soils become the same. Curve 1 retains the same slope and a smaller absolute value of air entry h_e, but higher water contents at all pressures. Curve 3 also retains the same slope and smaller air entry, but has lower water contents at all pressures.

A limited number of laboratory studies exist in which a disturbed and sieved soil sample was packed to different bulk densities and the soil water (or another fluid) retention curves were measured on the packed soil cores (Laliberte and Brooks, 1967; Hall et al., 1977; Gupta and Larson, 1979). The results for these packed soil cores indicated that the air-entry pressure head, h_e, generally increased (became less negative) as the bulk density decreased (or as the θ_s increased) such as happens in tilled soils. It was also found that in the wet range (below the air-entry value), the soil water content at a given h value was higher with a lower bulk density; this means that the position of the retention curve corresponded with Curve 1 in Fig. 1b for tilled soil. However, the log-log curve for the smaller bulk density was not parallel to the curve for the higher bulk density as drawn in Fig. 1b. The results of Gupta and Larson (1979) and Hall et al. (1977) showed a decreasing effect of bulk density on water retention with decreasing soil water pressure head, h (Curve 1 in Fig. 1c). This means that the slope λ of Eq. [1] increased in absolute value with a decrease

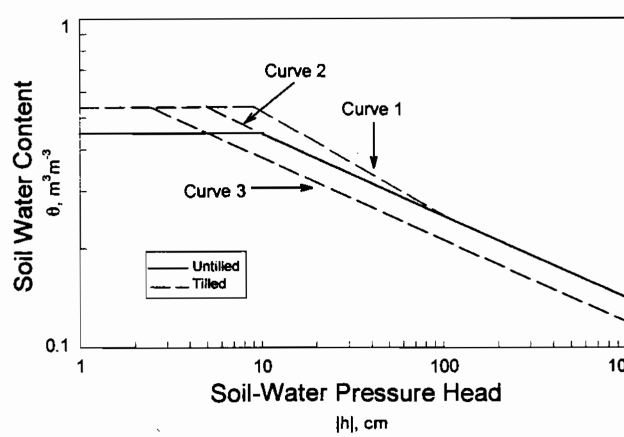

Fig. 1c. Schematic but unreduced log-log soil water retention curves for untilled and tilled soil conditions based on the extended similar-media concept. Curves 1, 2, and 3 are the three possible options for the tilled condition. Curve 1 is modified to illustrate the trend in experimental data.

in bulk density. On the other hand, the results of Laliberte (1966), who used a light hydrocarbon oil as a wetting fluid in place of water, showed that the slope λ decreased; this result is generally not expected.

A limited number of field studies exist in which undisturbed soil cores were taken from tilled and reconsolidated or untilled conditions of a soil, and water retention curves were measured on these cores in the laboratory (Gantzer and Blake, 1978; Mapa et al., 1986; Hill et al., 1985; Hill, 1990; Powers et al., 1992). Statistical analysis of Powers et al. (1992) on Nebraska and Iowa soils showed there was no significant difference in the air-entry pressure, h_e, between tilled and untilled conditions of a surface soil, but the slope λ was statistically larger in absolute value (had more negative value) in the tilled condition than in untilled condition. Our own examination of other field data (Gantzer and Blake, 1978; Mapa et al., 1986) also showed that the effect of tillage on h_e was variable and small, and slope λ was invariably increased in absolute value by tillage. The h_e is generally obtained by curve fitting, and the error involved in obtaining h_e may be responsible for the above results. In other words, the h_e change with tillage may be within the error of measurement. It is also possible, however, that the tillage does not increase the largest continuous soil pore (and hence change h_e), but only increases the volume fraction of large pores and creates some discontinuous macropores.

The above field results also indicated that the effects of tillage vs. no-tillage or naturally reconsolidated soil conditions were restricted to the wet range or less negative h values; at more negative h values, the water retention was essentially unchanged. In these experimental data (Gantzer and Blake, 1978; Mapa et al., 1986) the h value up to which the tillage affected water retention varied from soil to soil, between 7 and 13 times the air-entry pressure, h_e, of the soil; this h value seems to be related to air-entry value. It should be noted that this statement applies to tilled vs. untilled soils under naturally reconsolidated conditions, not when the soil is compacted under wheel track, and it is purely empirical at this stage. The limited undisturbed-core results in the literature indicate the tillage effects on water retention are limited to a pressure head ranging from about −60 cm (Lindstrom and Onstad, 1984; Gantzer and Blake, 1978) to about −300 cm (Mapa et al., 1986). A physical basis for this limiting pressure and its relationship to the air-entry pressure head value is yet to be developed. At this point, one may surmise that since (i) the h_e corresponds with the largest continuous pore in a soil and varies with soil type or the pore-size distribution, and (ii) the tillage influences only a certain fraction of the pores which also varies with the soil type or pore-size distribution, the h_e is related to the fraction of pores affected.

Empirical Models of Changes in Water Retention of the Tilled Soil vs. Untilled or Reconsolidated Soil

Model 1

Based on the referenced experimental results for a variety of soils, we can hypothesize that the air-entry pressure head, h_e, of the tilled soil, $h_{e\,\mathrm{till}}$, is essentially the same as that of the untilled soil:

$$h_{e\,\mathrm{till}} = h_{e\,\mathrm{notill}} \qquad [6]$$

The value of $h_{e\,\mathrm{notill}}$ is assumed known. Future work will show if this equation holds for all different soil types.

Based on the available experimental results, we can also hypothesize that the tillage increases the soil water retention in the wet range only, between the h values of zero and about −300 cm, and in this range the λ_{till} is larger in absolute value than the $\lambda_{\mathrm{notill}}$; below this range $\lambda_{\mathrm{till}} = \lambda_{\mathrm{notill}}$. Let us designate the h value that is the end point of this wet range as h_f. Let us also assume, based on the literature, that:

$$h_{f\,\mathrm{till}} \approx 10h_{e\,\mathrm{notill}} = 10h_{e\,\mathrm{till}} \qquad [7]$$

Now assuming that the curve for the tilled soil between $h_{e\,\mathrm{till}}$ and $10h_{e\,\mathrm{till}}$ is still log-log linear its λ_{till} is simply:

$$\lambda_{\mathrm{till}} = \frac{\log(\theta_{s\,\mathrm{till}} - \theta_r) - \log[\theta_{\mathrm{notill}}(10h_{e\,\mathrm{till}}) - \theta_r]}{\log|h_{e\,\mathrm{till}}| - \log|10h_{e\,\mathrm{till}}|}$$

$$10h_e < h < h_e \qquad [8]$$

In other words the changed portion of the water retention curve for the tilled soil is simply given by linearly joining the points $h_{e\,\mathrm{till}}$ and $10h_{e\,\mathrm{till}}$ on a log-log scale.

Again, Eq. [8] assumes Eq. [1] and [2] form the water retention curve. If Eq. [3] is used instead of Eq. [2], the θ_s value used in Eq. [8] will be replaced by θ at the $h_{e\,\mathrm{till}}$ value. Furthermore, since $h_{e\,\mathrm{till}}$ is assumed equal to $h_{e\,\mathrm{notill}}$ (Eq. [6]), for using Eq. [3], $A_{\mathrm{till}}(\theta_{s\,\mathrm{till}} - \theta_{r\,\mathrm{till}})$ will be assumed equal to $A_{\mathrm{notill}}(\theta_{s\,\mathrm{notill}} - \theta_{r\,\mathrm{notill}})$ to obtain θ at $h_{e\,\mathrm{till}}$:

$$\theta_{e\,\mathrm{till}} = \theta_{s\,\mathrm{till}} - (\theta_{s\,\mathrm{notill}} - \theta_{e\,\mathrm{notill}}) \qquad [8a]$$

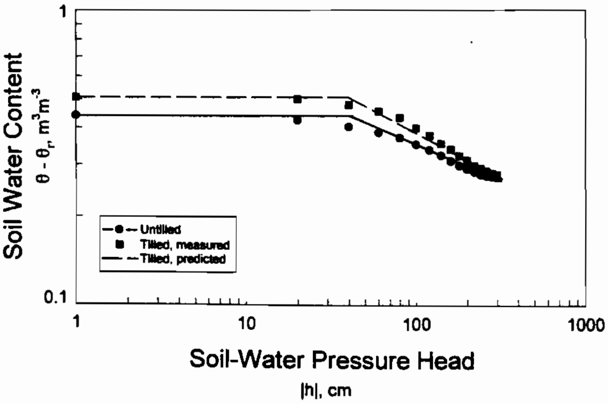

Fig. 2. Soil water retention curve of a tilled Molokai silty clay loam estimated from the untilled soil curve assuming that the air-entry value remains the same and the change due to tillage effects extend up to a pressure head, $|h|$, 10 times the air-entry value. θ_r is the residual soil water content and equaled 0.05. Equations [6, 7, 8] were used.

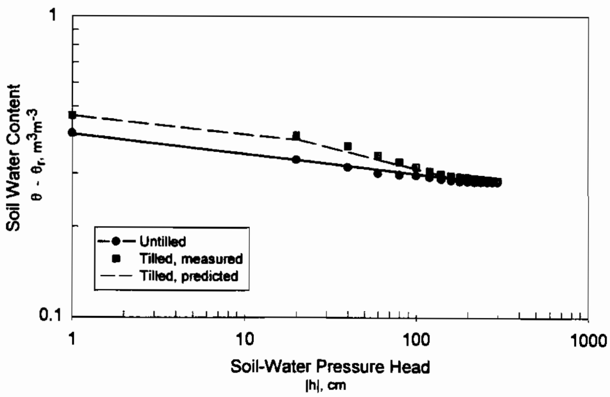

Fig. 3. Soil water retention curve of a tilled Waialua clay estimated from the untilled soil curve assuming that the air-entry value remains the same and the change due to tillage effects extend up to a pressure head, $|h|$, 10 times the air-entry value. θ_r is the residual soil water content and equaled 0.06. Equations [6, 7, 8] were used with Eq. [8a] to estimate θ at $h_{e\,\mathrm{till}}$.

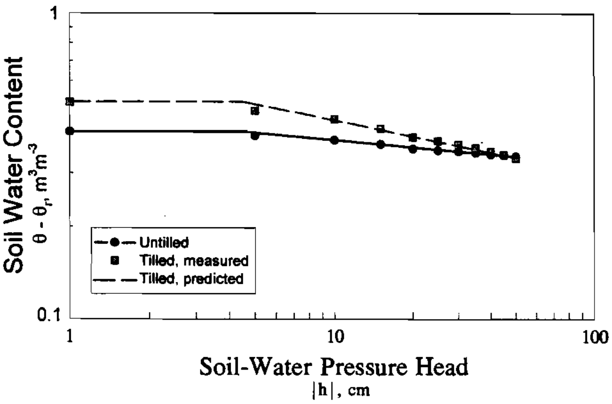

Fig. 4. Soil water retention curve of a tilled Le Sueur clay loam (sampled in May) estimated from the untilled soil curve assuming that the air-entry value remains the same and the change due to tillage effects extend up to a pressure head, $|h|$, 10 times the air-entry value. θ_r is the residual soil water content and equaled 0.06. Equations [6, 7, 8] were used.

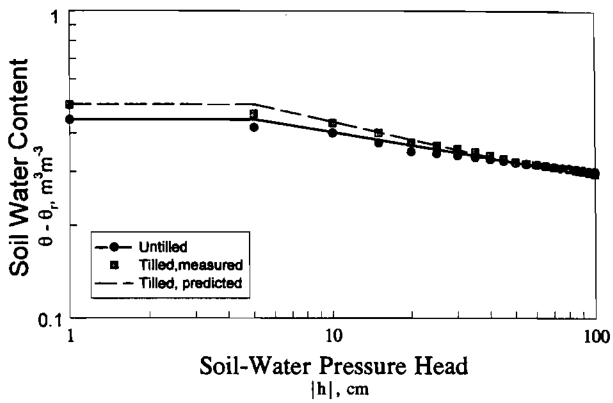

Fig. 5. Soil water retention curve of a tilled Le Sueur clay loam (sampled in September) estimated from the untilled soil curve assuming that the air-entry value remains the same and the change due to tillage effects extend up to a pressure head, $|h|$, 10 times the air-entry value. θ_r is the residual soil water content and equaled 0.06. Equations [6, 7, 8] were used.

Model 2

This model is designed for the situations where the curve for tilled soil between $h_{e\,till}$ and $10h_{e\,till}$ deviates significantly from a log-log linear relationship or the curve for even the untilled soil between these h values cannot be adequately represented as a log-log linear relationship of Eq. [1]. Equations [6] and [7] are still assumed to hold.

Let the difference of the volumetric soil water content, θ, between the tilled soil and untilled soil at any fixed pressure head, h, be denoted as $\Delta\theta(h)$. Let us further assume that $\Delta\theta(h)$ changes inversely with h as follows, below the air-entry value h_e:

$$\frac{d(\Delta\theta)}{d|h|} = \frac{B}{|h|} \qquad h < h_e \qquad [9]$$

where $\Delta\theta$ is a function of h, $\Delta\theta(h) = \theta_{till}(h) - \theta_{notill}(h)$, h is any fixed value of h, and B is a constant. This equation of change is at least qualitatively correct and perhaps adequate at this point in our knowledge. Integrating Eq. [9] gives:

$$\Delta\theta(h) = B\, ln|h| + C \qquad [10]$$

with C another constant. This equation is subject to boundary conditions as follows:

$$h = h_{e\,till}: \quad \Delta\theta = \Delta\theta_{max} = \theta_{s\,till} - \theta_{s\,notill} \qquad [11]$$

$$h = 10h_{e\,till}: \quad \Delta\theta = 0 \qquad [12]$$

Substituting Eq. [11] and [12] into [10] and rearranging finally results in:

$$\Delta\theta_{max} = B \ln|h_{e\,till}| + C \qquad 0 = B \ln|10h_{e\,till}| + C$$

$$C = -B \ln|h_{e\,till}|$$

$$\Delta\theta = B[\ln|h_{e\,till}| - \ln|10h_{e\,till}|]$$

$$= B \ln(h_{e\,till}/10h_{e\,notill})$$

$$= B \ln(0.1)$$

$$B = \frac{\Delta\theta_{max}}{\ln(0.1)} \qquad [13]$$

hence,

$$\Delta\theta(h) = \frac{\Delta\theta_{max}}{\ln(0.1)}[\ln|h| - \ln|10\,h_{e\,till}|]$$

$$= \frac{\Delta\theta_{max}\ln[h/(10\,h_{e\,till})]}{\ln(0.1)}$$

$$= -0.4343\Delta\theta_{max}\ln[h/(10h_{e\,till})] \qquad [14]$$

and

$$\theta(h)_{till} = \theta(h)_{notill} + \Delta\theta(h) \qquad [15]$$

The value of $\Delta\theta_{max}$ in Eq. [13] equals $\theta_{s\,till} - \theta_{s\,notill}$ and can be obtained from knowledge of soil bulk densities under tilled and untilled conditions. The bulk densities are assumed known by measurement or estimation. The estimated value of $h_{e\,till}$ is assumed equal to $h_{e\,notill}$. If Eq. [3] is used, $A_{till}(\theta_{s\,till} - \theta_{r\,till}) = A_{notill}(\theta_{s\,notill} - \theta_{r\,notill})$, and $\theta_{r\,till}$ is assumed equal to $\theta_{r\,notill}$. Thus, all parameters are available to estimate $\theta(h)_{till}$ by using Eq. [14] and [15].

MATERIALS AND METHODS

The concepts of Eq. [6, 7, 8] and Eq. [6, 7, 14] were tested against the water retention data for four pairs of tilled vs.

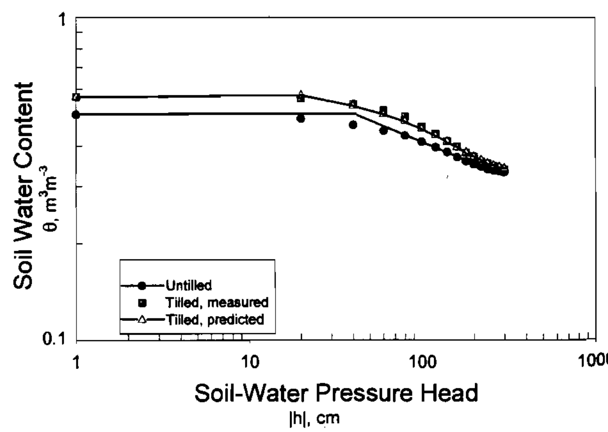

Fig. 6. Soil water retention curve of a tilled Molokai silty clay loam estimated from the untilled soil curve assuming that the change in soil water retention is inversely proportional to $|h|$ in the pressure head range from air-entry value to 10 times the air-entry value. Equations [6, 7, 15] were used.

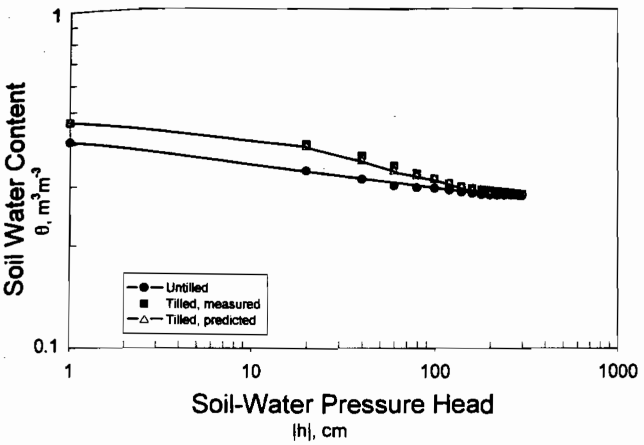

Fig. 7. Soil water retention curve of a tilled Waialua clay estimated from the untilled soil curve assuming that the change in soil water retention is inversely proportional to $|h|$ in the pressure head range from air-entry value to 10 times the air-entry value. Equations [6, 7, 8a, 15] were used.

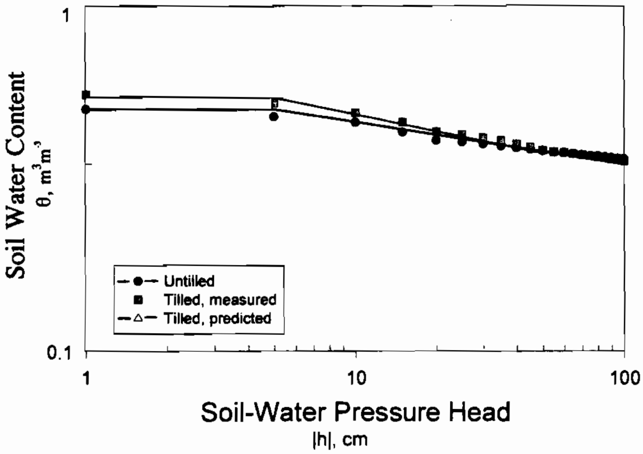

Fig. 9. Soil water retention curve of a tilled Le Sueur clay loam (sampled in September) estimated from the untilled soil curve assuming that the change in soil water retention is inversely proportional to $|h|$ in the pressure head range from air-entry value to 10 times the air-entry value. Equations [6, 7, 15] were used.

untilled or fully reconsolidated water retention curves available in the literature — for Molokai and Waialua soils (Mapa et al., 1986) and for Le Sueur soil (Gantzer and Blake, 1978).

For a Molokai silty clay loam (very-fine, kaolinitic, isohyperthermic Rhodic Eutrustox) and a Waialua clay variant (clayey, kaolinitic, hyperthermic vertic Haplustoll), Mapa et al. (1986) measured the soil water retention curves on undisturbed soil cores taken right after tillage and after each wetting and drying cycle. Their results showed that the soil water retention curves changed the most during the first wetting and drying cycle, much less in subsequent cycles, and there was practically no change during the fifth cycle. We treated the curves measured after the fifth cycle as the fully reconsolidated condition, equivalent to the no-till condition.

For the Le Sueur soil (fine-loamy, mixed, mesic Aquic Argiudoll), Gantzer and Blake (1978) measured water retention curves on undisturbed soil cores taken from adjoining tilled and untilled locations at two different times of the year, May and September 1969.

For each pair of water retention curves, we took the curve for untilled soil or the fully reconsolidated soil as the reference for Eq. [6, 7, 8] or Eq. [6, 7, 14]. The calculations were compared with the experimentally measured data points for the tilled condition. For using Eq. [6, 7, 8], the residual soil water content, θ_r, was set equal to 0.06 in all cases. Based on initial trials, this value of θ_r seemed to be close to optimal. The air-entry value for the untilled soil was determined by plotting the data on a log-log graph, fitting a linear regression to the points that seemed to fall along a straight line, then extending this fitted line to $\theta = \theta_s$, and finding the value of h corresponding with θ_s on the x axis.

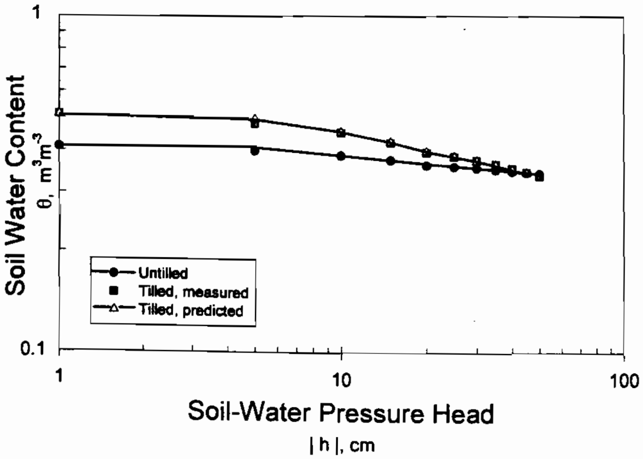

Fig. 8. Soil water retention curve of a tilled Le Sueur clay loam (sampled in May) estimated from the untilled soil curve assuming that the change in soil water retention is inversely proportional to $|h|$ in the pressure head range from air-entry value to 10 times the air-entry value. Equations [6, 7, 15] were used.

RESULTS AND DISCUSSION

The result of calculations of the soil water retention curves for the tilled condition from the reference untilled or fully reconsolidated condition using Model 1, Eq. [6, 7, 8], are shown in Fig. 2 through 5 for the four pairs of data. For all soils, the assumption of no change in the air-entry pressure head due to tillage held reasonably well. For the Waialua soil, the water retention between the saturated value and the air-entry value was not assumed to be constant but was assumed to follow

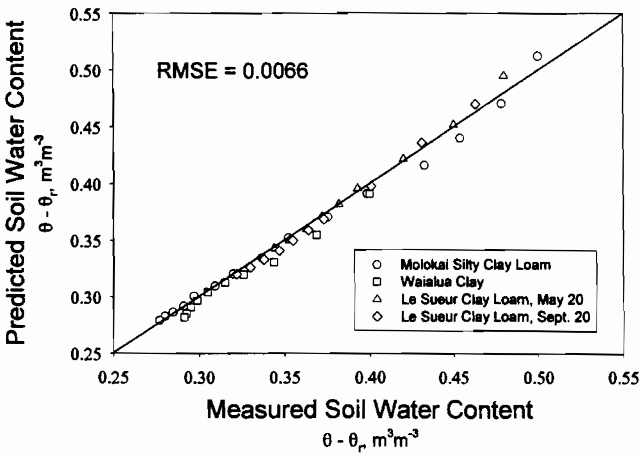

Fig. 10a. Predicted vs. measured soil water content for all pressure heads, $|h| < h_b$, and all soil data sets for Model 1 and the root mean square error (RMSE).

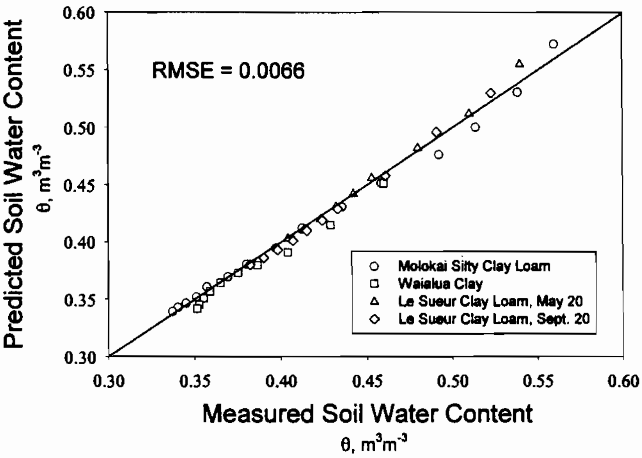

Fig. 10b. Predicted vs. measured soil water content for all pressure heads, $h < h_f$, and all soil data sets for Model 2 and the root mean square error (RMSE).

a linear decrease as in Eq. [3]. For pressure heads at and smaller than the air-entry value, the water retentions calculated by using Eq. [6, 7, 8] were very close to the measured values, all within the 0.00 to 0.032 m^3 m^{-3} range.

The calculations made for tilled conditions using Model 2, Eq. [6, 7, 15], are compared with the measured data in Fig. 6 through 9. Again, the calculated values at and below the air-entry value are reasonably close to the measured values, all within the 0.00 to 0.016 m^3 m^{-3} range. This model gives better results and does not require that the Brooks and Corey (1964) log-log function fit the data.

In Fig. 10a, we plotted Model 1 predicted vs. measured values of soil water content for all pressure heads, $h < h_f$, and all date sets. The root mean square error (RMSE) was 0.0066 and the R^2 was 0.99. In Fig. 10b, a similar plot for Model 2 results showed an RSME of 0.0066 and again, a R^2 of 0.99.

The results indicate either of the two simple empirical models provide a reasonable estimation of the soil water retention curve for a tilled soil, given the curve for the untilled soil and the soil bulk density changes due to tillage. Model 2, based on Eq. [6, 7, 15], is more general than Model 1 based on Eq. [6, 7, 8]. In this work, we have used these models to estimate the water retention curve of a tilled soil from that of an untilled or fully reconsolidated soil. Obviously, the models could also estimate curves for partially reconsolidated soil conditions, if the corresponding transient soil bulk density is known.

We emphasize that both of these simple empirical models are first approximations; we consider them as a starting point for the future development of more physically based models. We hope that this work will encourage interest among our colleagues toward this area of study. However, the above simple models may apply only for the case of tillage followed by natural reconsolidation, not wheel-track compaction. The effects of compaction on the soil water retention is another potential research area.

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