PREDICTING WATER CHARACTERISTIC CURVES FOR UNSATURATED SOILS FROM BULK DENSITY AND PARTICLE SIZE DISTRIBUTIONS

D. L. Nofziger, Jin-Song Chen, and B. J. Carter
Department of Agronomy
Oklahoma State University

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University Center for Water Research
Oklahoma State University
Stillwater, Oklahoma

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ABSTRACT

Simulation models are useful in estimating the fate of agricultural chemicals and their impact on ground water quality. These models require soil hydraulic properties to estimate water and chemical movement. Characterization of soils in Oklahoma did not include measurement of basic hydraulic properties so these parameters must be determined before models can be used. The objective of this research is to evaluate several methods of estimating the water characteristic curve from parameters included in the soil survey. Four approaches were evaluated for eleven selected Oklahoma soils for depths up to 1.60 m. The approach based on fractal scaling of soil particle-size distribution by Tyler and Wheatcraft (1989) was not satisfactory. Regression models of Campbell (1985) and Saxton (1986) which also use particle size distributions provided good water content estimates for most soils at tensions greater than 10 kPa, although the results were not good for the very sandy Eufaula soil. In general, Campbell's model produced better estimates than Saxton's. Saxton's equations for estimating saturated water content overestimated the measured values in most soils. Estimates with the one-parameter model of Gregson et al (1987) were slightly better than those from Campbell's method, but this approach requires one measured value on the water characteristic curve. Predictions of the depth of chemical as a function of time for water contents determined with Campbell's and Gregson's methods approximated results from measured values very well when differences between measured values across sites for a particular soil were considered. Monte Carlo simulation was used to obtain distributions of depth of aldicarb and atrazine at specific times after application for different weather records at one location in Caddo County, Oklahoma. The distributions of the depths for estimated and measured parameters were very similar for Campbell's and Gregson's methods. It appears that these two methods provide good estimates of water release curves for all but the extremely sandy soils.

INTRODUCTION

Protecting ground water quality from degradation by agricultural chemicals and industrial and municipal wastes is a research priority for Oklahoma, the region, and the nation. Previous work has shown that the rate and pattern of movement of chemicals and the amount of chemical reaching ground water depend upon the pattern and the rate of water movement in the unsaturated soil, the adsorption of the chemical on the soil solids, and the degradation rate of the chemical. Models have been developed to estimate the rate and the amount of chemical movement through soils. These models are being incorporated into decision-making and natural resource management tools (Nofziger and Hornsby, 1986; Zhang et al, 1990). A lack of soil hydraulic properties limits widespread use of these tools.

The soil water characteristic function or the relationship between soil water content and tension is often not available for soils. Different laboratory and *in situ* field procedures have been used to determine water characteristics. However, most of these methods are tedious, time consuming, and expensive. Frequently, intensive field or laboratory measurements are not feasible for obtaining water characteristics for large areas such as counties or states. Therefore, scientists are investigating methods of estimating the water characteristic functions from existing data such as soil texture. The objective of this project was to evaluate published techniques for estimating the water characteristic curves for soils in Oklahoma. Estimated water contents are compared with measured values at different tensions.

Since our immediate use of the water characteristic curves is modeling movement of agricultural chemicals in soils, measured and estimated water contents were used in the Chemical Movement In Layered Soils (CMLS) model of Nofziger and Hornsby (1986). Model outputs for measured and estimated parameters were compared for different chemicals and different weather sequences with and without supplemental irrigation. The CMLS model requires estimates of water content at "field capacity" and "permanent wilting point" for each soil layer. These values were taken to be the water content of the soil at tensions of 10 kPa and 1500 kPa, respectively.

METHODOLOGY

Experimental Measurements:

Four soils from Caddo County, Oklahoma, were selected for this study as listed in Table 1. Sites containing these soil series were identified by professional soil scientists from the Soil Conservation Service. Soil cores (73 mm diameter, 76 mm long) were taken to a depth of 1.60 m at intervals of 0.2 m. Three sites were sampled for each series. Particle size distribution, bulk density, soil water content at 1, 5, 10, 15, 33.3, 100, 500, and 1500 kPa soil water tension, and organic carbon were determined for each sample. Unpublished data of J.M. Davidson for seven Oklahoma soils were also analyzed. Those soils are also listed in Table 1. Since organic carbon, OC, was not determined on those seven soils, values of OC for the same soil series in Oklahoma were used (Ford et al, 1976; Gray and Roozitalab, 1976).

Table 1. Classification of soil used in the study.

Soil	Classification
Cobb loamy sand	Fine-loamy, mixed, thermic Udic Haplustalfs
Eufaula sand	Sandy, siliceous, thermic Psammentic Paleustalfs
Noble sandy loam	Coarse-loamy, siliceous, thermic Udic Ustdchrepts
Pond Creek sandy loam	Fine-silty, mixed, thermic Pachic Agriustolls
Cobb sandy loam[a]	Fine-loamy, mixed, thermic Udic Haplustalfs
McLain silty clay loam[a]	Fine, mixed, thermic Pachic Agriustoll
Port silty clay[a]	Fine-silty, mixed, thermic Cumulic Haplustolls
Teller loam[a]	Fine-loamy, mixed, thermic Udic Agriustolls
Tuttle silt loam[a]	Fine, mixed, thermic Pachic Agriustolls
Richfield loam[a]	Fine, montmorillonitic, mesic Aridic Argiustolls
Zaneis loam[a]	Fine-loamy, mixed thermic Udic Argiustolls

a. From unpublished data of J. M. Davidson. Formerly at Oklahoma State University. Presently at University of Florida, Gainesville, FL.

Estimation Methods:

Four methods were evaluated for predicting soil water characteristics from soil texture and bulk density. Method 1 is that of Tyler and Wheatcraft (1989). This method uses fractal analysis to give physical significance to a parameter in the empirical model of Arya and Paris (1981). Pore sizes of the porous media were correlated with the particle size using the equation

$$r_i = R_i[2/3eN_i^{1-D}]^{1/2}. \tag{1}$$

where R_i is the radius of particle group, N_i is number of particles making up the particle group, e is void ratio, r_i is the pore size of a single cylinder which represents the entire pore volume formed by the assemblage of particles in the *i*th size group, and D is the fractal dimension determined experimentally. Water content, θ_i, ($m^3\ m^{-3}$), at given soil water tension, ψ_i, (kPa), is calculated from cumulative volume of pores of radius equal to or smaller than the radius, r_i, of a capillary tube at tension ψ_i.

Methods 2, 3, and 4 are regression models based on the empirical relationship between soil water tension, ψ, and volumetric water content, θ, of Brooks and Corey (1964). This relationship for tensions greater than the air-entry value, ψ_e, is given by

$$\psi = \psi_e\ [(\theta - \theta_r)/(\theta_s - \theta_r)]^B \tag{2}$$

where θ_s is the saturated water content and θ_r is the residual water content. The regression coefficients used in this study are those reported by the authors of the methods. No calibration for Oklahoma soils was done.

Method 2 is a regression model developed by Saxton et al (1986), in which the θ_r is taken to be zero and equation 2 is then rewritten in the form

$$\psi = A\ \theta^B \tag{3}$$

where $A = \psi_e/\theta_s^B$. Regression equations for A and B in terms of clay and sand content were obtained based on the work of Rawls et al (1982) analyzing 2541 soil horizons. Saxton et al also developed equations for tensions less than the air-entry value. The equations and coefficients used are shown in Table 2.

Method 3 is a regression model developed by Campbell (1985) which relates ψ_e and B in equation 2 to the geometric particle diameter, d_g, the geometric standard deviation, σ_g, and bulk density, ρ_b (θ_r was assumed to be zero). These equations are

$$\psi_{es} = 0.5\ (d_g)^{-0.5} \tag{4}$$

and

$$B = 2\ \psi_{es} + 0.2\ \sigma_g \tag{5}$$

and

$$\psi_e = \psi_{es}(\rho_b/1.3)^{-0.67B} \tag{6}$$

where d_g is in millimeters, ρ_b is in Mg m^{-3}, and tensions are in kPa. In these equations, $d_g = \exp(a)$ and $\sigma_g = \exp(b)$ where

$$a = \Sigma\ m_i\ \ln(d_i)$$

$$b = \{\Sigma\ m_i[\ln(d_i)]^2 - a^2\}^{0.5}$$

and m_i is the fraction of the soil mass in texture group i and d_i is the arithmetic mean diameter of class i. Summations are taken over three texture

Table 2. Equations for method of Saxton et al (1986).

For $10 \text{ kPa} \leq \psi < 1500 \text{ kPa}$, $\psi = A\theta^B$ where

$$A = 100\exp[-4.396 - 0.0715(\%C)^2 - 4.880\times10^{-4}(\%S)^2 - 4.285\times10^{-5}(\%S)^2(\%C)]$$

$$B = -3.140 - 2.22\times10^{-3}(\%C)^2 - 3.484\times10^{-5}(\%S)^2(\%C)$$

For $\psi_e \leq \psi < 10$,

$$\psi = 10.0 - (\theta - \theta_{10})(10.0 - \psi_e)/(\theta_s - \theta_{10})$$

where

$$\theta_{10} = \exp[(2.302 - \ln A)/B]$$

$$\psi_e = 100.0\ [-0.108 + 0.341\ \theta_s]$$

$$\theta_s = 0.332 - 7.251\times10^{-4}(\%S) + 0.1276 \log_{10}(\%C)$$

For $0 \leq \psi < \psi_e$, $\theta = \theta_s$

Symbols:

ψ	soil-water tension, kPa
ψ_e	soil-water tension at air entry, kPa
θ	volumetric water content, m^3m^{-3}
θ_s	volumetric water content at saturation, m^3m^{-3}
θ_{10}	volumetric water content 10 kPa tension, m^3m^{-3}
(%S)	percent sand
(%C)	percent clay

Restrictions:

$5\% \leq \%$ sand $\leq 30\%$ and $8\% \leq \%$ clay $\leq 58\%$

or

$30\% \leq \%$ sand $\leq 95\%$ and $5\% \leq \%$ clay $\leq 60\%$

classes, sand, silt, and clay, with mean diameters of 1.025 mm, 0.026 mm, and 0.001 mm, respectively. Saturated water content, θ_s, is required for this procedure. In this study, this value was taken to be 90% of the soil porosity calculated from bulk density (assuming a particle density of 2.65 Mg m^{-3}).

Equation 3, written in a slightly different form by Gregson et al (1987) forms the basis for method 4. In this case, equation 3 takes the form

$$\ln(\psi) = A' + B \ln(\theta) \tag{7}$$

where $A' = \ln(A) - B \ln(\theta_s)$. Gregson found that the coefficients A′ and B in this equation were highly negatively correlated and that A′ could be determined if B is known using the regression equation

$$A' = p + q B \tag{8}$$

where $p = -7.89$ and $q = -4.02$ (for ψ in MPa and θ percent by volume) for a wide range of soils from England, Wales, Scotland, Australia (Gregson et al, 1987) and Oklahoma (Williams et al, 1990). This relationship allows equation 7 to be written in terms of B only. That value of B can be determined by using one paired measurement of soil water content and potential. In this study, the measured water content at 10 kPa was used to evaluate B. The coefficients used for our units of tension and water content (kPa and m^3 m^{-3}) were $p = -0.98$ and $q = 0.585$.

Methods 2, 3, and 4 have abrupt changes in slope of the water characteristic curve at the tension of air entry. Hutson and Cass (1987) presented a method of smoothing the curve using a parabolic function. That approach was used in this research in the neighborhood of the air-entry value.

Evaluation of Estimation Methods:

In addition to graphical analyses, the root mean squared (RMS) error was used to evaluate the estimation methods. The root mean squared error was calculated as

$$RMS = [1/n \, \Sigma(S_{mi} - S_{pi})^2]^{0.5} \tag{9}$$

where the sum is taken over the range i = 1, 2, ..., n where n is the number of data points on the curve. S_{mi} and S_{pi} represent corresponding measured and predicted parameter values, respectively.

In addition to comparisons of measured and estimated water characteristic curves, the measured and estimated values were used as input into the CMLS model for predicting chemical movement in unsaturated soils. The model requires water contents at "field capacity" and "permanent wilting point" for each soil layer. These were taken as the water contents at 10 and 1500 kPa, respectively. The weather generator of Richardson and Wright (1984) was interfaced to CMLS to permit repeated simulation for many different weather records for one site in Caddo County, Oklahoma. Travel time for aldicarb and atrazine to reach selected depths and the predicted depth of the chemical at selected times were recorded. Simulated results were obtained for dryland and irrigated systems. Irrigation consisted of weekly applications of 50 mm from June 1 to September 30 each year. The mean depth of chemical movement and the distribution of depth of chemical movement at a specified time are compared based on results of one hundred simulations for each site. The organic carbon partition coefficients used for aldicarb and atrazine were 20 and 100 ml/g OC, respectively (Wauchope, 1990).

RESULTS AND DISCUSSION

Comparison of Measured and Estimated Water Contents:

Water characteristic curves determined in this study are shown for the upper three layers for each soil analyzed in Figures 1 to 19. Figures 1 to 12 show the measured water contents at each of three sites for each tension. Figures 13 to 19 show average water contents from unpublished data of J.M. Davidson. Water characteristic curves are shown in the figures for the four estimation methods used. Measured water contents at specific tensions vary from less than 0.01 m^3 m^{-3} to more than 0.10 m^3 m^{-3}. These differences reflect variability in hydraulic properties from site to site within a soil series as well as possible measurement error. These results span many soil textures as shown in Tables 3 and 4. The quality of estimates in these three layers are representative of those for other layers. Figures 20 to 30 show results for estimated water content versus measured water content. Data points for the entire profile are included on each graph.

The estimation method of Tyler and Wheatcraft consistently performed unsatisfactorily. This is consistent with Tyler and Wheatcraft (1990, personal communication) in which the authors point out that the magnitude of the fractal dimension found in their previous work (Tyler and Wheatcraft, 1989) was more a function of the plotting and fitting algorithm than of the fractal nature of the particle size distribution. No additional discussion of this method will be made in this report.

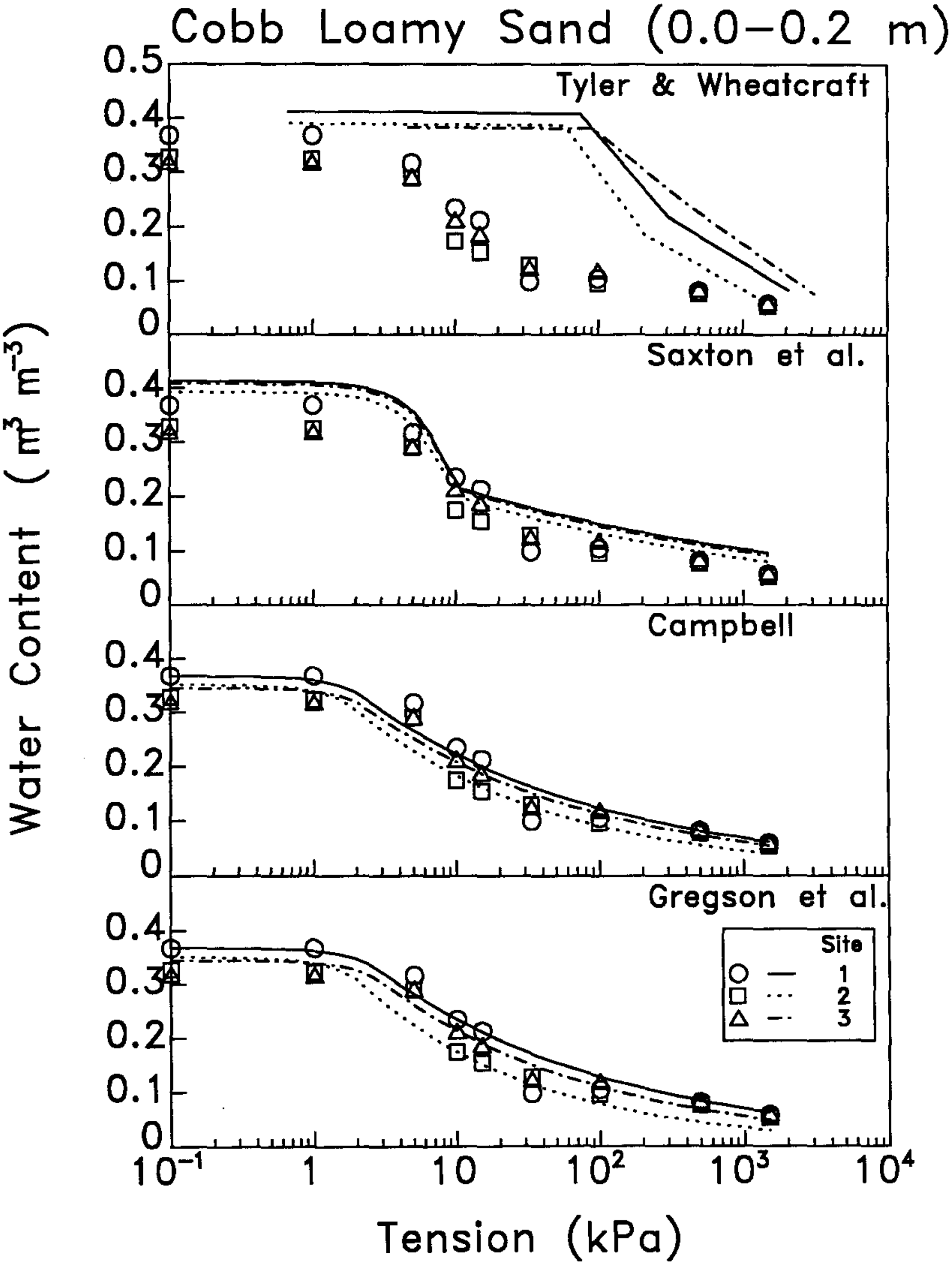

Figure 1. Measured and estimated soil water characteristics of Cobb loamy sand at the 0.0 to 0.2 m depth.

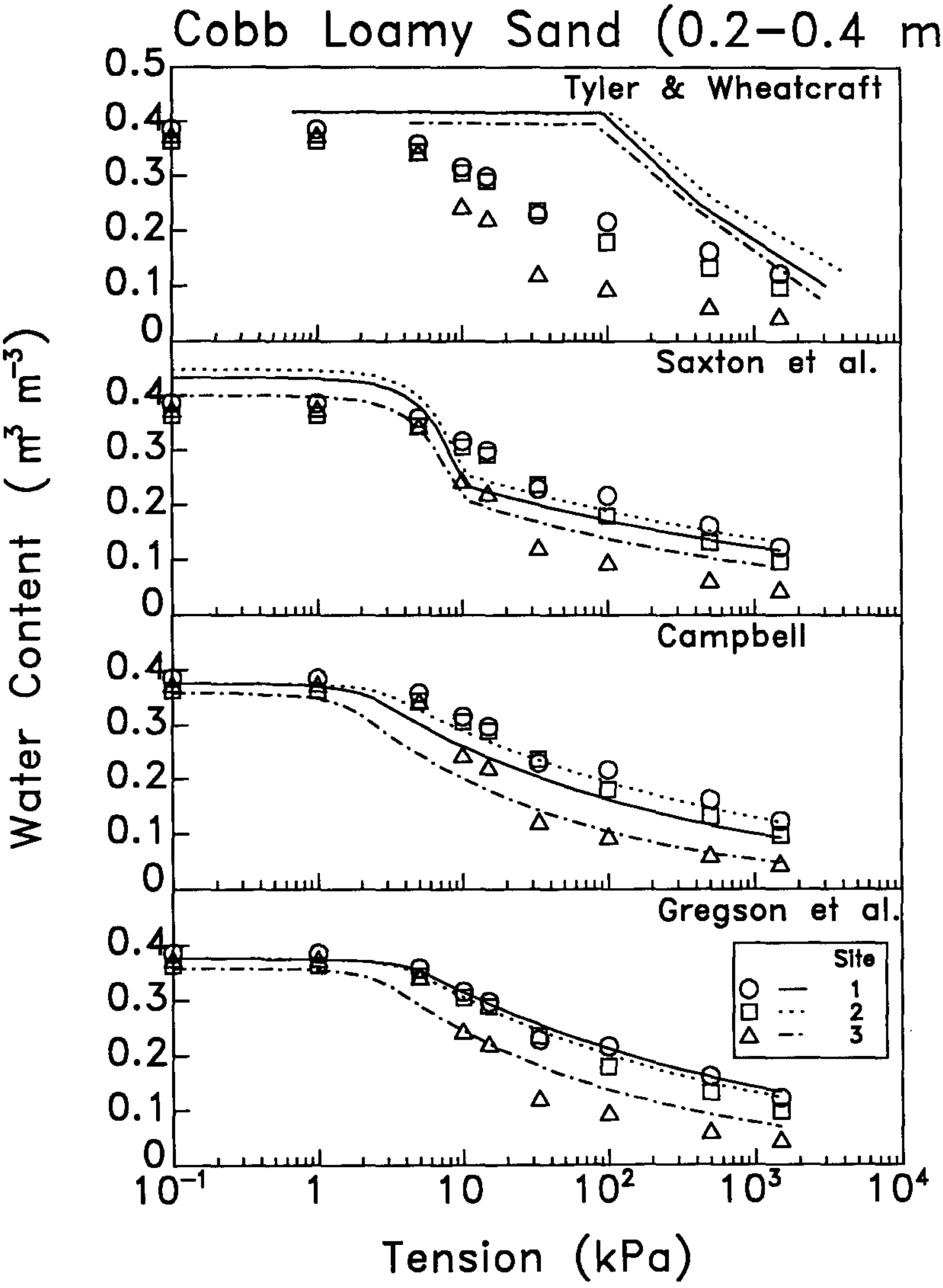

Figure 2. Measured and estimated soil water characteristics of Cobb loamy sand at the 0.2 to 0.4 m depth.

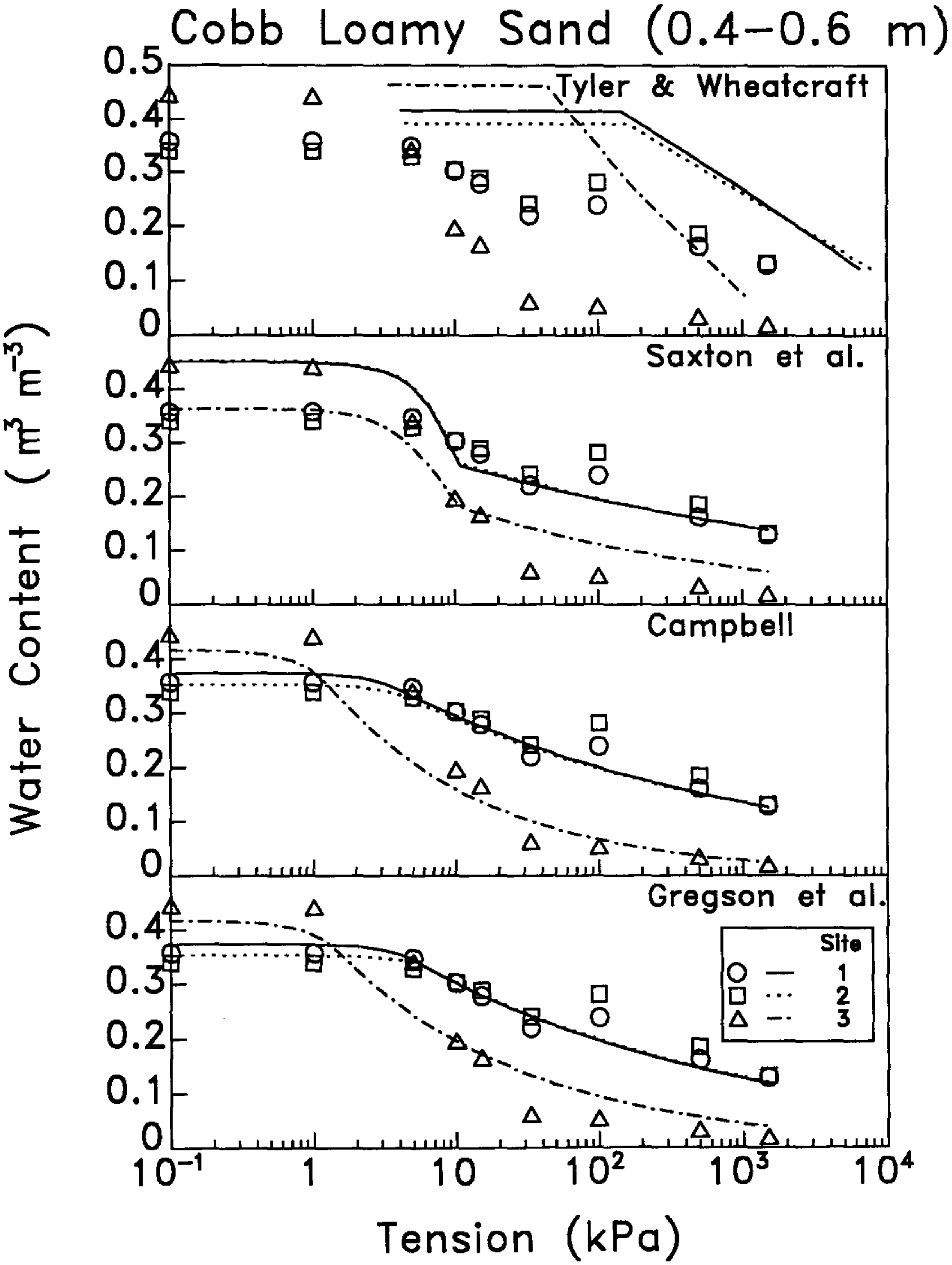

Figure 3. Measured and estimated soil water characteristics of Cobb loamy sand at the 0.4 to 0.6 m depth.

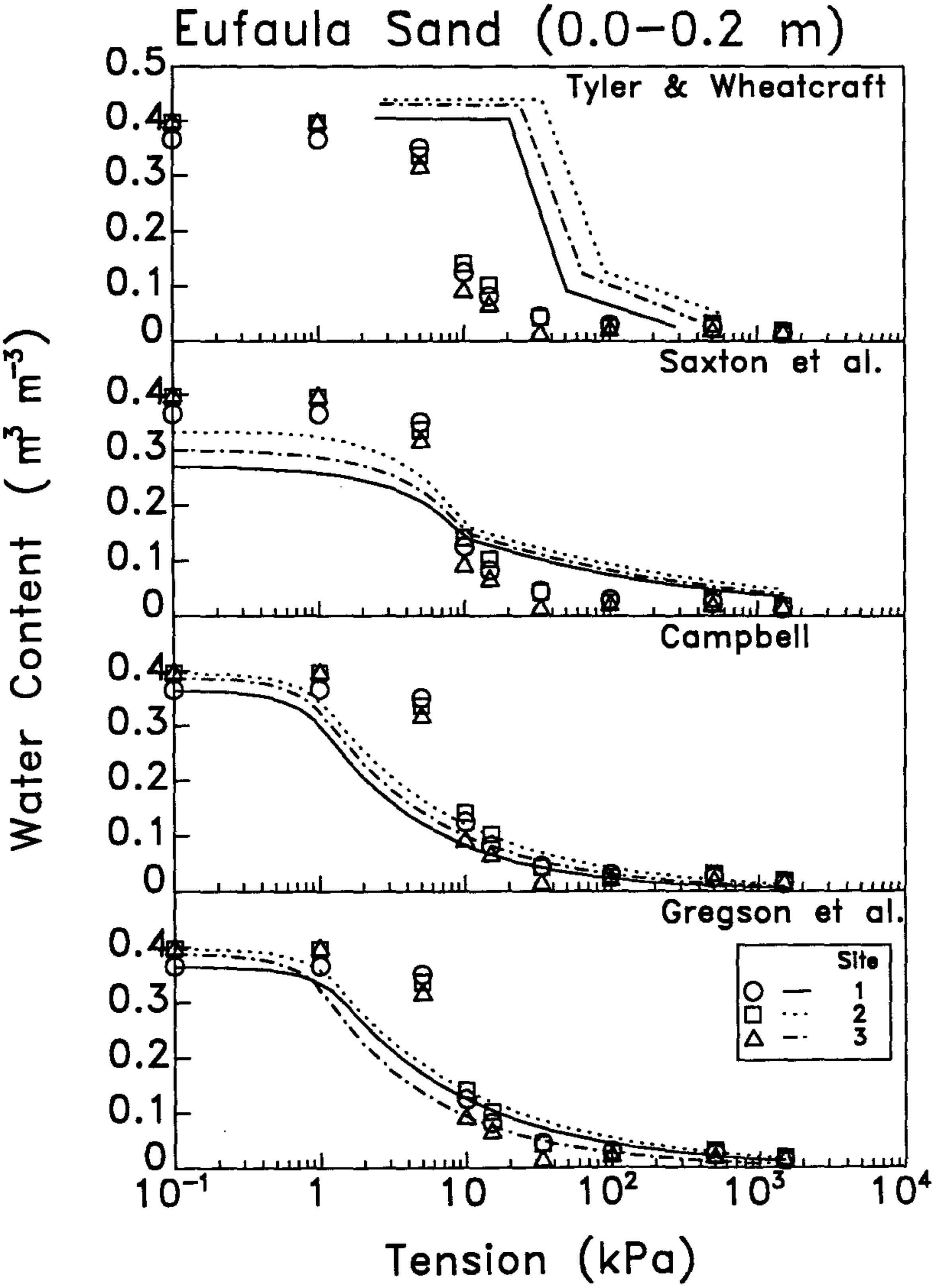

Figure 4. Measured and estimated soil water characteristics of Eufaula sand at the 0.0 to 0.2 m depth.

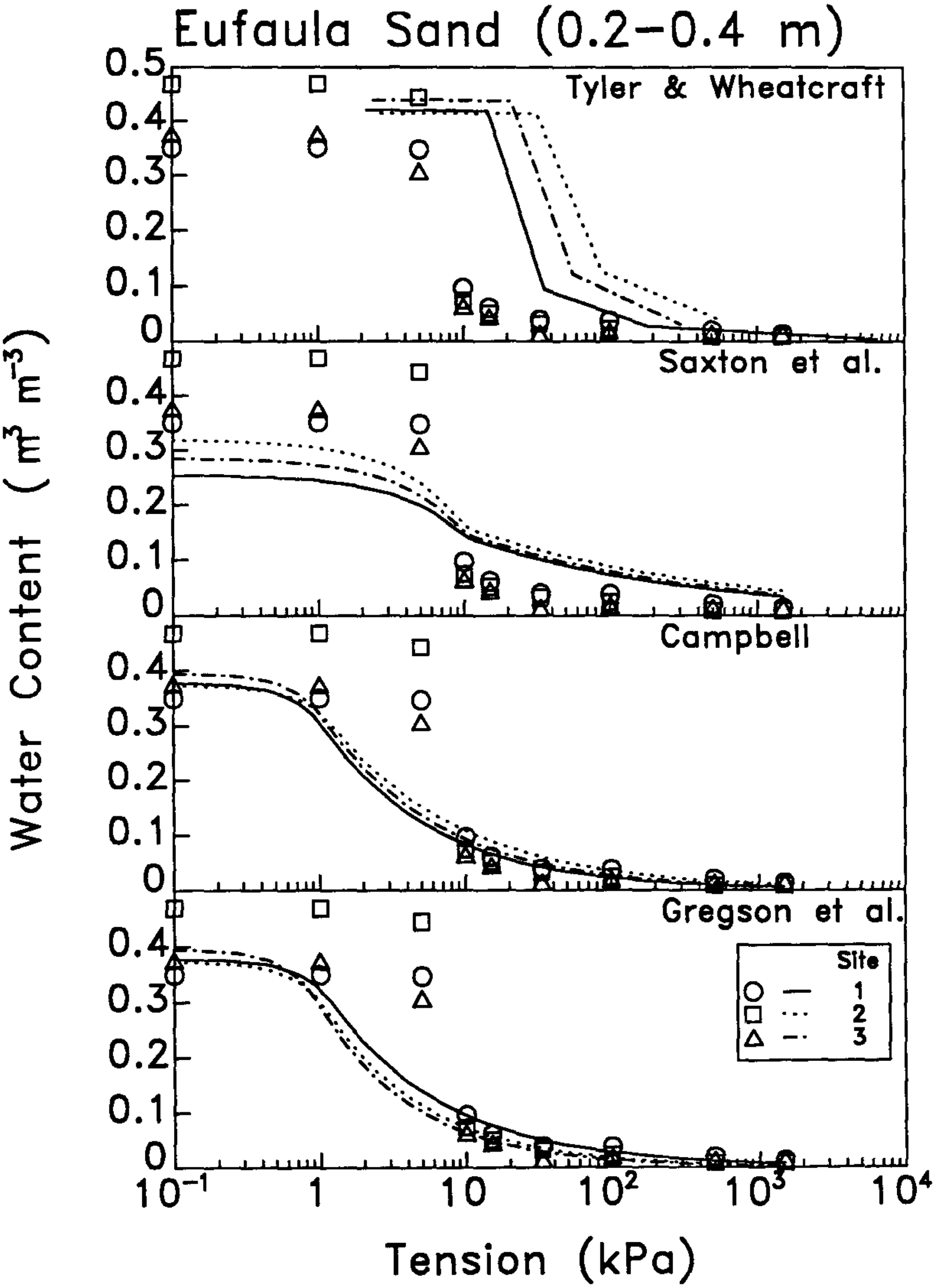

Figure 5. Measured and estimated soil water characteristics of Eufaula sand at the 0.2 to 0.4 m depth.

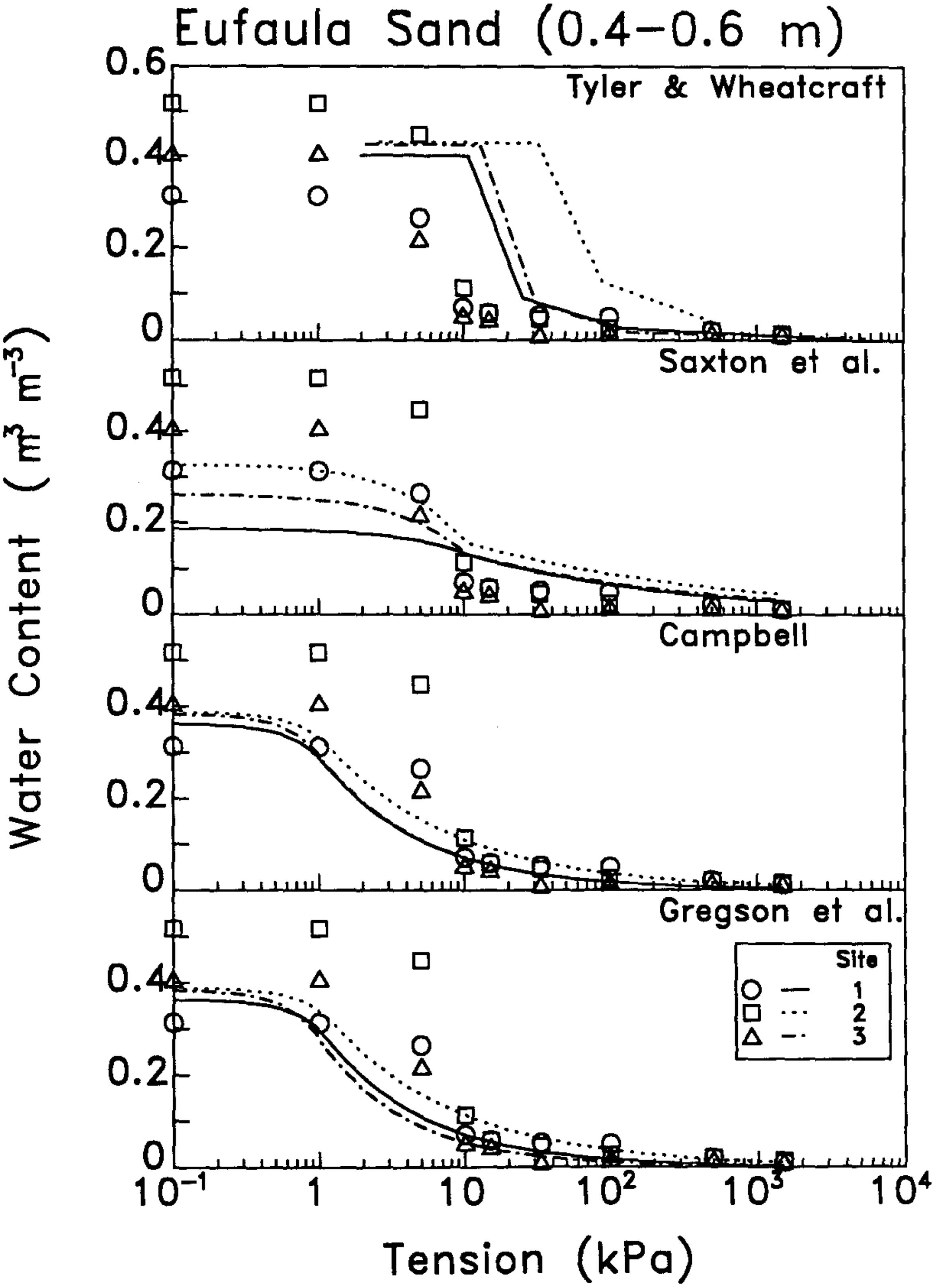

Figure 6. Measured and estimated soil water characteristics of Eufaula sand at the 0.4 to 0.6 m depth.

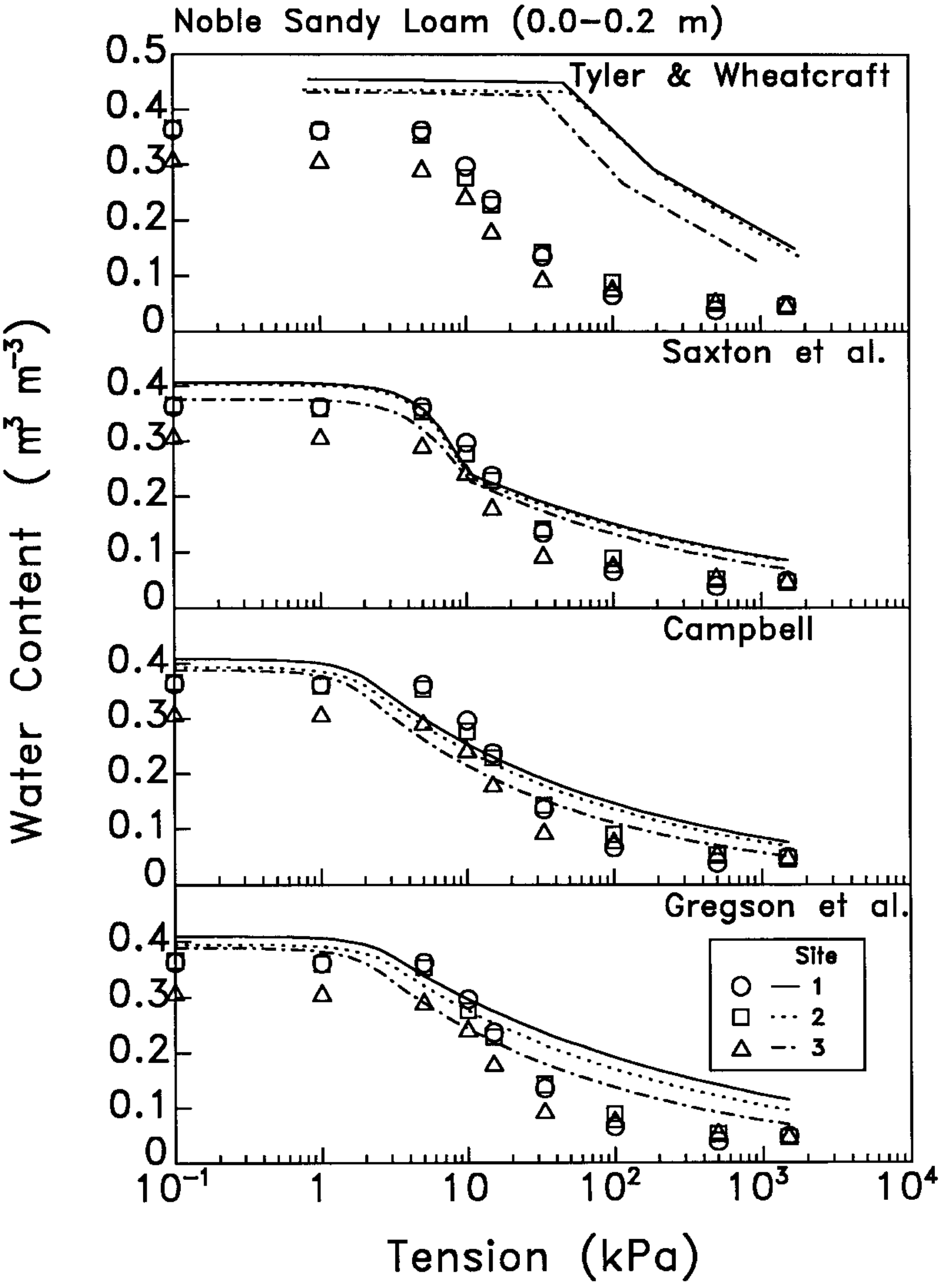

Figure 7. Measured and estimated soil water characteristics of Noble sandy loam at the 0.0 to 0.2 m depth.

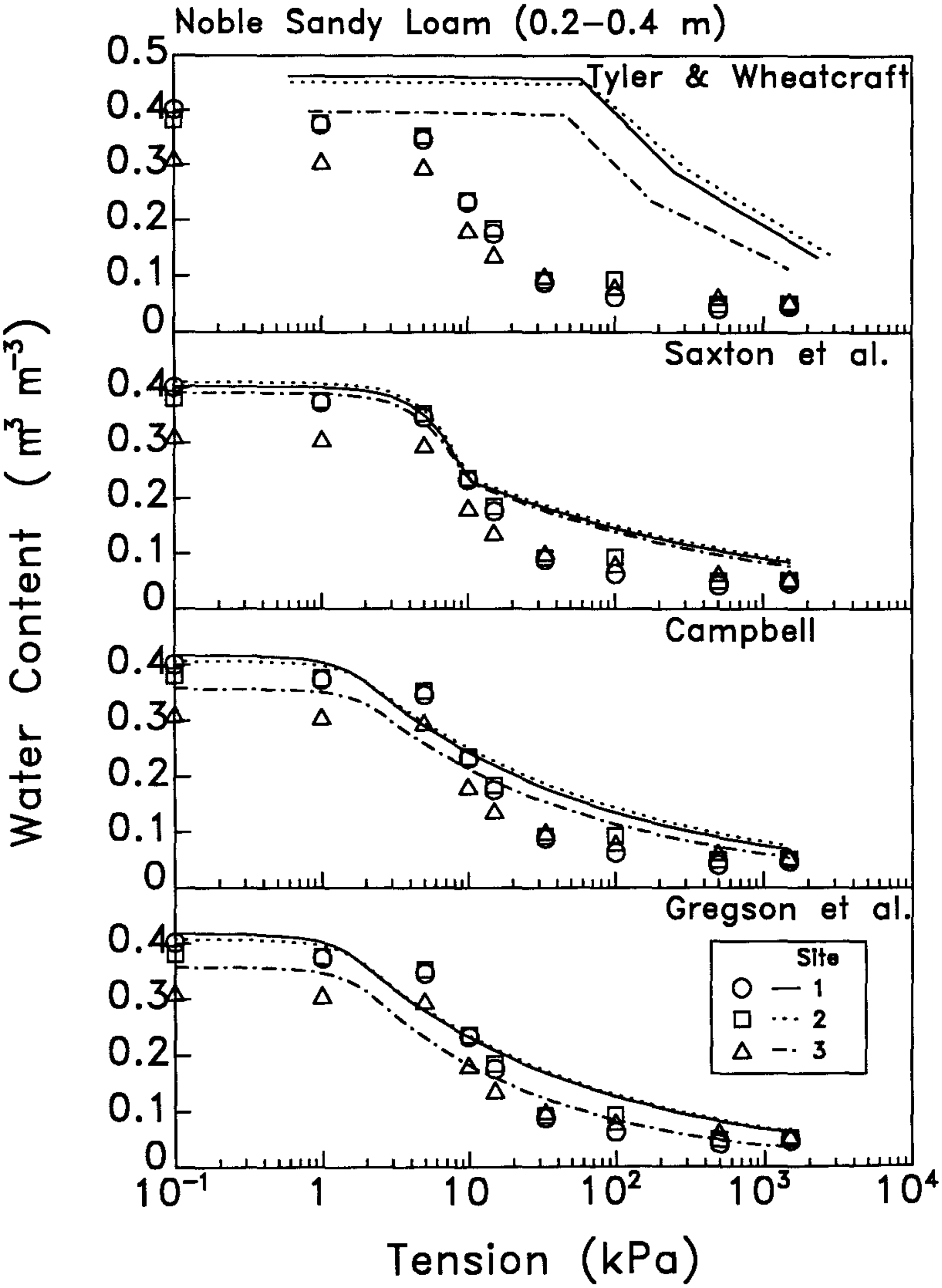

Figure 8. Measured and estimated soil water characteristics of Noble sandy loam at the 0.2 to 0.4 m depth.

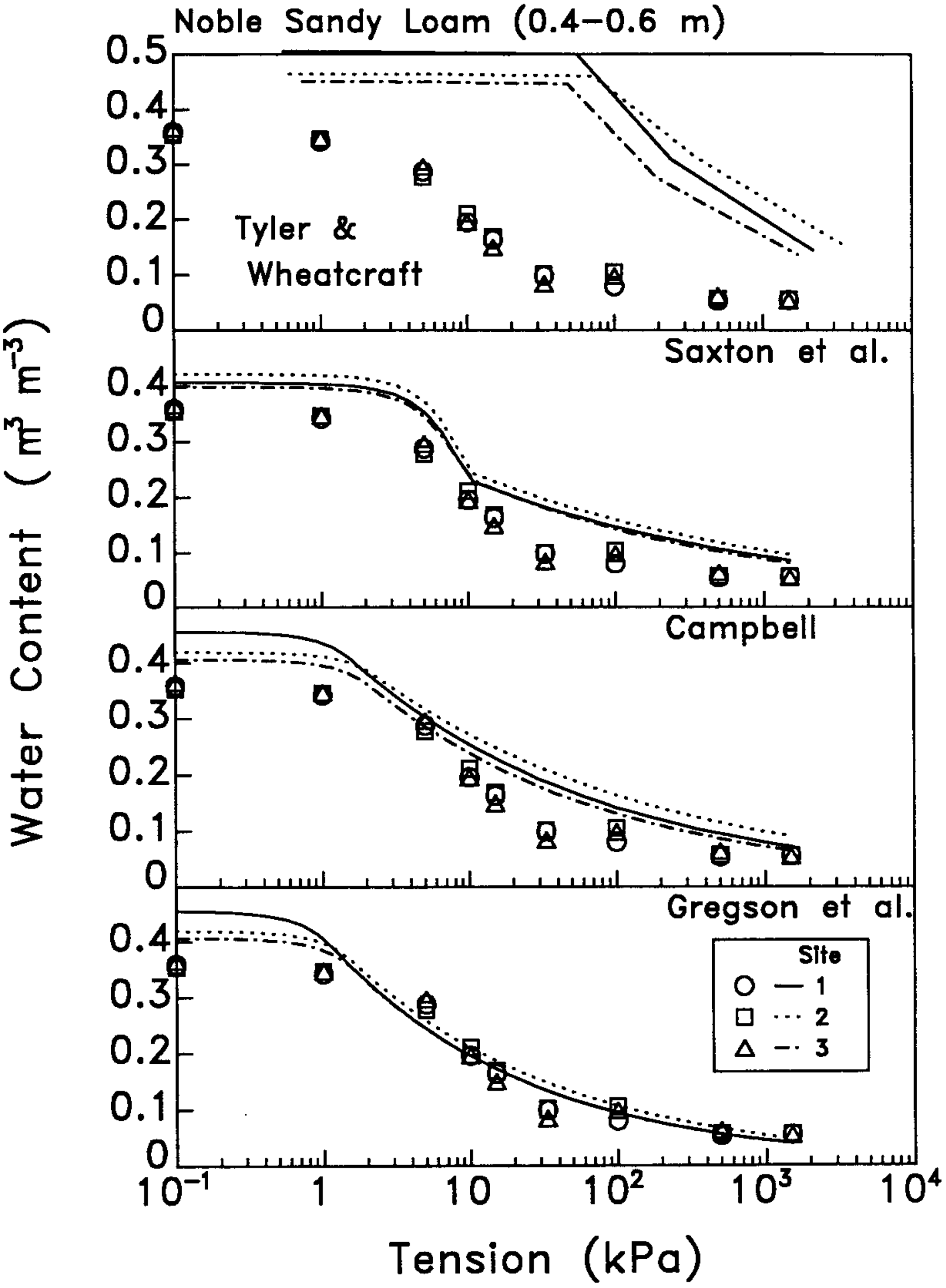

Figure 9. Measured and estimated soil water characteristics of Noble sandy loam at the 0.4 to 0.6 m depth.

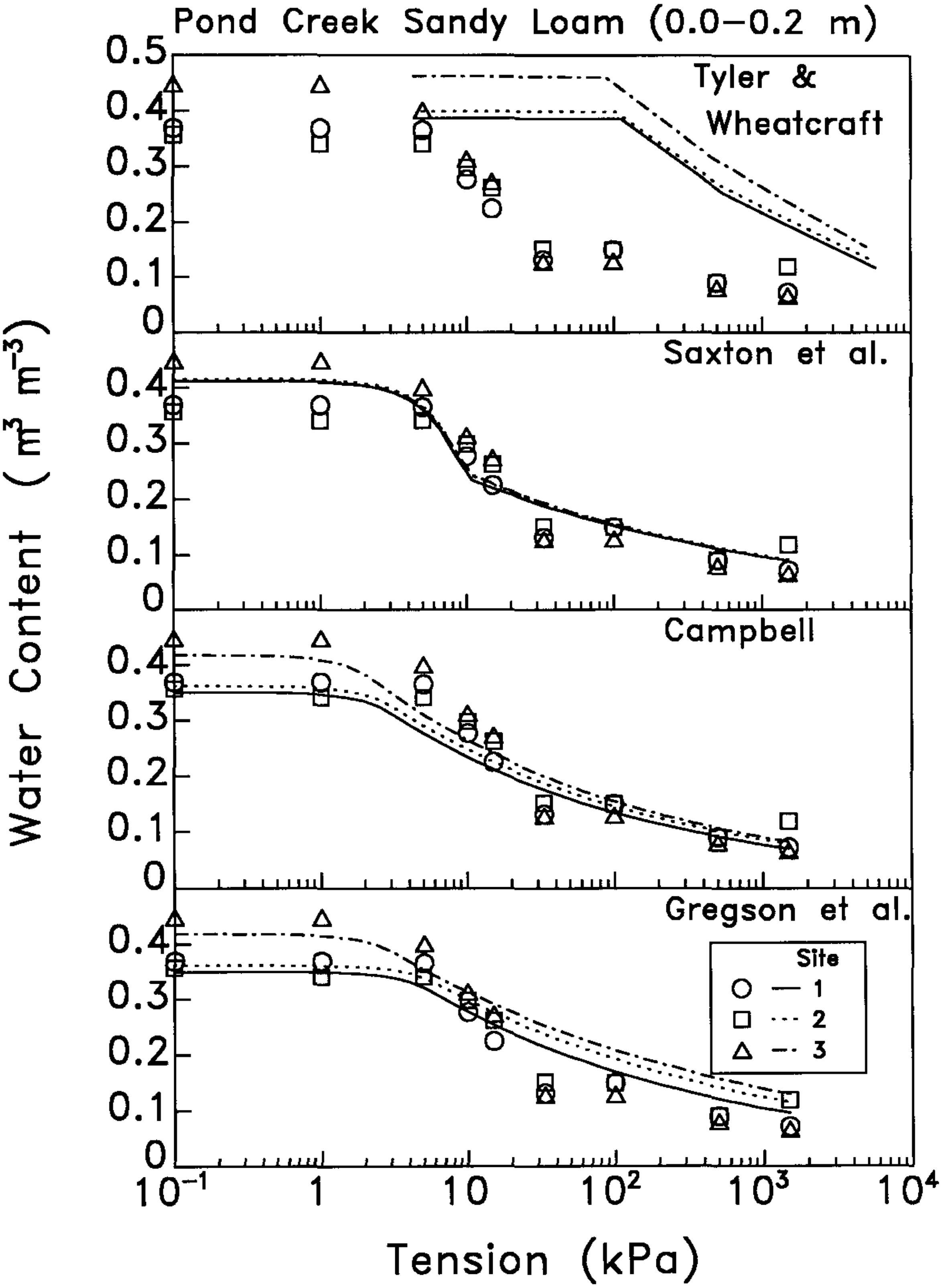

Figure 10. Measured and estimated soil water characteristics of Pond Creek sandy loam at the 0.0 to 0.2 m depth.

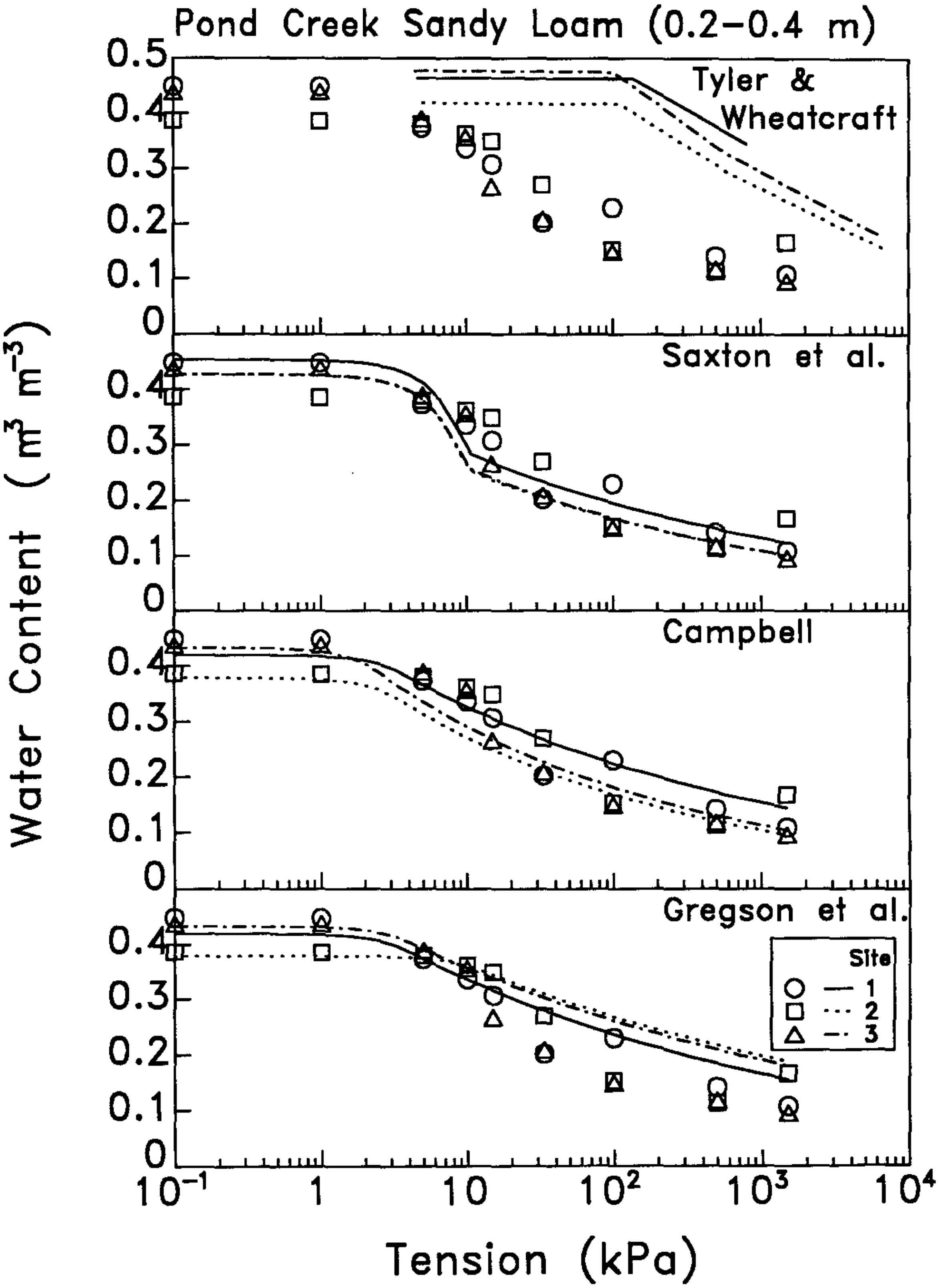

Figure 11. Measured and estimated soil water characteristics of Pond Creek sandy loam at the 0.2 to 0.4 m depth.

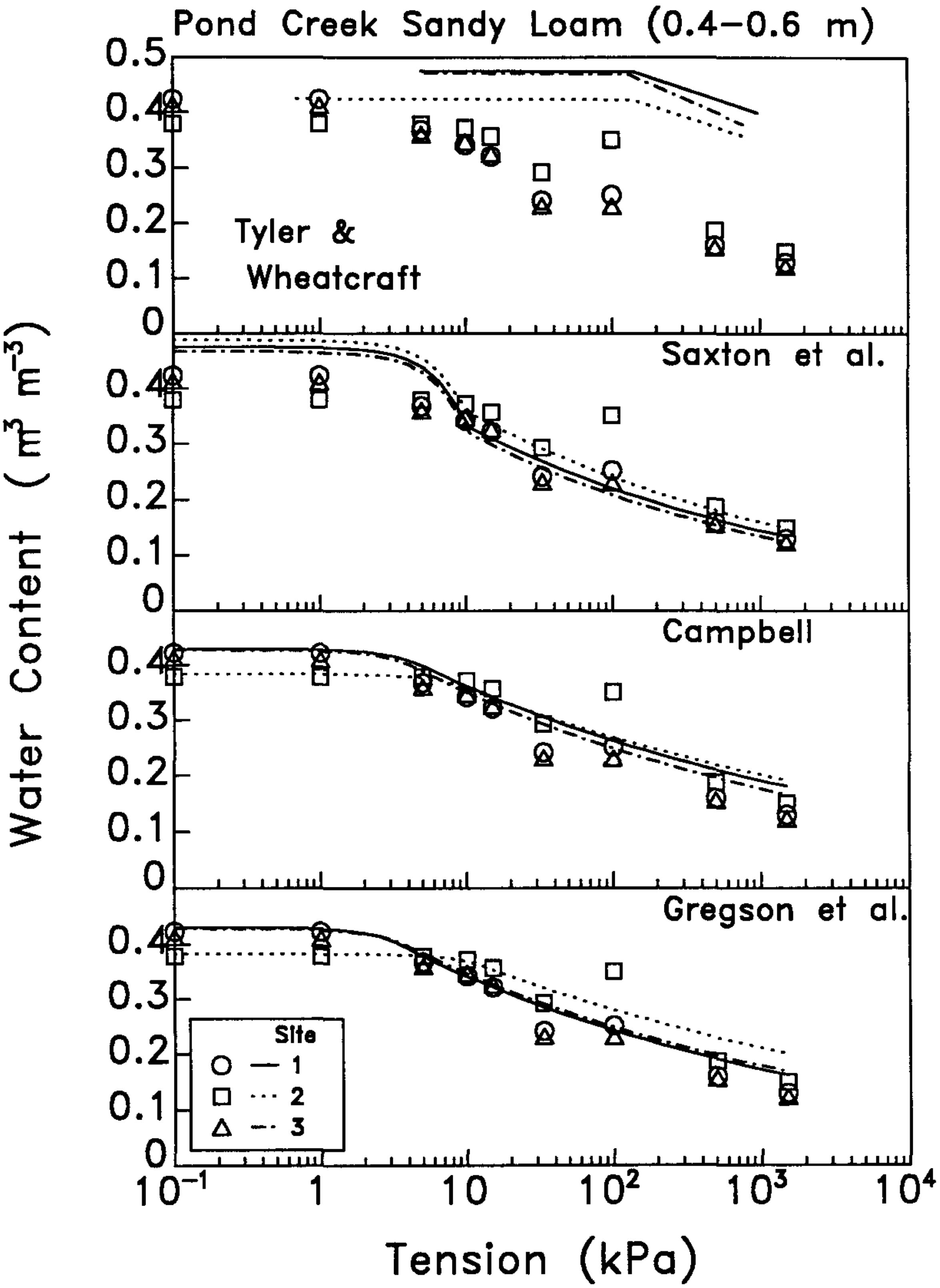

Figure 12. Measured and estimated soil water characteristics of Pond Creek sandy loam at the 0.4 to 0.6 m depth.

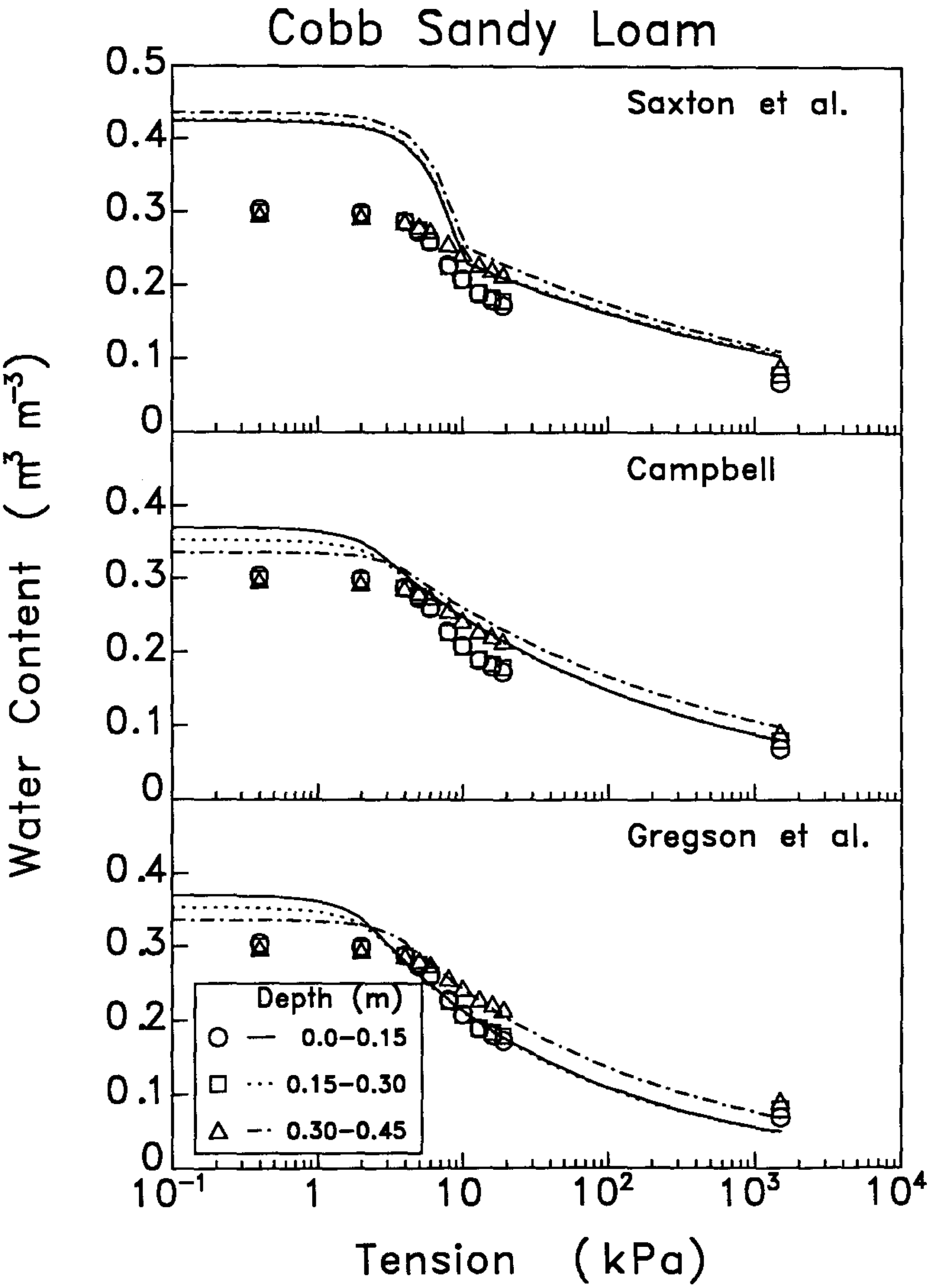

Figure 13. Measured and estimated soil water characteristics of Cobb sandy loam (Data from J.M. Davidson).

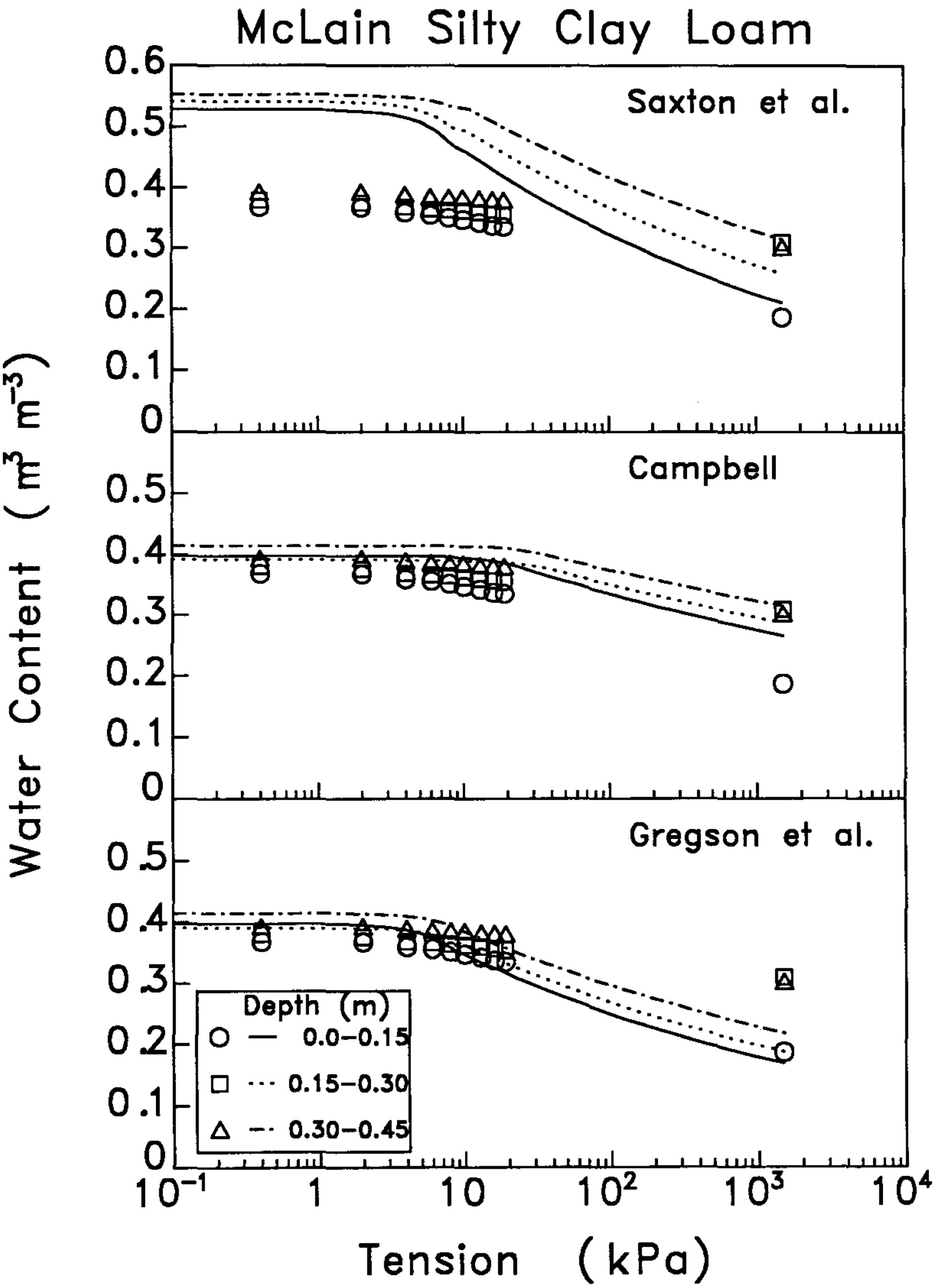

Figure 14. Measured and estimated soil water characteristics of McLain silty clay loam (Data from J.M. Davidson).

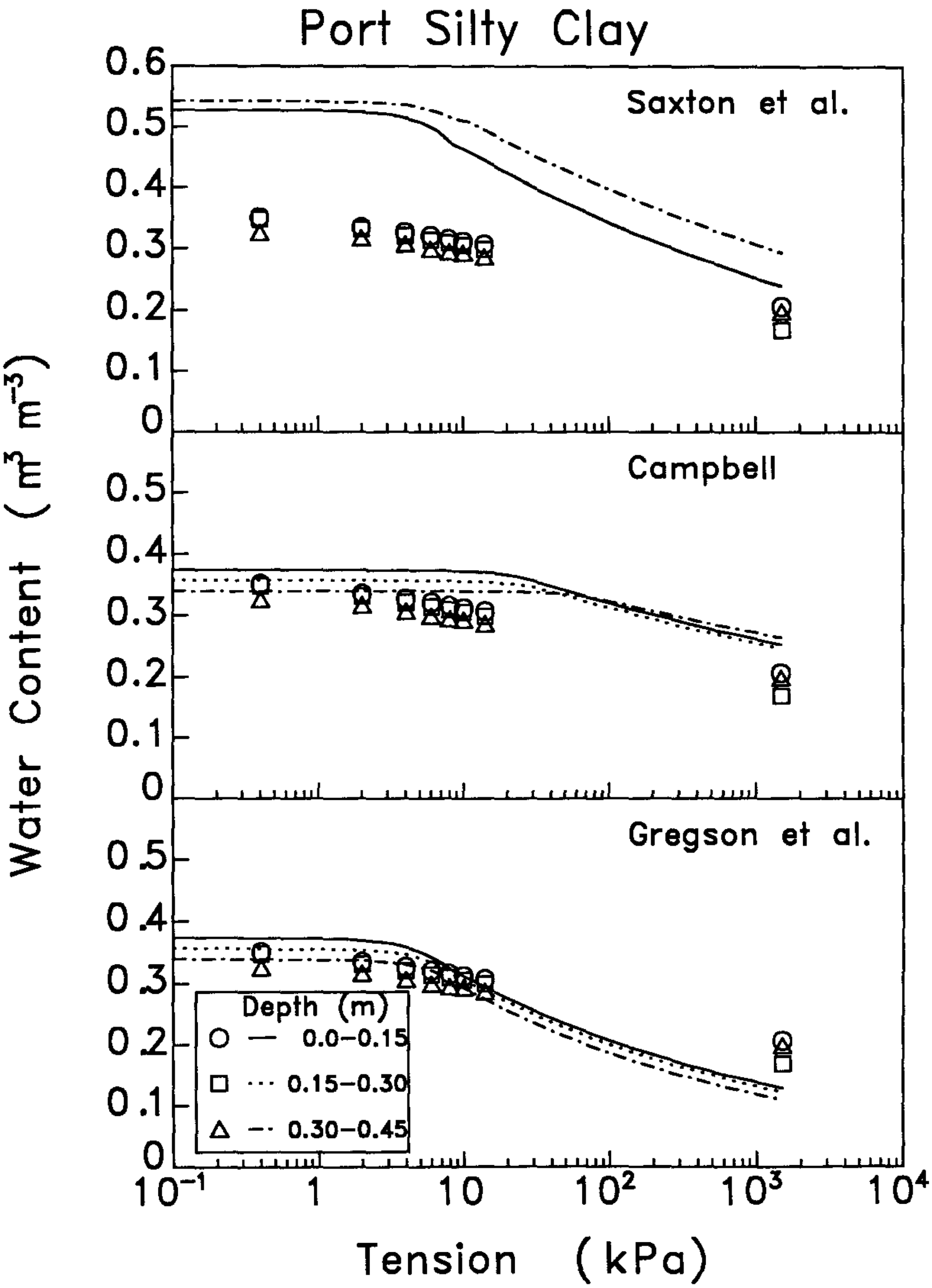

Figure 15. Measured and estimated soil water characteristics of Port silty clay (Data from J.M. Davidson).

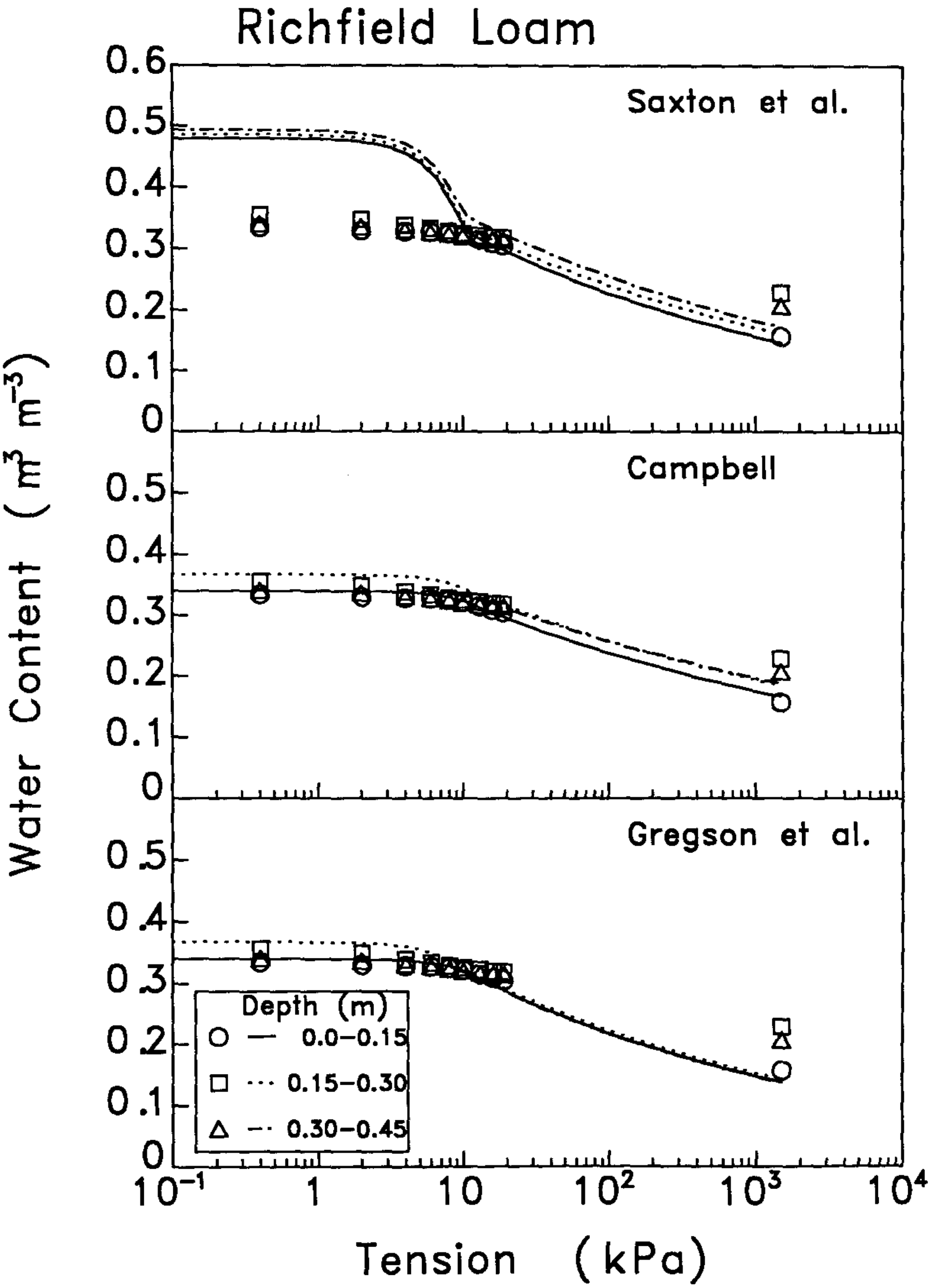

Figure 16. Measured and estimated soil water characteristics of Richfield loam (Data from J.M. Davidson).

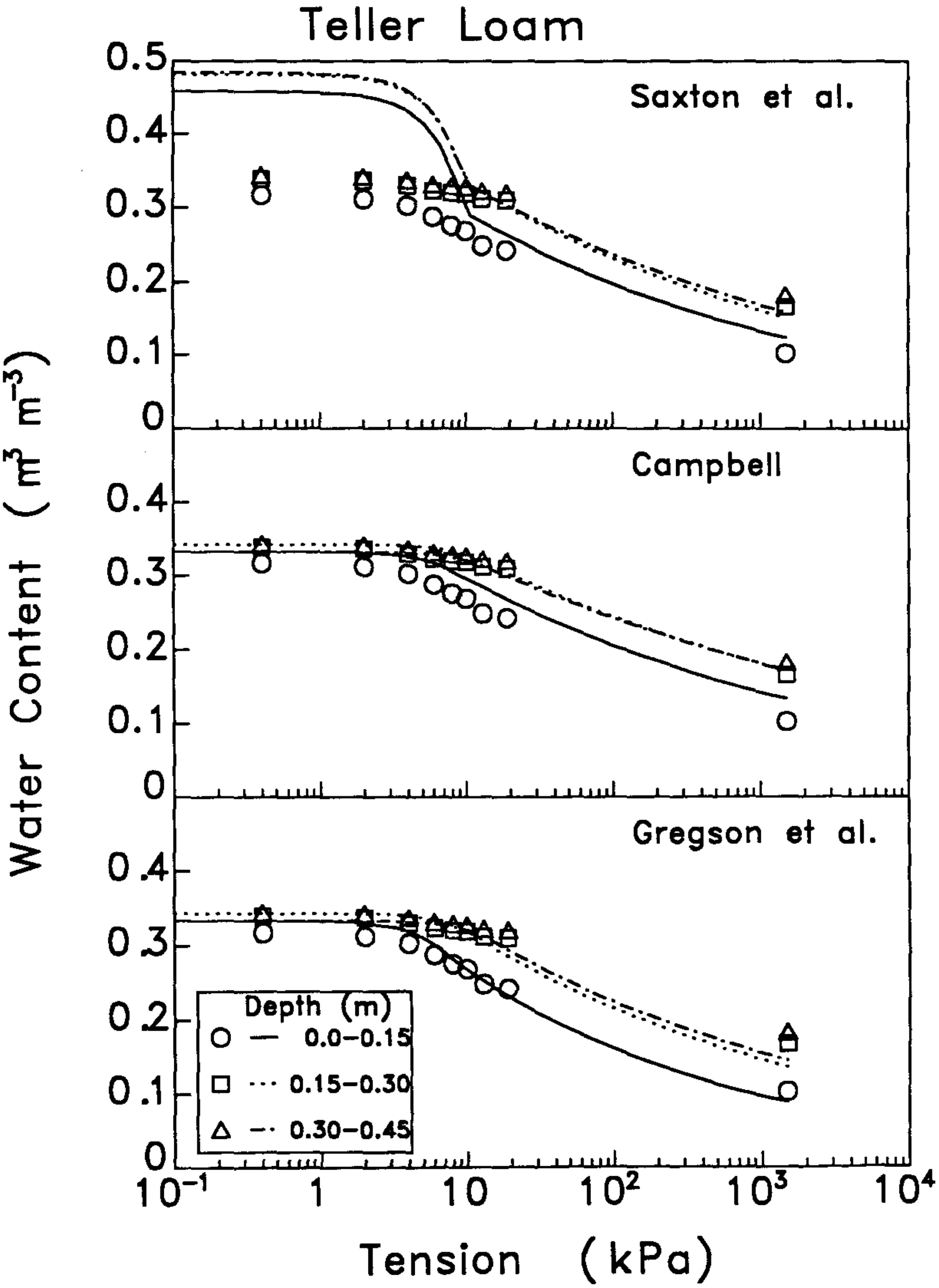

Figure 17. Measured and estimated soil water characteristics of Teller loam (Data from J.M. Davidson).

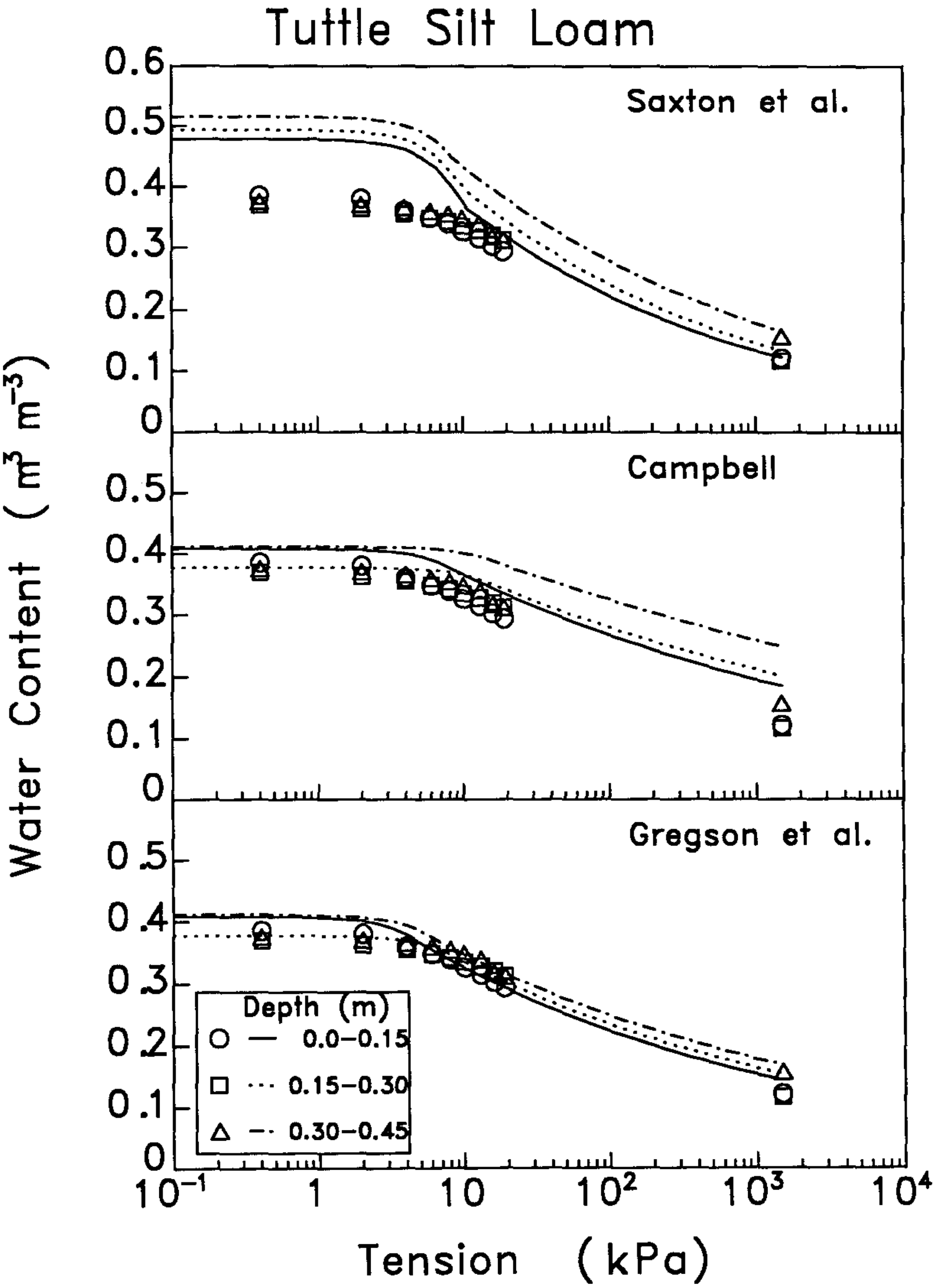

Figure 18. Measured and estimated soil water characteristics of Tuttle silt loam (Data from J.M. Davidson).

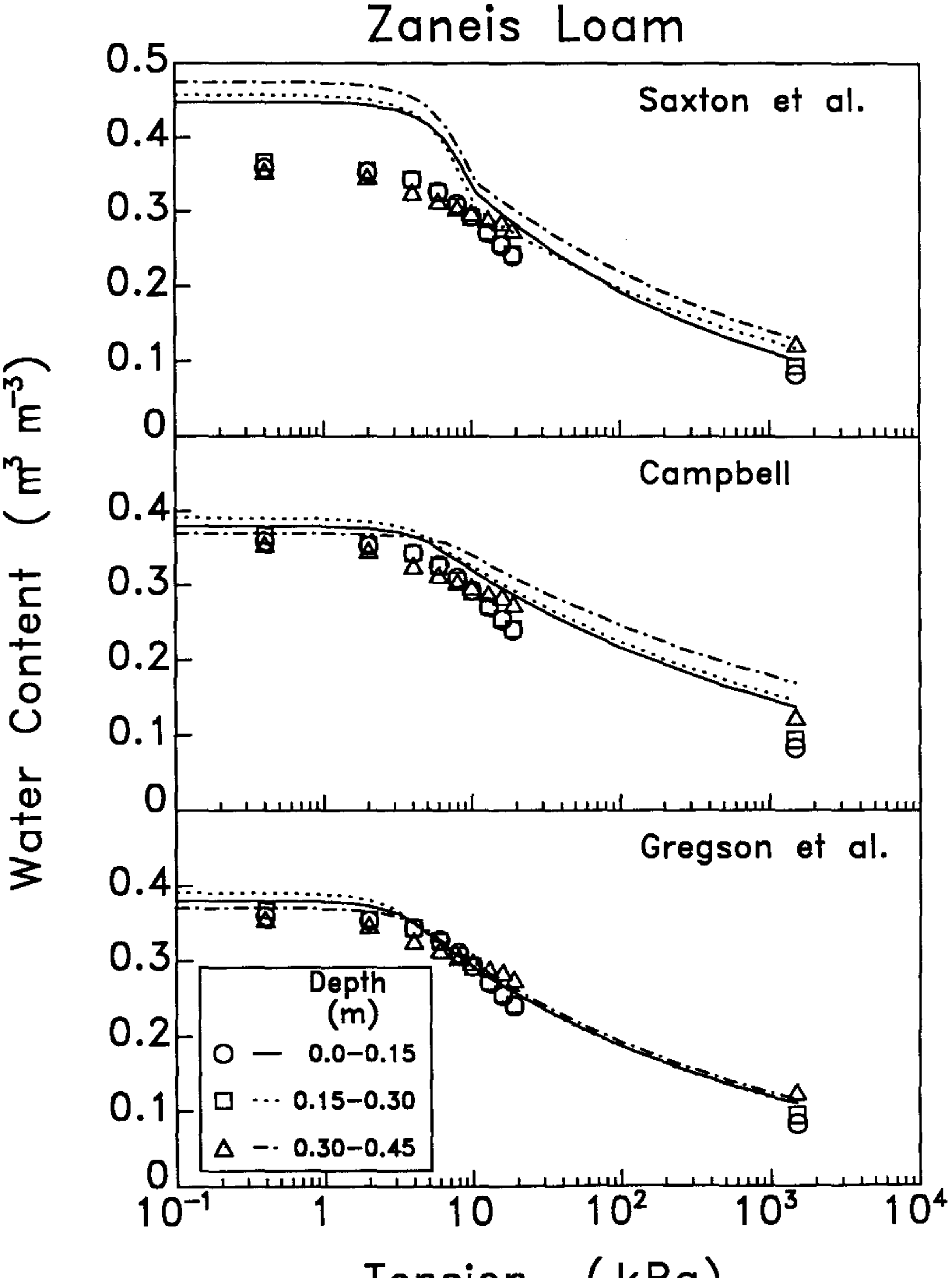

Figure 19. Measured and estimated soil water characteristics of Zaneis loam (Data from J.M. Davidson).

Table 3. Physical properties of soils used.

Soil	Depth	Sand	Silt	Clay	Bulk Density	Organic Carbon
	m	%			Mg m^{-3}	%
Eufaula (Site 1)	0.0-0.2	93.3	5.3	1.5	1.58	0.16
	0.2-0.4	92.9	5.9	1.2	1.54	0.04
	0.4-0.6	93.7	5.9	0.4	1.58	0.07
	0.6-0.8	95.9	3.5	0.6	1.38	0.08
	0.8-1.0	96.6	2.0	1.4	1.51	0.07
	1.0-1.2	95.1	1.8	3.2	1.59	0.08
	1.2-1.4	96.4	1.5	2.0	1.54	0.06
	1.4-1.6	95.7	2.0	2.3	1.58	0.10
Eufaula (Site 2)	0.0-0.2	89.8	7.0	3.3	1.48	0.39
	0.2-0.4	90.2	7.3	2.5	1.55	0.11
	0.4-0.6	91.2	5.8	3.0	1.51	0.08
	0.6-0.8	91.4	5.9	2.7	1.46	0.08
	0.8-1.0	92.1	5.1	2.8	1.49	0.06
	1.0-1.2	92.3	4.6	3.2	1.51	0.07
	1.2-1.4	94.7	2.5	2.8	1.53	0.06
	1.4-1.6	96.7	0.9	2.5	1.54	0.06
Eufaula (Site 3)	0.0-0.2	91.5	6.4	2.1	1.51	0.21
	0.2-0.4	92.4	5.8	1.8	1.49	0.09
	0.4-0.6	95.8	2.8	1.3	1.52	0.07
	0.6-0.8	95.1	0.8	4.1	1.59	0.08
	0.8-1.0	96.8	0.9	2.3	1.54	0.08
	1.0-1.2	95.6	1.0	3.4	1.55	0.07
	1.2-1.4	97.1	0.7	2.3	1.60	0.07
	1.4-1.6	93.4	0.8	5.9	1.59	0.08
Cobb (Site 1)	0.0-0.2	80.1	7.7	12.3	1.57	0.32
	0.2-0.4	75.8	7.7	16.5	1.54	0.32
	0.4-0.6	70.7	7.8	21.6	1.55	0.27
	0.6-0.8	--	--	--	--	0.27
	0.8-1.0	74.4	8.5	17.1	--	0.17
	1.0-1.2	81.6	7.3	11.1	1.52	0.17
	1.2-1.4	81.3	8.4	10.3	1.46	0.10
	1.4-1.6	75.2	9.6	15.2	1.51	0.10
Cobb (Site 2)	0.0-0.2	83.4	7.7	8.9	1.62	0.31
	0.2-0.4	70.3	9.6	20.1	1.54	0.36
	0.4-0.6	68.8	9.4	21.8	1.61	0.30
	0.6-0.8	68.7	9.4	22.0	1.64	0.29
	0.8-1.0	73.6	8.1	18.3	1.60	0.20
	1.0-1.2	76.8	10.4	12.9	1.44	0.13
	1.2-1.4	76.0	9.7	14.3	1.46	0.12
	1.4-1.6	81.7	10.9	7.4	1.45	0.06

Table 3. Continued

Soil	Depth	Sand	Silt	Clay	Bulk Density	Organic Carbon
	m	---------	%	----------	Mg m^{-3}	%
Cobb (Site 3)	0.0-0.2	80.1	8.8	11.2	1.63	0.26
	0.2-0.4	80.5	9.9	9.6	1.59	0.20
	0.4-0.6	86.2	8.4	5.4	1.42	0.10
	0.6-0.8	86.6	8.5	4.8	1.40	0.10
	0.8-1.0	83.5	7.9	8.6	1.43	0.10
	1.0-1.2	79.0	8.1	12.9	1.55	0.09
	1.2-1.4	78.1	8.6	13.3	1.56	0.07
	1.4-1.6	77.2	8.6	14.2	1.49	0.08
Noble (Site 1)	0.0-0.2	67.2	23.6	9.3	1.45	1.12
	0.2-0.4	70.9	20.0	9.0	1.42	0.31
	0.4-0.6	71.5	18.9	9.6	1.31	0.27
	0.6-0.8	67.8	20.2	12.0	1.44	0.24
	0.8-1.0	67.2	19.8	13.1	1.50	0.19
	1.0-1.2	67.1	20.1	12.8	1.52	0.21
	1.2-1.4	70.3	17.8	11.9	1.55	0.14
	1.4-1.6	73.0	14.4	12.6	1.52	0.13
Noble (Site 2)	0.0-0.2	69.6	21.5	8.9	1.49	0.50
	0.2-0.4	69.8	20.0	10.1	1.45	0.40
	0.4-0.6	67.3	20.7	12.0	1.41	0.33
	0.6-0.8	65.7	19.6	14.8	1.50	0.30
	0.8-1.0	65.8	19.4	14.9	1.48	0.16
	1.0-1.2	65.9	20.1	14.0	1.61	0.19
	1.2-1.4	70.3	16.8	12.9	1.61	0.13
	1.4-1.6	70.6	16.1	13.4	1.66	0.10
Noble (Site 3)	0.0-0.2	70.8	23.6	5.6	1.51	0.92
	0.2-0.4	71.4	21.3	7.3	1.60	0.38
	0.4-0.6	70.1	21.7	8.2	1.45	0.23
	0.6-0.8	68.5	20.8	10.7	1.58	0.22
	0.8-1.0	69.2	20.3	10.6	1.56	0.15
	1.0-1.2	69.3	20.6	10.0	1.61	0.17
	1.2-1.4	71.7	19.4	8.9	1.59	0.13
	1.4-1.6	73.4	18.5	8.1	1.56	0.12

Table 3. Continued

Soil	Depth	Sand	Silt	Clay	Bulk Density	Organic Carbon
	m	%			Mg m^{-3}	%
Pond Creek (Site 1)	0.0-0.2	70.1	19.5	10.4	1.62	0.51
	0.2-0.4	55.1	26.2	18.7	1.41	0.73
	0.4-0.6	40.3	37.3	22.4	1.38	0.66
	0.6-0.8	39.2	38.1	22.7	1.47	0.57
	0.8-1.0	33.9	39.0	27.1	1.46	0.52
	1.0-1.2	40.6	34.3	25.1	1.52	0.36
	1.2-1.4	51.9	29.7	18.4	1.50	0.29
	1.4-1.6	51.9	29.7	18.4	1.47	0.29
Pond Creek (Site 2)	0.0-0.2	67.2	22.0	10.8	1.58	0.56
	0.2-0.4	64.0	23.3	12.8	1.53	0.58
	0.4-0.6	34.4	39.6	26.0	1.52	0.82
	0.6-0.8	29.6	44.4	26.0	1.43	0.66
	0.8-1.0	48.4	33.6	18.0	1.46	0.50
	1.0-1.2	56.3	26.2	17.5	1.53	0.30
	1.2-1.4	64.9	19.5	15.6	1.55	0.22
	1.4-1.6	69.8	17.3	12.9	1.54	0.14
Pond Creek (Site 3)	0.0-0.2	66.3	23.5	10.1	1.42	0.60
	0.2-0.4	62.5	24.8	12.7	1.37	0.58
	0.4-0.6	43.3	36.9	19.8	1.39	0.68
	0.6-0.8	36.7	41.9	21.4	1.40	0.58
	0.8-1.0	38.2	40.8	21.1	1.49	0.45
	1.0-1.2	55.0	28.2	16.8	1.53	0.29
	1.2-1.4	70.7	16.3	13.0	1.54	0.17
	1.4-1.6	73.4	15.6	10.9	1.53	0.13

Table 4. Physical properties for soils of J. M. Davidson.

Soil	Depth	Sand	Silt	Clay	Bulk Density	Organic[a] Carbon
	m		%		Mg m^{-3}	%
Cobb	0.00-0.15	74.7	11.3	14.0	1.56	0.38
	0.15-0.30	74.4	11.1	14.5	1.61	0.38
	0.30-0.45	66.0	18.5	15.5	1.66	0.16
	0.45-0.60	52.8	28.4	18.8	1.52	0.16
	0.60-0.75	39.2	39.2	21.6	1.57	0.16
	0.75-0.90	48.1	29.5	22.4	1.55	0.05
	0.90-1.05	57.0	25.2	17.8	1.57	0.05
	1.05-1.20	64.9	20.4	14.7	1.58	0.04
	1.20-1.45	65.0	18.5	16.5	1.63	0.04
	1.35-1.50	64.5	21.5	14.0	1.64	0.04
	1.50-1.65	70.3	19.8	9.9	1.62	0.04
McLain	0.00-0.15	6.7	55.6	37.7	1.48	1.21
	0.15-0.30	2.0	53.1	44.9	1.50	1.21
	0.30-0.45	0.0	46.9	53.1	1.43	0.68
	0.45-0.60	1.8	38.3	59.9	1.54	0.68
	0.60-0.75	0.0	41.9	58.1	1.50	0.56
	0.75-0.90	0.0	50.4	49.6	1.64	0.56
	0.90-1.05	8.3	74.7	17.0	1.52	0.56
	1.05-1.20	26.0	63.0	11.0	1.49	0.40
	1.20-1.35	20.0	62.6	17.4	1.44	0.40
	1.35-1.50	26.6	63.2	10.2	1.49	0.23
	1.50-1.65	28.9	58.0	13.1	1.42	0.23
Port	0.00-0.15	17.0	40.5	42.5	1.55	1.28
	0.15-0.30	17.0	40.5	42.5	1.60	1.28
	0.30-0.45	10.2	39.3	50.5	1.65	0.80
	0.45-0.61	36.0	27.8	36.2	1.67	0.80
	0.61-0.76	51.0	18.5	30.5	1.65	0.58
	0.76-0.91	39.0	31.0	30.0	1.63	0.58
	0.91-1.06	36.0	32.5	31.5	1.58	0.58
	1.06-1.21	15.5	46.5	38.0	1.44	0.58
	1.21-1.37	14.5	47.5	38.0	1.56	0.58
	1.37-1.52	8.0	46.0	46.0	1.68	0.58
	1.52-1.67	3.5	48.5	48.0	1.69	0.58
Richfield	0.00-0.15	43.4	31.5	25.1	1.65	1.21
	0.15-0.30	44.2	27.5	28.3	1.57	0.68
	0.30-0.45	40.0	29.3	30.7	1.65	0.56
	0.45-0.61	39.1	28.9	32.0	1.57	0.40
	0.61-0.76	37.2	31.8	31.0	1.52	0.27
	0.76-0.91	21.9	39.6	38.5	1.44	0.27
	0.91-1.06	29.0	40.4	30.6	1.40	0.27
	1.06-1.21	39.0	30.5	30.5	1.43	0.23

Table 4. Continued.

Soil	Depth	Sand	Silt	Clay	Bulk Density	Organic Carbon[a]
	m	%			Mg m^{-3}	%
Teller	0.00-0.15	52.9	29.5	19.3	1.67	0.62
	0.15-0.30	43.6	31.9	26.2	1.64	0.70
	0.30-0.45	45.0	27.5	27.9	1.67	0.59
	0.45-0.60	55.4	20.3	24.3	1.74	0.59
	0.60-0.75	65.5	17.4	17.2	1.79	0.44
	0.75-0.90	69.1	17.2	13.3	1.82	0.27
	0.90-1.20	72.7	16.2	11.1	1.86	0.27
	1.20-1.50	71.0	13.0	19.3	1.78	0.27
Tuttle	0.00-0.15	27.0	53.0	20.0	1.45	1.21
	0.15-0.30	18.0	58.7	23.3	1.54	1.21
	0.30-0.45	7.2	62.7	30.1	1.44	0.68
	0.45-0.60	1.5	69.2	29.3	1.35	0.56
	0.60-0.75	0.0	76.6	23.4	1.37	0.56
	0.75-0.90	22.0	61.1	16.9	1.36	0.40
	0.90-1.05	41.4	46.6	12.0	1.42	0.40
	1.05-1.20	60.8	29.6	9.6	1.48	0.23
	1.20-1.35	63.0	30.9	6.1	1.48	0.23
	1.35-1.50	1.4	62.2	36.4	1.49	0.23
	1.50-1.65	6.0	65.8	28.2	1.44	0.23
Zaneis	0.00-0.15	39.5	46.8	13.7	1.53	1.08
	0.15-0.30	47.2	35.0	17.8	1.50	1.08
	0.30-0.45	36.5	42.1	21.4	1.56	0.92
	0.45-0.60	35.7	38.7	25.8	1.57	0.77
	0.60-0.75	31.8	35.7	32.5	1.60	0.77
	0.75-0.90	37.0	35.3	37.7	1.70	0.39
	0.90-1.05	49.0	13.2	37.8	1.75	0.39
	1.05-1.20	61.0	15.4	23.6	1.77	0.39
	1.20-1.35	62.7	15.8	21.5	1.76	0.15
	1.35-1.50	68.1	13.8	18.1	1.77	0.15
	1.50-1.65	69.5	13.0	17.5	1.79	0.15

a. Estimated from organic matter data of Ford et al (1976) and Gray and Roozitalab (1976) for the same soil series.

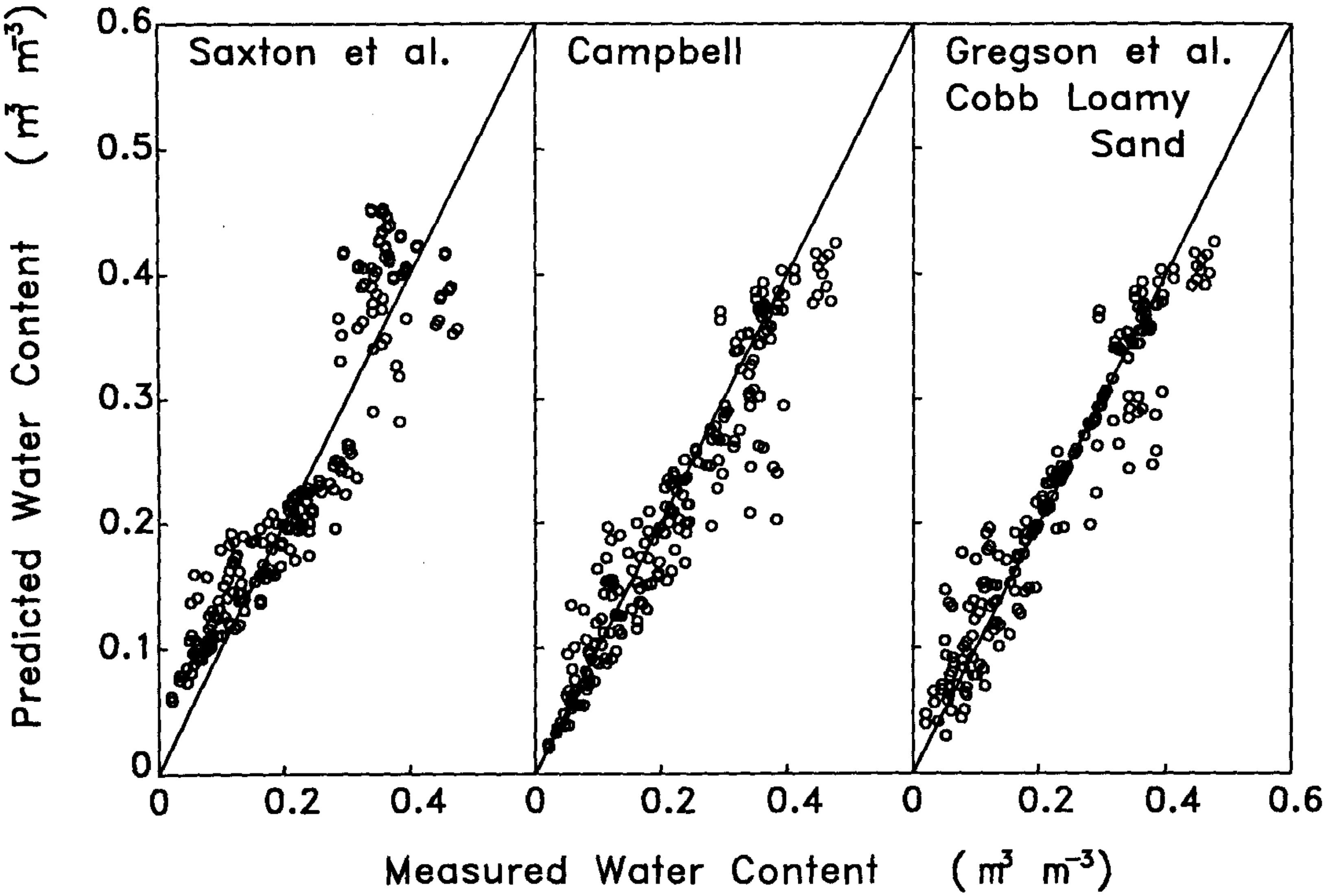

Figure 20. Predicted versus measured water contents for all depths of Cobb loamy sand.

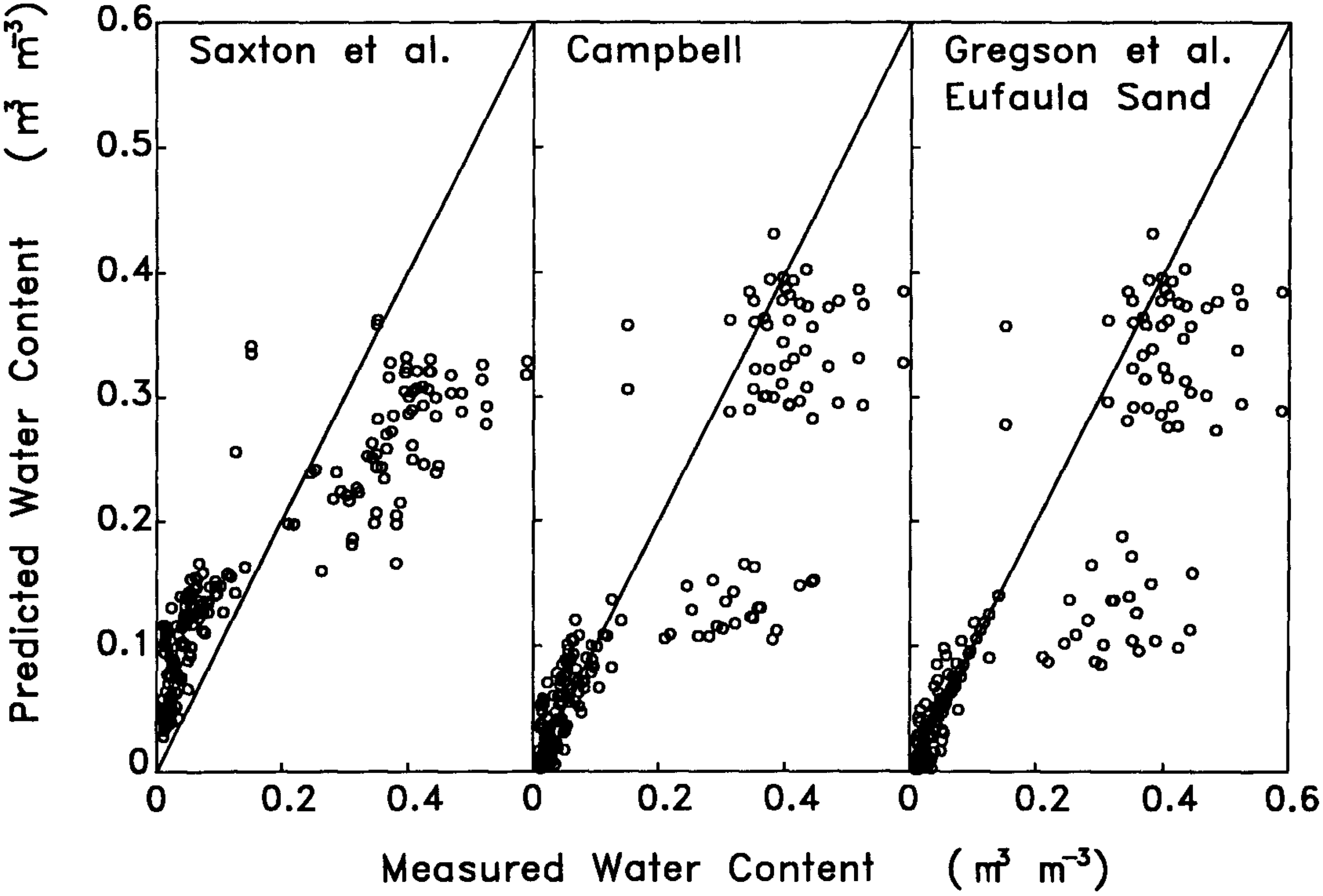

Figure 21. Predicted versus measured water contents for all depths of Eufaula sand.

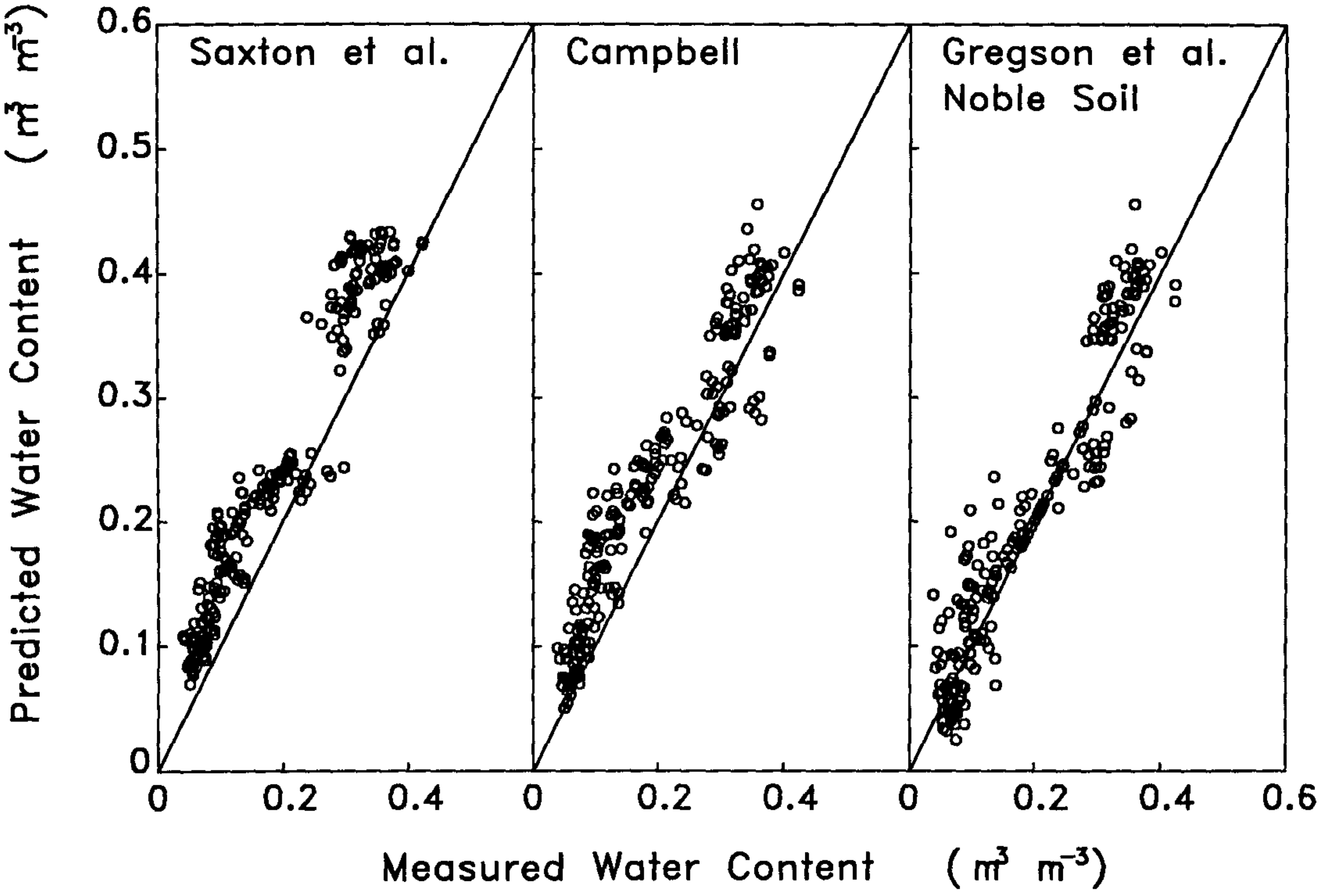

Figure 22. Predicted versus measured water contents for all depths of Noble sandy loam.

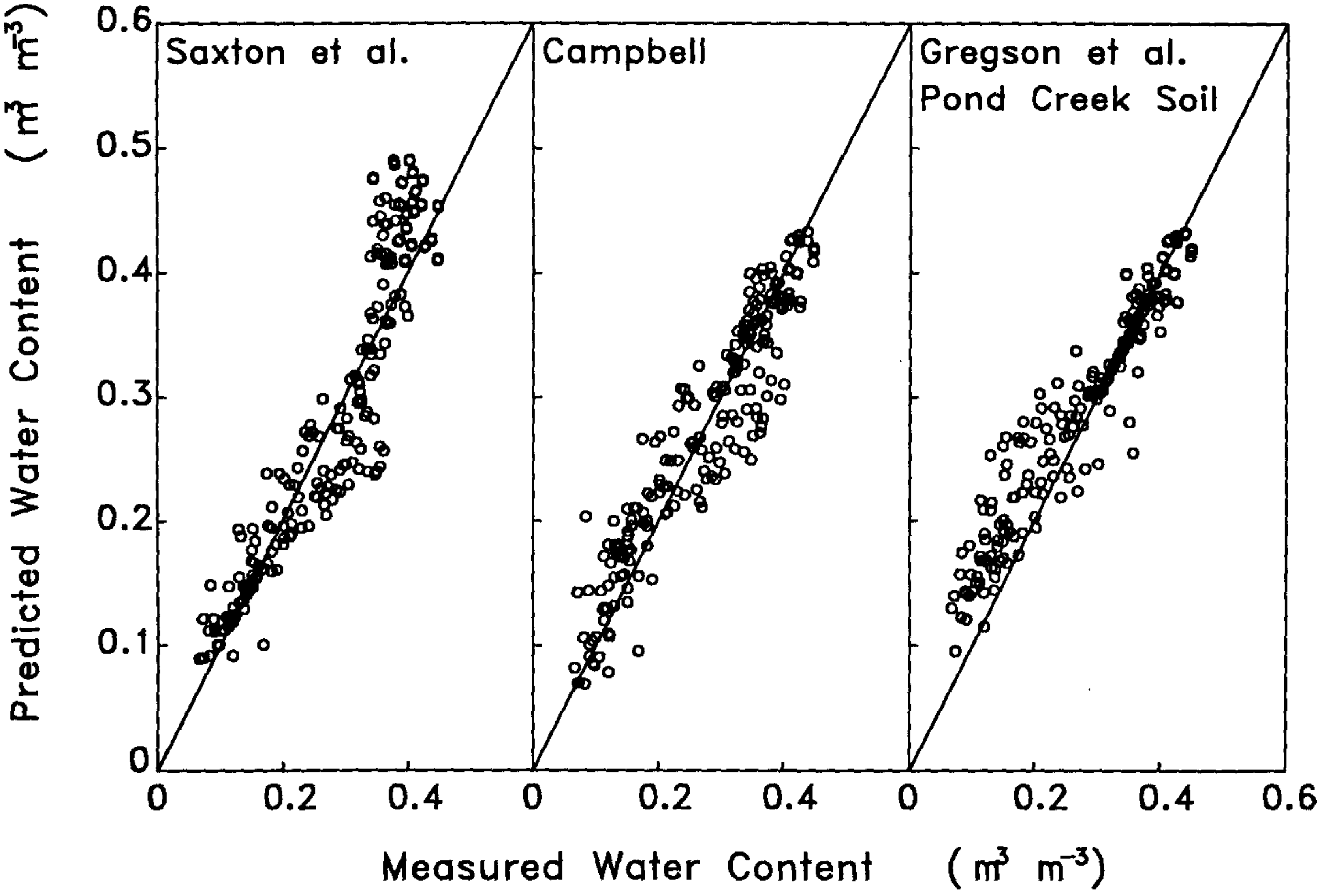

Figure 23. Predicted versus measured water contents for all depths of Pond Creek sandy loam.

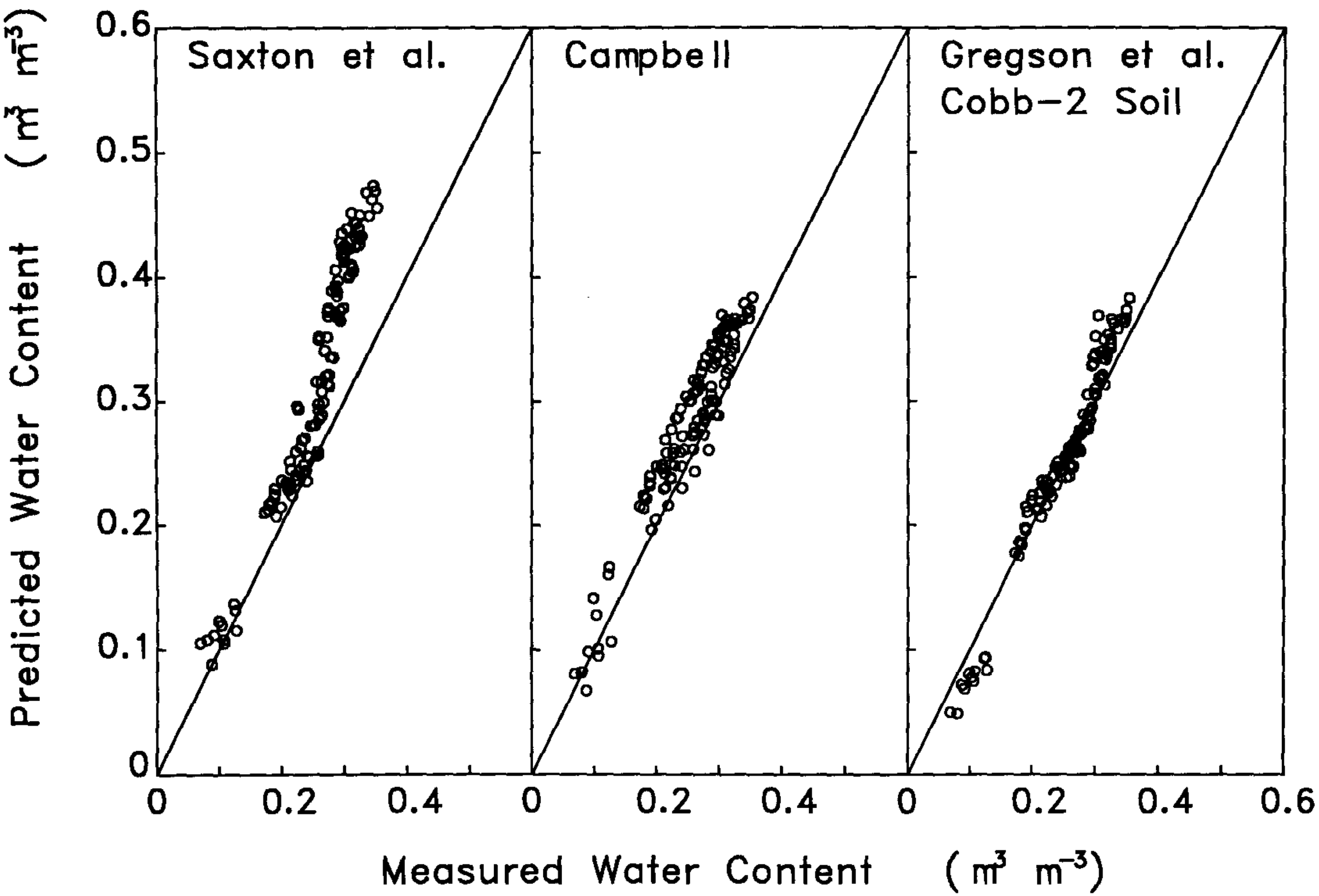

Figure 24. Predicted versus measured water contents for all depths of Cobb sandy loam (Davidson).

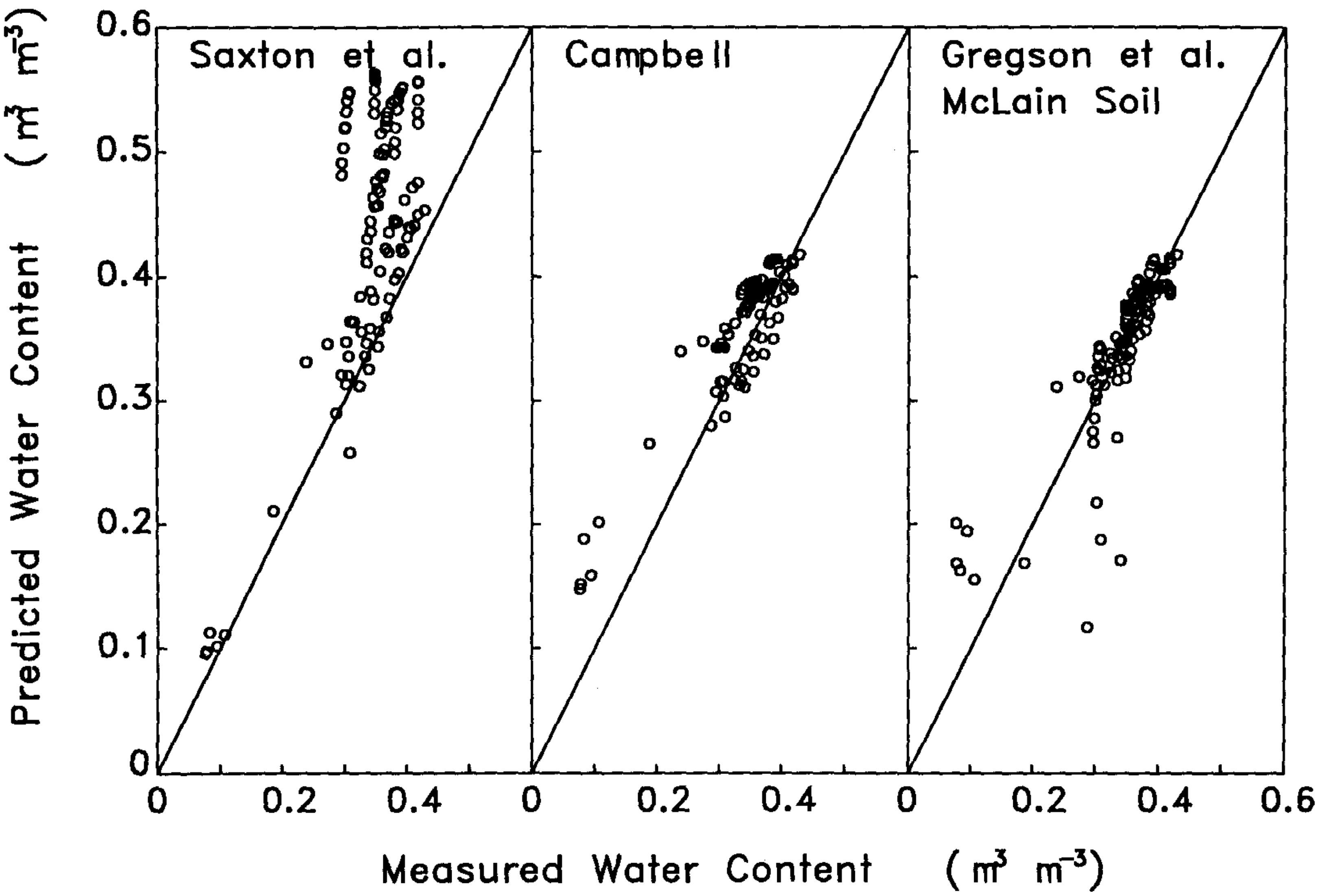

Figure 25. Predicted versus measured water contents for all depths of McLain silty clay loam (Davidson).

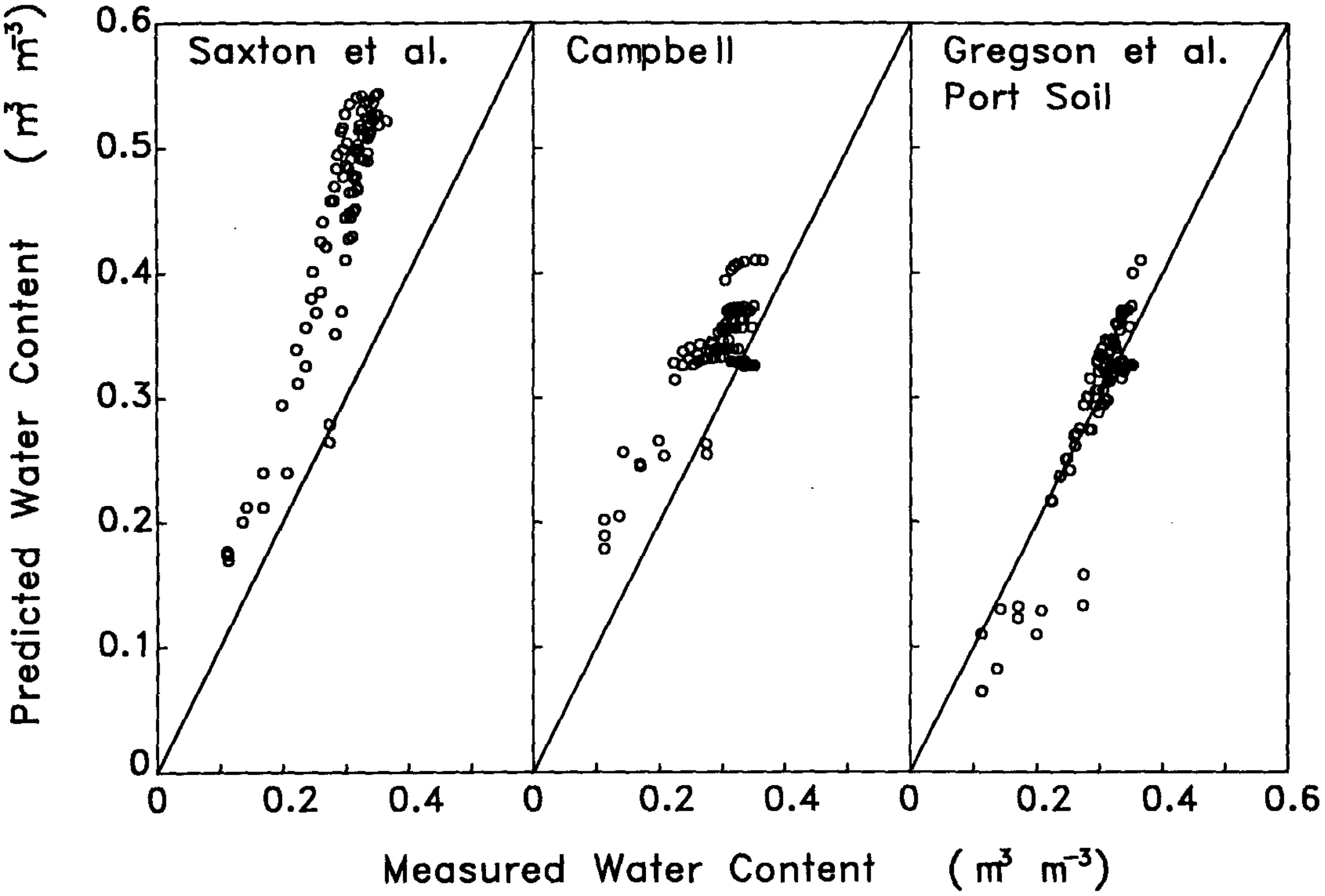

Figure 26. Predicted versus measured water contents for all depths of Port silty clay (Davidson).

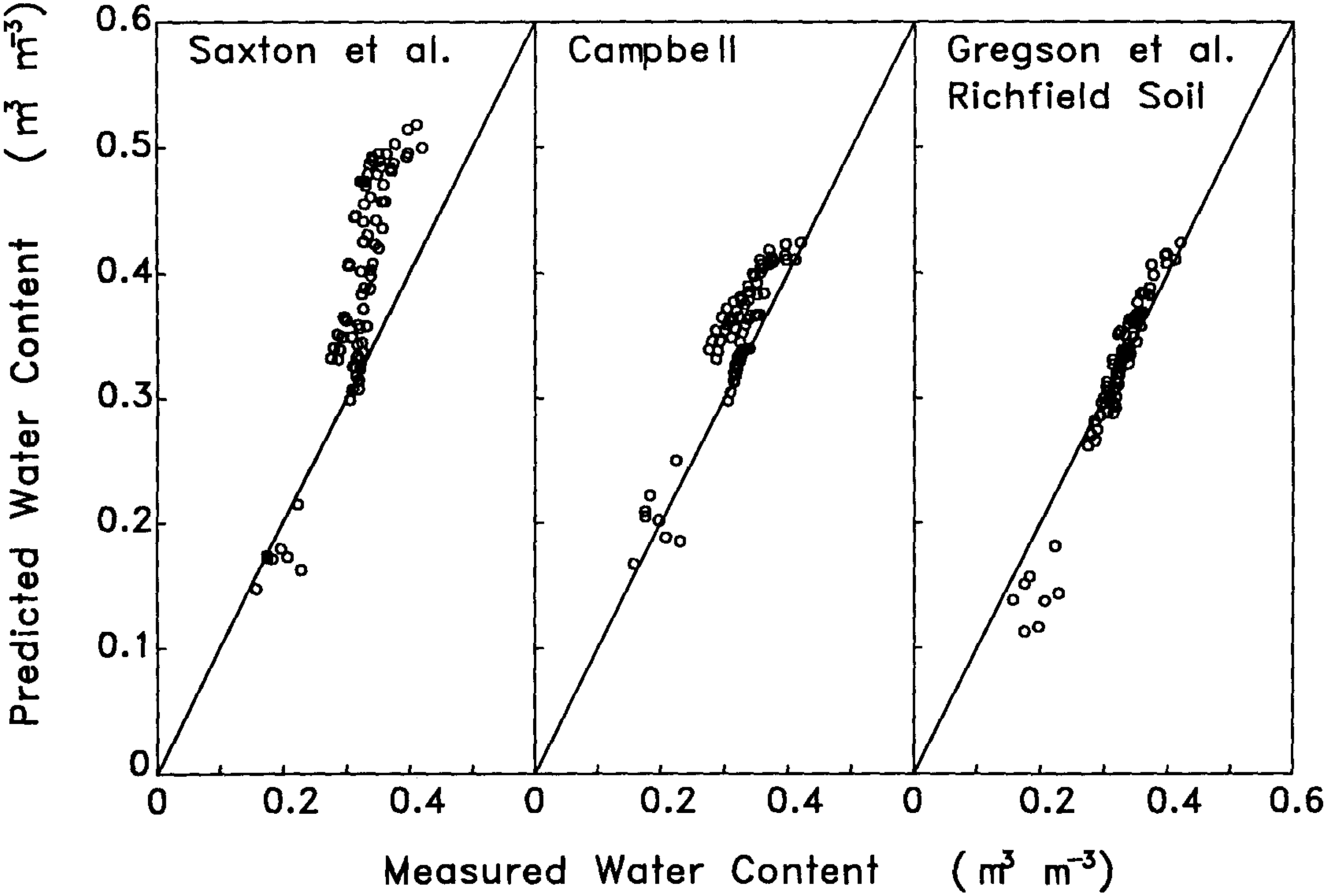

Figure 27. Predicted versus measured water contents for all depths of Richfield loam (Davidson).

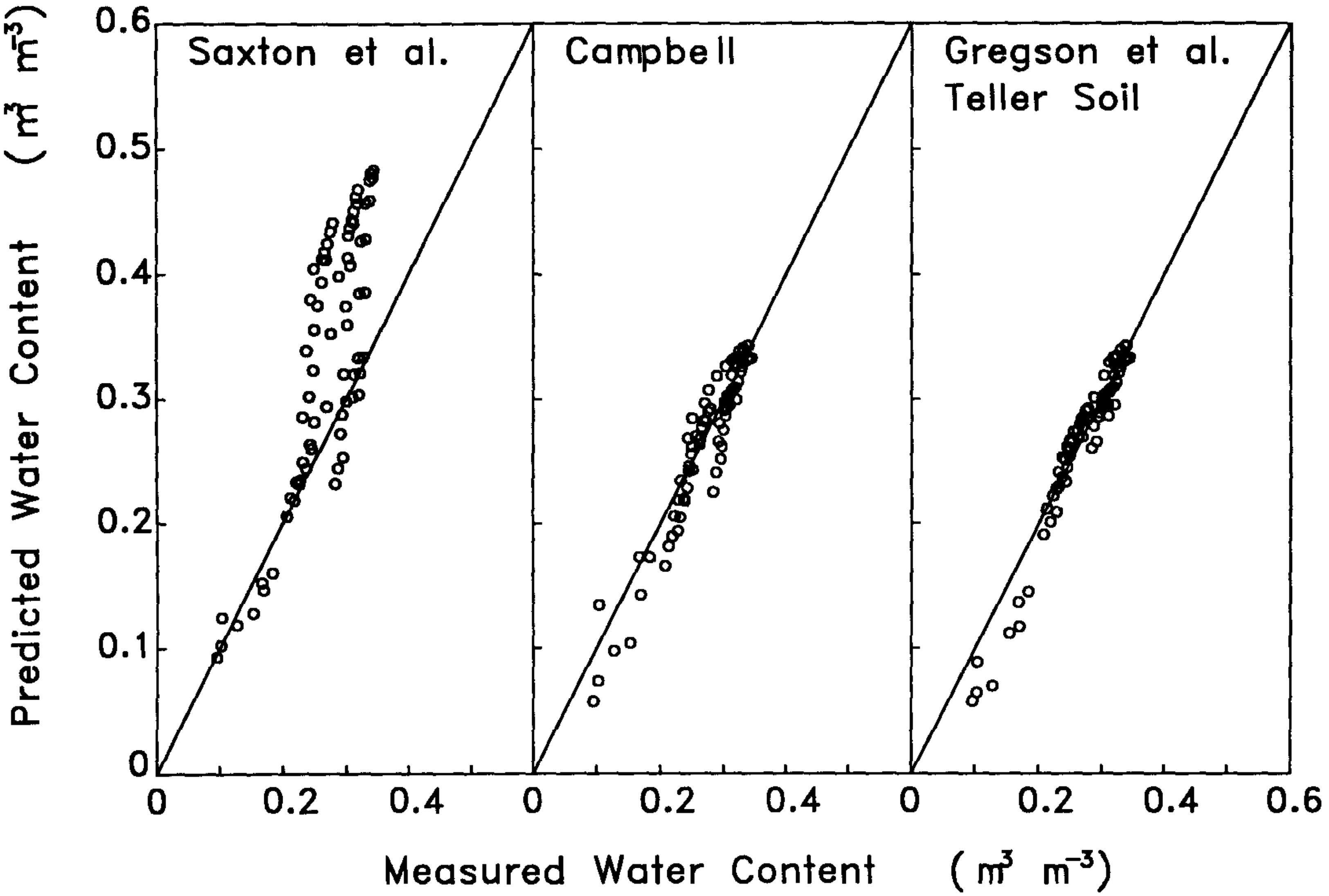

Figure 28. Predicted versus measured water contents for all depths of Teller loam (Davidson).

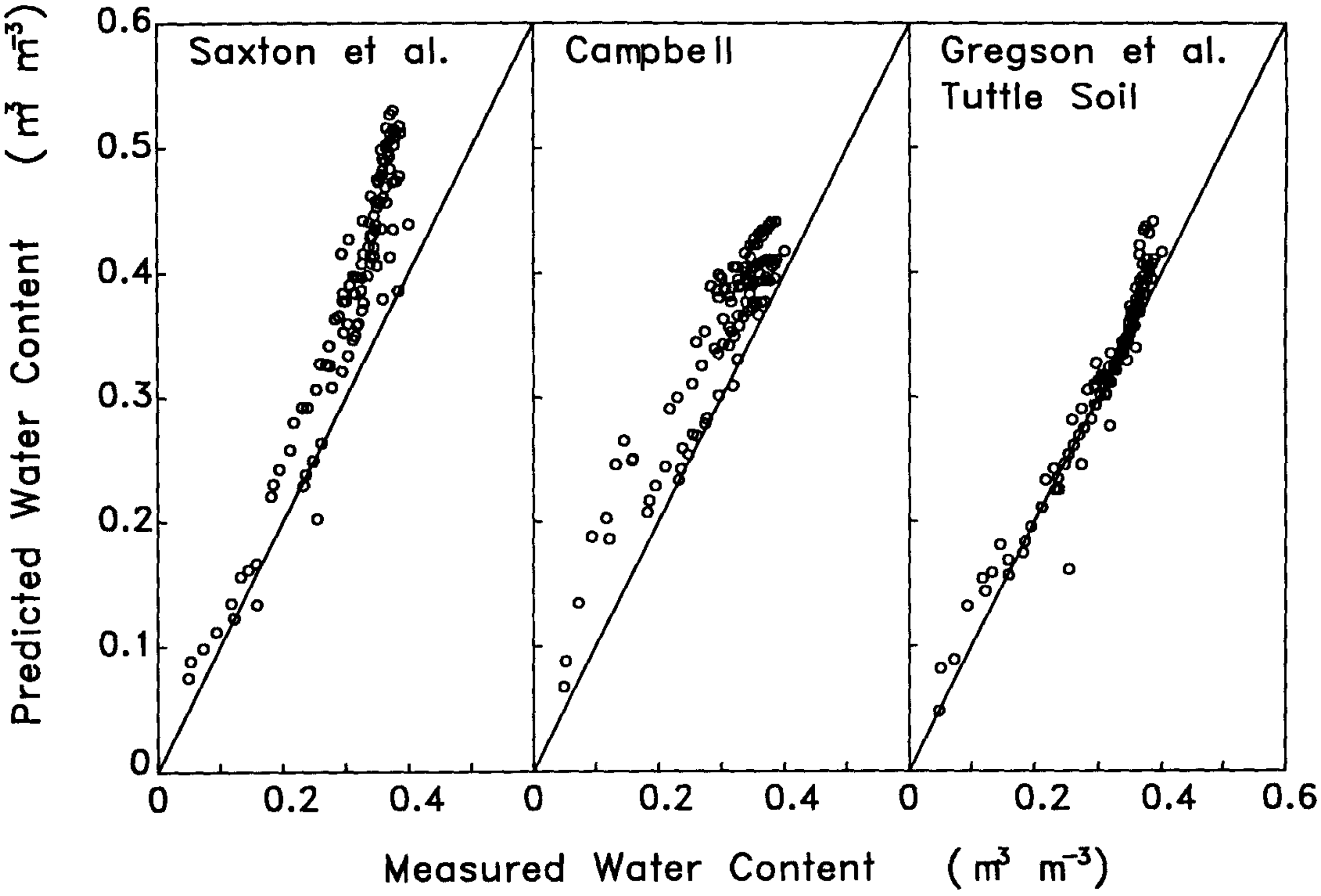

Figure 29. Predicted versus measured water contents for all depths of Tuttle silt loam (Davidson).

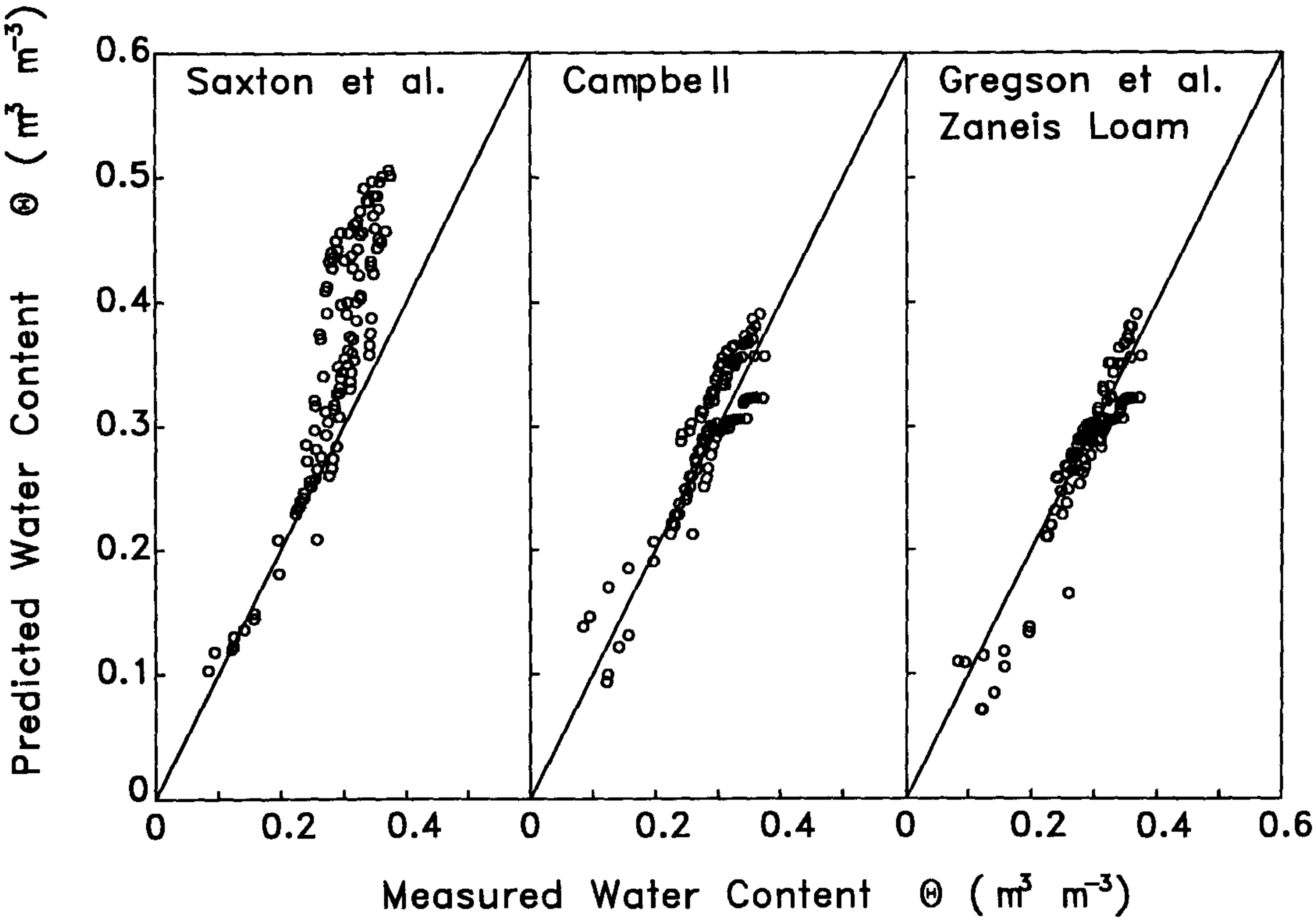

Figure 30. Predicted versus measured water contents for all depths of Zaneis loam (Davidson).

The methods of Saxton et al (1986), Campbell (1985), and Gregson et al (1987) provided good estimates of the results, especially at tensions above 10 kPa. Table 5 contains the root mean square (RMS) error for each soil and estimation method. The table also includes a column for the RMS value obtained when the empirical equation of Brooks and Corey (1964) (Eqn.2) was fitted to the measured data. Low RMS values for curve-fitting the measured water contents indicate that the function used by these three methods is capable of describing most of the data. Higher RMS values obtained for Eufaula soil appear to be due to the sharp decline in water content after the air-entry value. Higher RMS values also occurred for the McLain profiles in which the water content changed very little over all tensions.

The RMS values shown in Table 5 and the figures indicate that the method of Gregson provides the best estimate, followed by that of Campbell, and then by Saxton. In many cases, all three methods provide good estimates. Saxton's method differs from those of Campbell and Gregson in that Saxton estimates the saturated water content from the particle size data without the use of the bulk density. The methods of Campbell and Gregson require estimates of the saturated water content which in this study were taken as 90% of the porosity of the soil (assuming a particle density of 2.65 Mg m^{-3}). Although Saxton's method produces reasonable estimates of the saturated water content in some cases, it tends to overestimate θ_s in soils such as Cobb (Figure 13), McLain (Figure 14), Port (Figure 15), Richfield (Figure 16), Teller, (Figure 17), Tuttle (Figure 18), and Zaneis (Figure 19). Saxton's estimates of θ_s are too low for the Eufaula soil. However, this soil texture is outside of the published texture range for Saxton's method (see Table 2).

Table 5. Root Mean Square (RMS) error between measured and predicted water contents by using different estimation methods.

Soil	Saxton et al	Campbell	Gregson et al	Curve-fitting
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
	$m^3\ m^{-3}$			
	0 to 1500 kPa			
Cobb	0.048(0.012)	0.035(0.015)	0.032(0.015)	0.021(0.009)
Eufaula	0.088(0.026)	0.081(0.027)	0.082(0.030)	0.049(0.015)
Noble	0.061(0.013)	0.050(0.010)	0.038(0.011)	0.023(0.005)
Pond Creek	0.045(0.013)	0.036(0.010)	0.038(0.013)	0.022(0.009)
Cobb-2	0.076(0.013)	0.033(0.014)	0.019(0.003)	0.009(0.005)
McLain	0.106(0.064)	0.034(0.011)	0.037(0.013)	0.019(0.031)
Port	0.161(0.022)	0.051(0.023)	0.031(0.010)	0.005(0.003)
Teller	0.091(0.006)	0.019(0.010)	0.017(0.003)	0.005(0.002)
Tuttle	0.083(0.028)	0.053(0.022)	0.021(0.008)	0.008(0.003)
Richfield	0.087(0.012)	0.032(0.018)	0.021(0.008)	0.004(0.002)
Zaneis	0.087(0.013)	0.025(0.011)	0.022(0.008)	0.005(0.002)
	10 to 1500 kPa			
Cobb	0.036(0.010)	0.027(0.009)	0.027(0.010)	0.021(0.008)
Eufaula	0.058(0.014)	0.019(0.006)	0.013(0.004)	0.029(0.009)
Noble	0.055(0.008)	0.052(0.013)	0.031(0.017)	0.022(0.006)
Pond Creek	0.035(0.013)	0.038(0.012)	0.044(0.017)	0.026(0.011)
Cobb-2	0.025(0.011)	0.034(0.016)	0.015(0.005)	0.008(0.005)
McLain	0.087(0.060)	0.041(0.016)	0.048(0.020)	0.019(0.030)
Port	0.117(0.031)	0.062(0.028)	0.036(0.024)	0.003(0.002)
Teller	0.017(0.012)	0.024(0.014)	0.022(0.007)	0.006(0.002)
Tuttle	0.059(0.025)	0.062(0.025)	0.016(0.011)	0.008(0.004)
Richfield	0.036(0.019)	0.034(0.019)	0.025(0.012)	0.003(0.002)
Zaneis	0.025(0.015)	0.026(0.014)	0.025(0.011)	0.004(0.002)

Examination of Figure 21 indicates that all three estimators fail to predict measured results for Eufaula soil at water contents above 0.2 m^3 m^{-3} or tensions less than 10 kPa. This soil contains more than 90% sand in all layers and less than 6% clay. This suggests a potential problem in using these estimators for soils with very high sand content.

Since the three methods being considered here all assume the Brooks and Corey functional form, it was of interest to compare the air-entry value and coefficient B obtained by curve-fitting and by the three estimation techniques. These results are shown in Figures 31 and 32. The air-entry values are grouped nicely about the 1 to 1 line for all the methods, with the scatter for Campbell's method somewhat less than the other two. The B values are also nicely centered, but the range in values from curve fitting is much greater than the range from any estimation method.

Since the flux of water passing through a profile and hence the amount of water available for leaching chemicals is related to the amount of water that can be stored in the profile above the chemical, it was of particular interest to examine the ability of the different methods to estimate this storage. For purposes of this study, the water storage capacity per unit depth of soil was estimated as the difference in water content at "field capacity", FC, and at "permanent wilting point", WP. Assuming the water content at FC and WP can be approximated as the water content at tensions of 10 and 1500 kPa, respectively, comparisons were made of measured and estimated water storage capacity. These comparisons are shown in Figures 33 to 35 for three soils. The estimated values differ from the measured values by as much as 0.1 m^3 m^{-3} with values using Saxton's method being generally poorer than those for the other methods. In many soils the range in measured storage capacity exceeded the range in predicted values. The significance of these differences upon predicted chemical movement is presented in the following section.

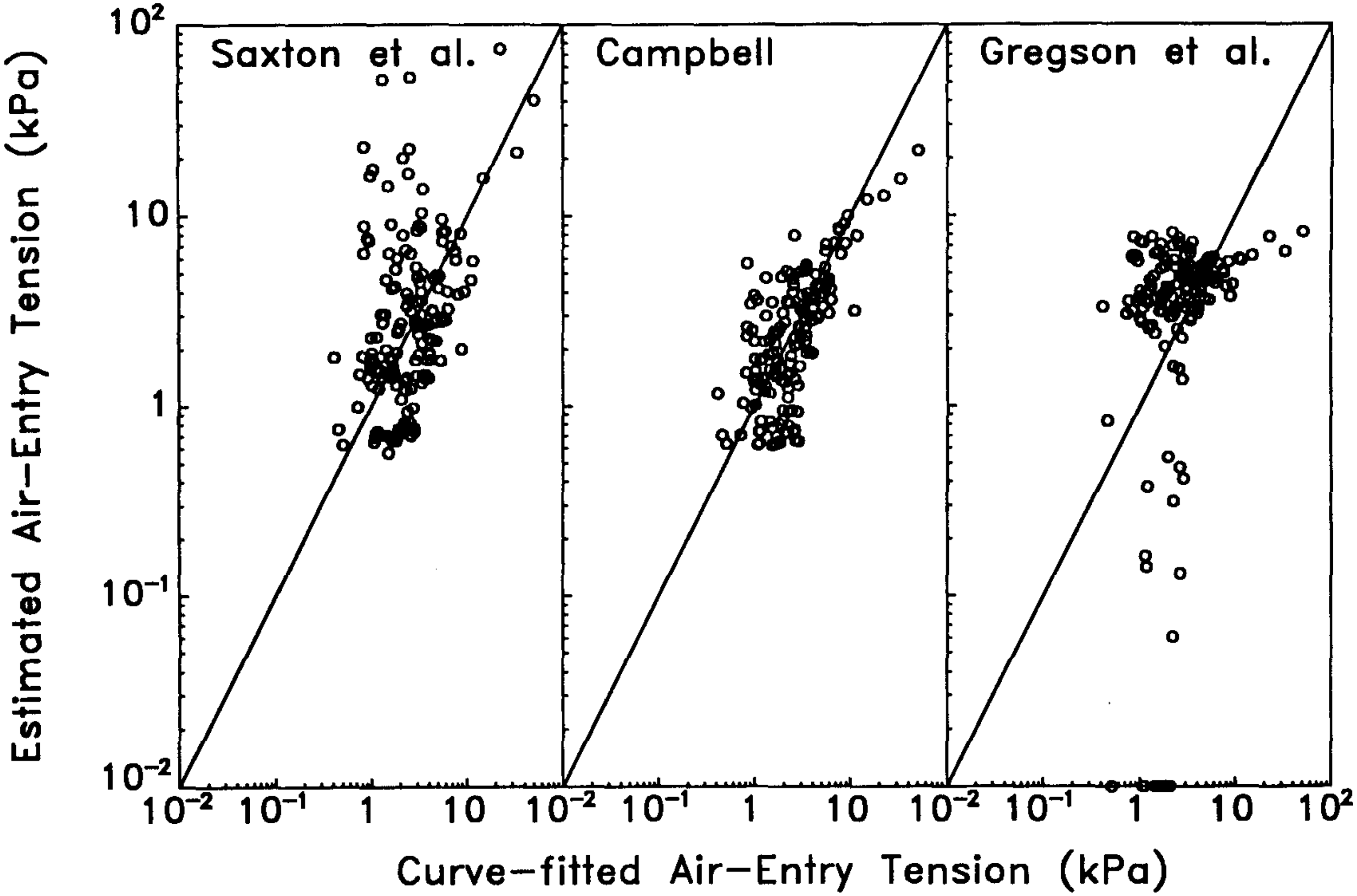

Figure 31. Comparison of air-entry values from estimation techniques and from curve-fitting.

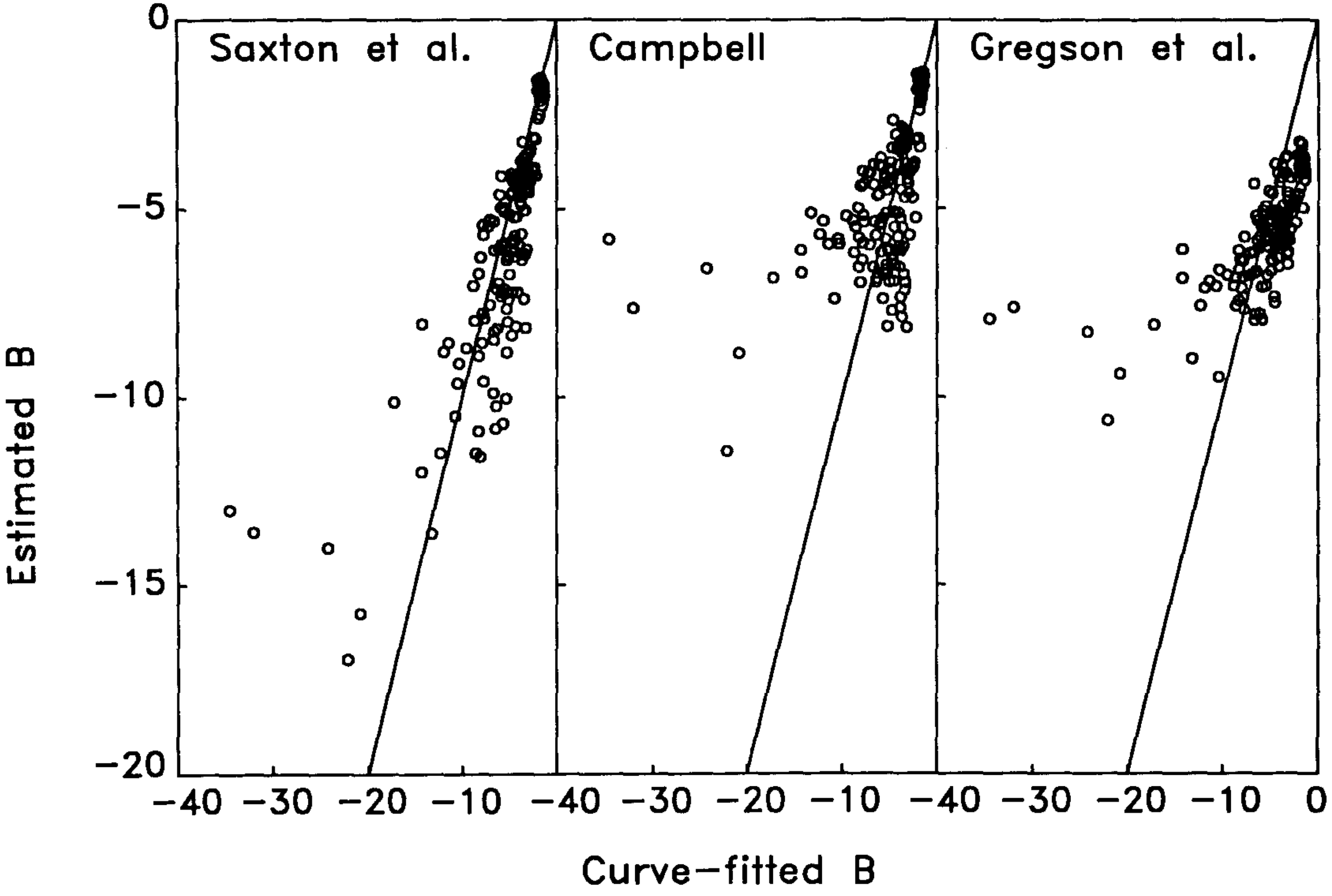

Figure 32. Comparison of values of coefficient B in equation 2 obtained from estimation techniques and from curve-fitting.

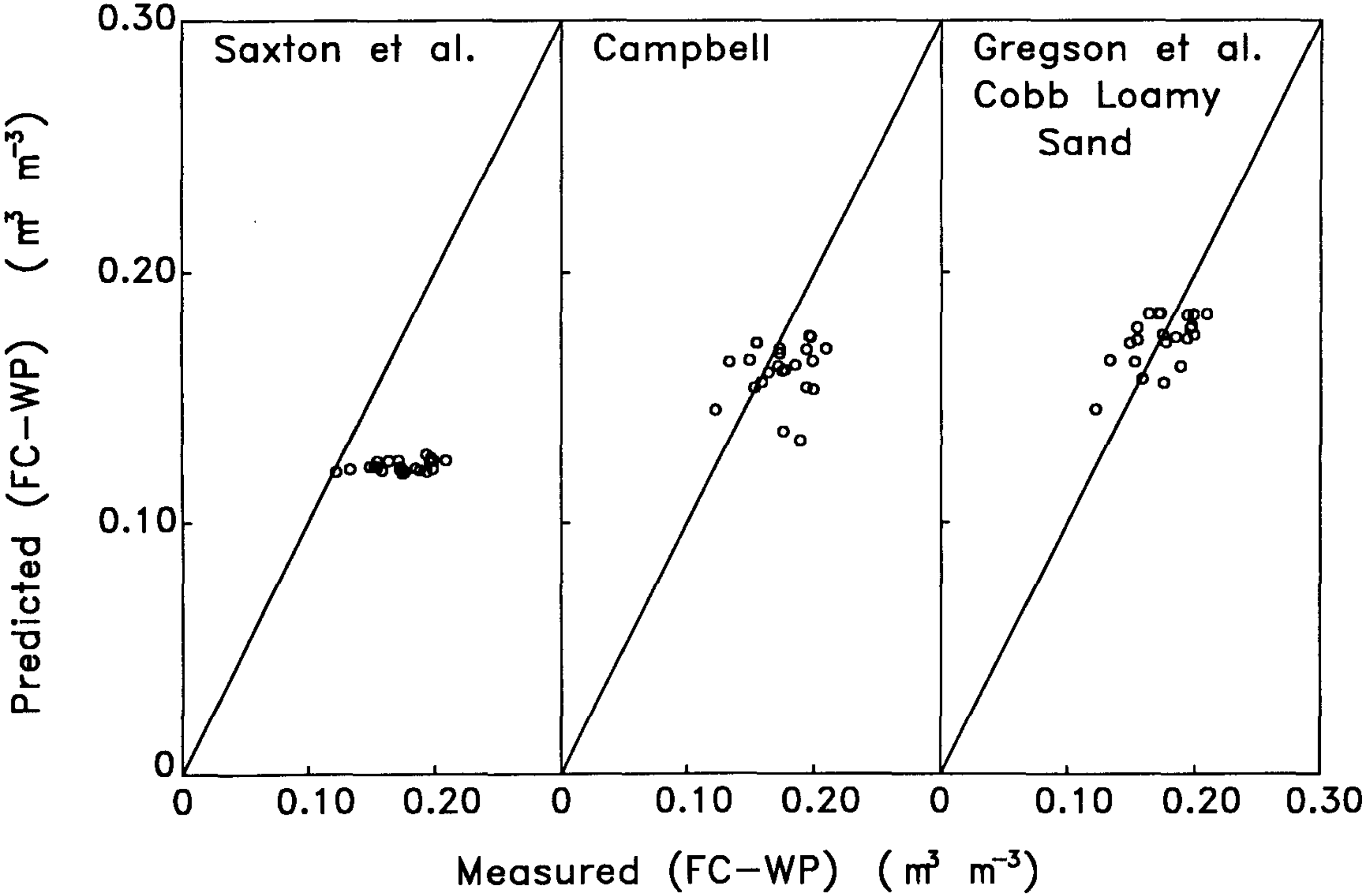

Figure 33. Comparison of measured and estimated water storage capacity for Cobb loamy sand.

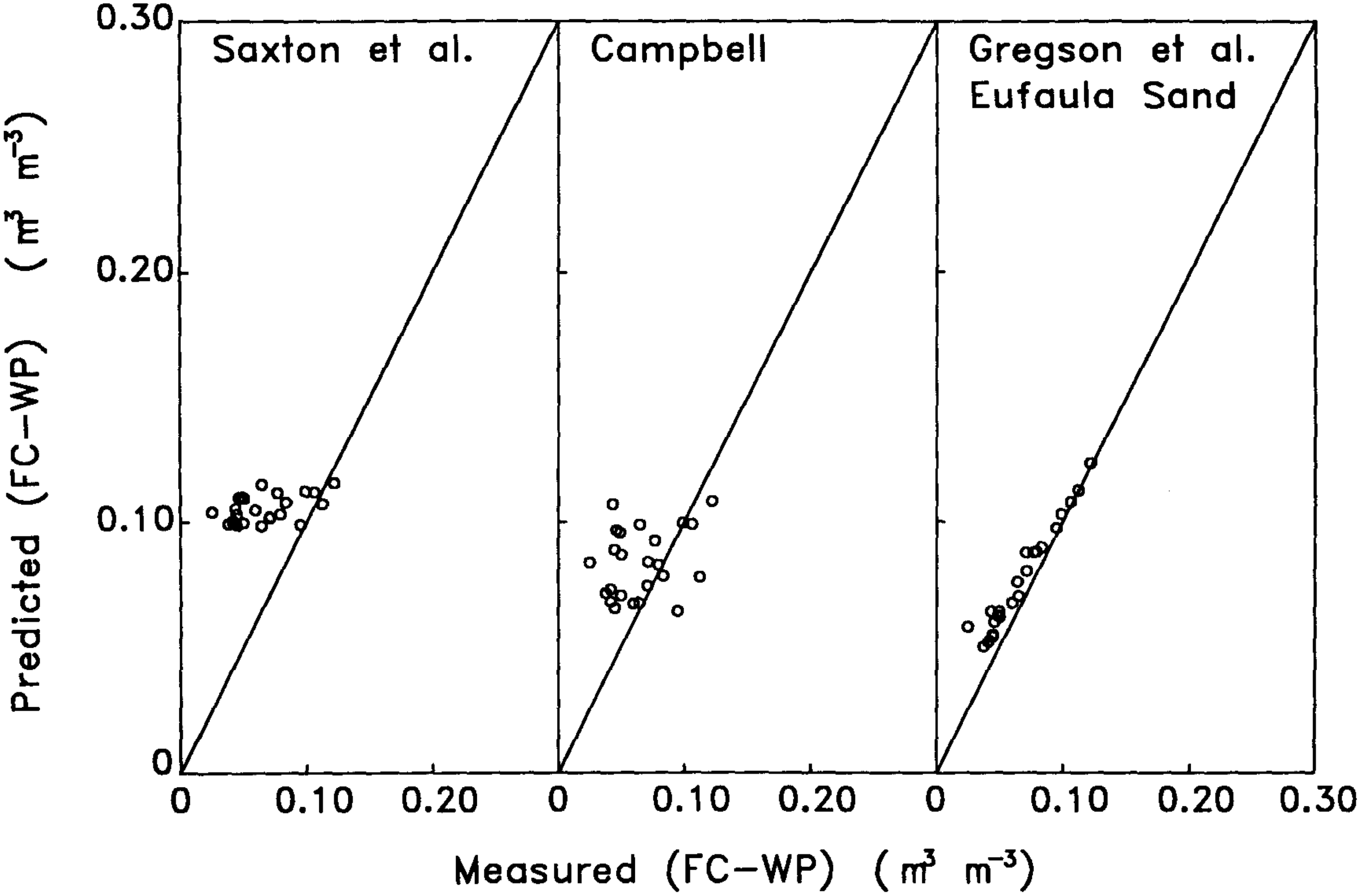

Figure 34. Comparison of measured and estimated water storage capacity for Eufaula sand.

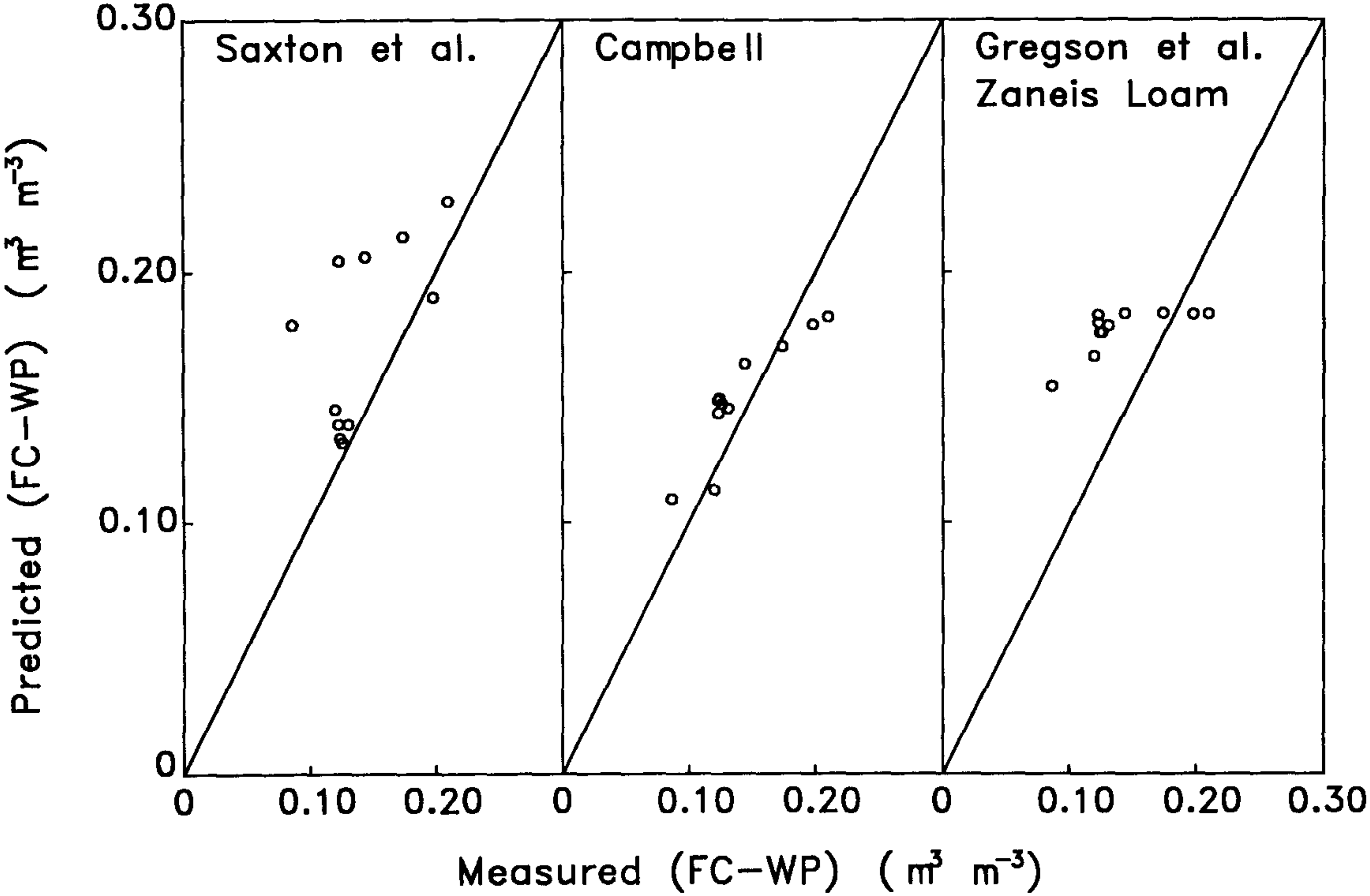

Figure 35. Comparison of measured and estimated water storage capacity for Zaneis loam.

Simulation of Chemical Movement in Soils:

One of the immediate needs of soil water characteristics in Oklahoma is the development of a state-wide agricultural chemical management system. This system combines a geographic information system with the CMLS model (Nofziger and Hornsby, 1986) to create a tool for assessing the impact of agricultural chemicals on ground water quality (Zhang et al, 1990). The CMLS model requires estimates of the water content at "field capacity" and at "permanent wilting point." Therefore it was of particular interest to compare simulated chemical movement using estimated and measured values for these parameters. Figures 36 to 41 show calculated depth of aldicarb and atrazine for three soils using measured and estimated water characteristic functions. Results are presented for irrigated and dryland conditions.

Examination of Figures 36 to 39 reveals a large difference in simulated time to reach 1 m for measured parameters from three sites in the same soil series. For dryland conditions, Saxton's method greatly underestimated the time required to move the chemical to the 1 m depth in the Cobb soil and overestimated the travel time in Eufaula soil. These differences were large even when compared to differences between sites. Campbell's method and Gregson's method produced much better estimates with errors in the same direction as Saxton, but with a much smaller magnitude. All three methods provided good estimates for movement in the Zaneis soil. Simulations for irrigated conditions resulted in even better agreement for all methods for Cobb and Zaneis soil. Results for Saxton's method for Eufaula were unacceptable.

Simulated depth versus time graphs presented above represent mean travel times for each depth plotted. The mean is over 100 different weather

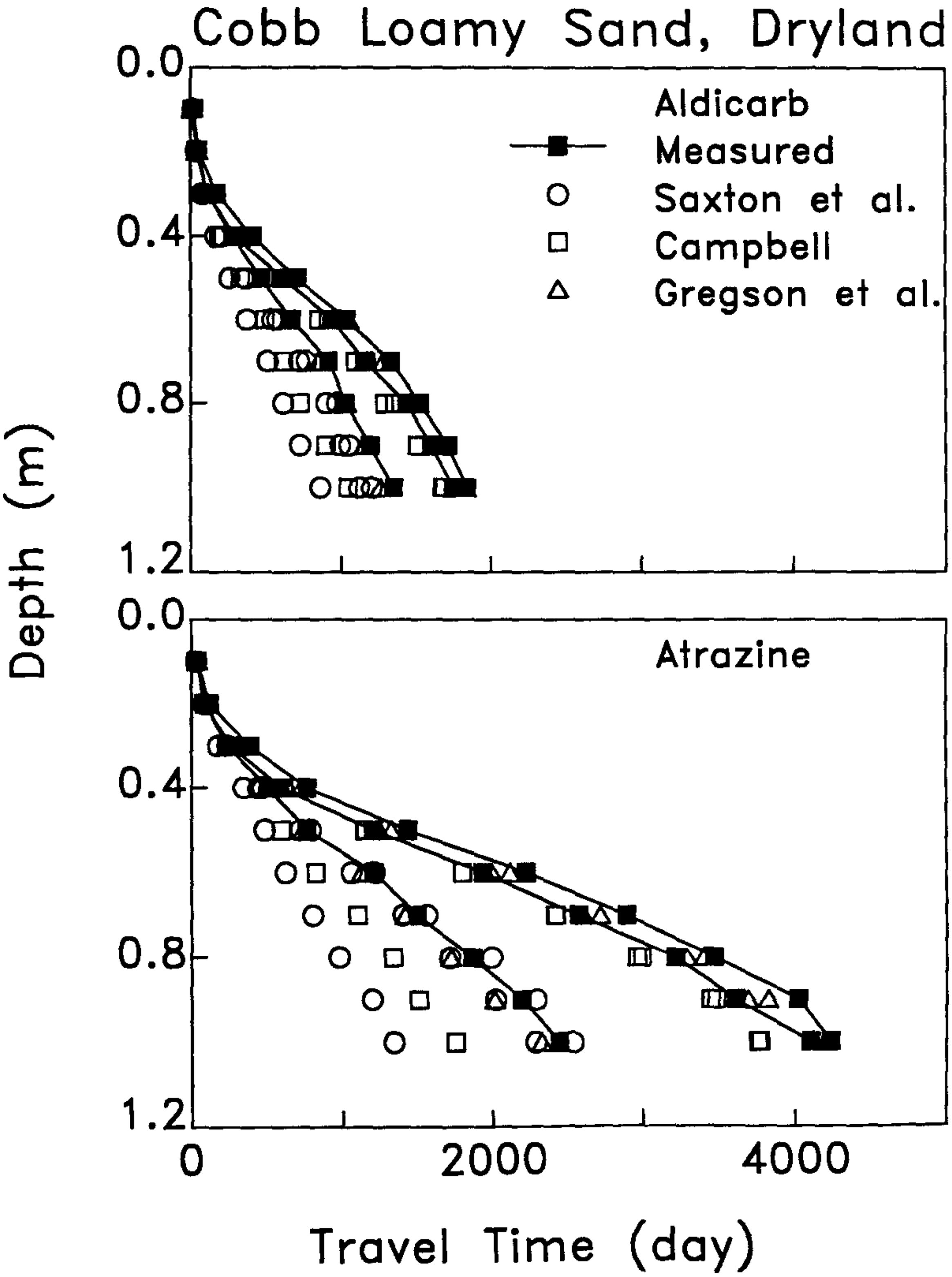

Figure 36. Depth of chemical as a function of travel time as predicted by CMLS for measured and estimated parameters at three sites of Cobb loamy sand.

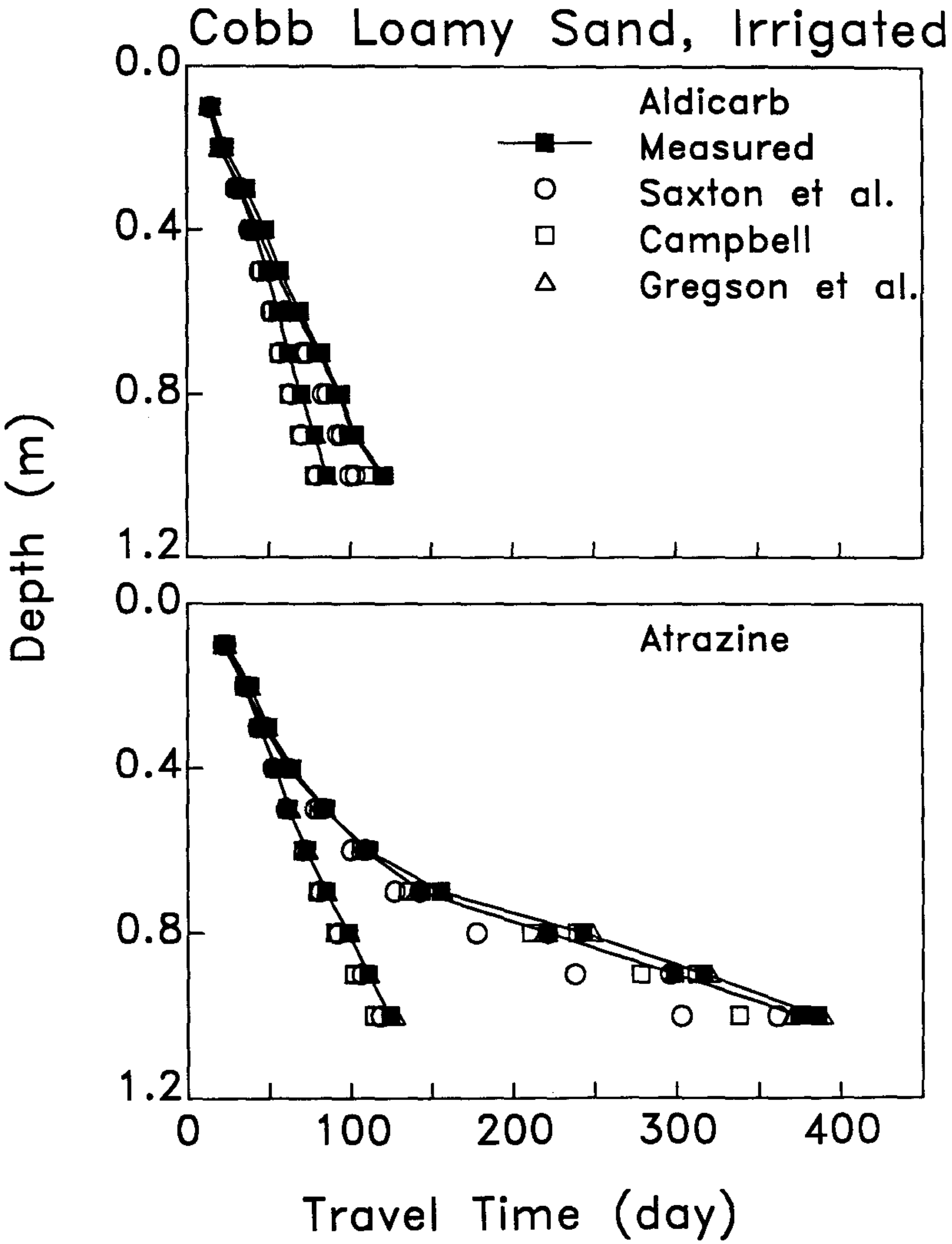

Figure 37. Depth of chemical as a function of travel time as predicted by CMLS for measured and estimated parameters at three sites of Cobb loamy sand.

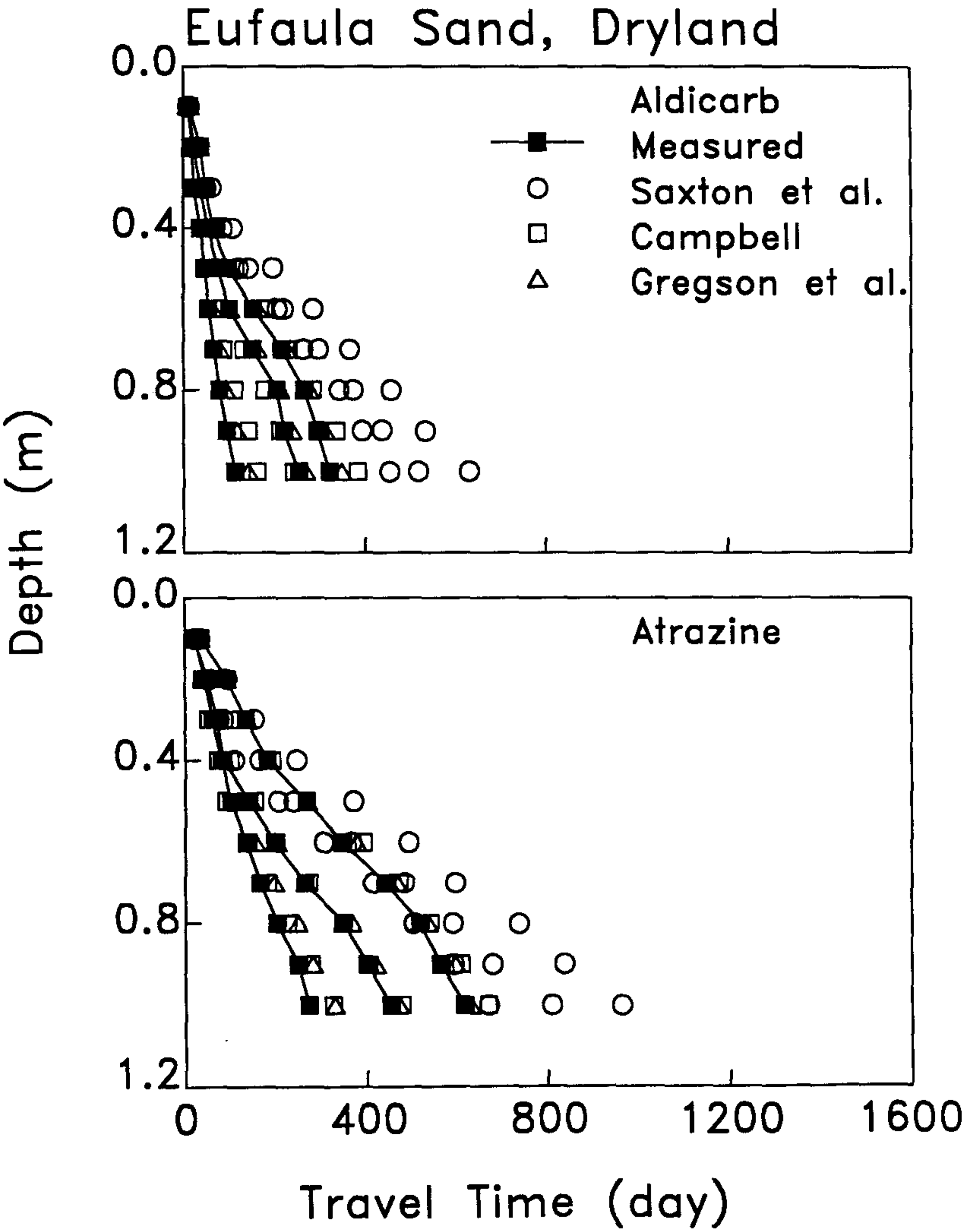

Figure 38. Depth of chemical as a function of travel time as predicted by CMLS for measured and estimated parameters at three sites of Eufaula sand.

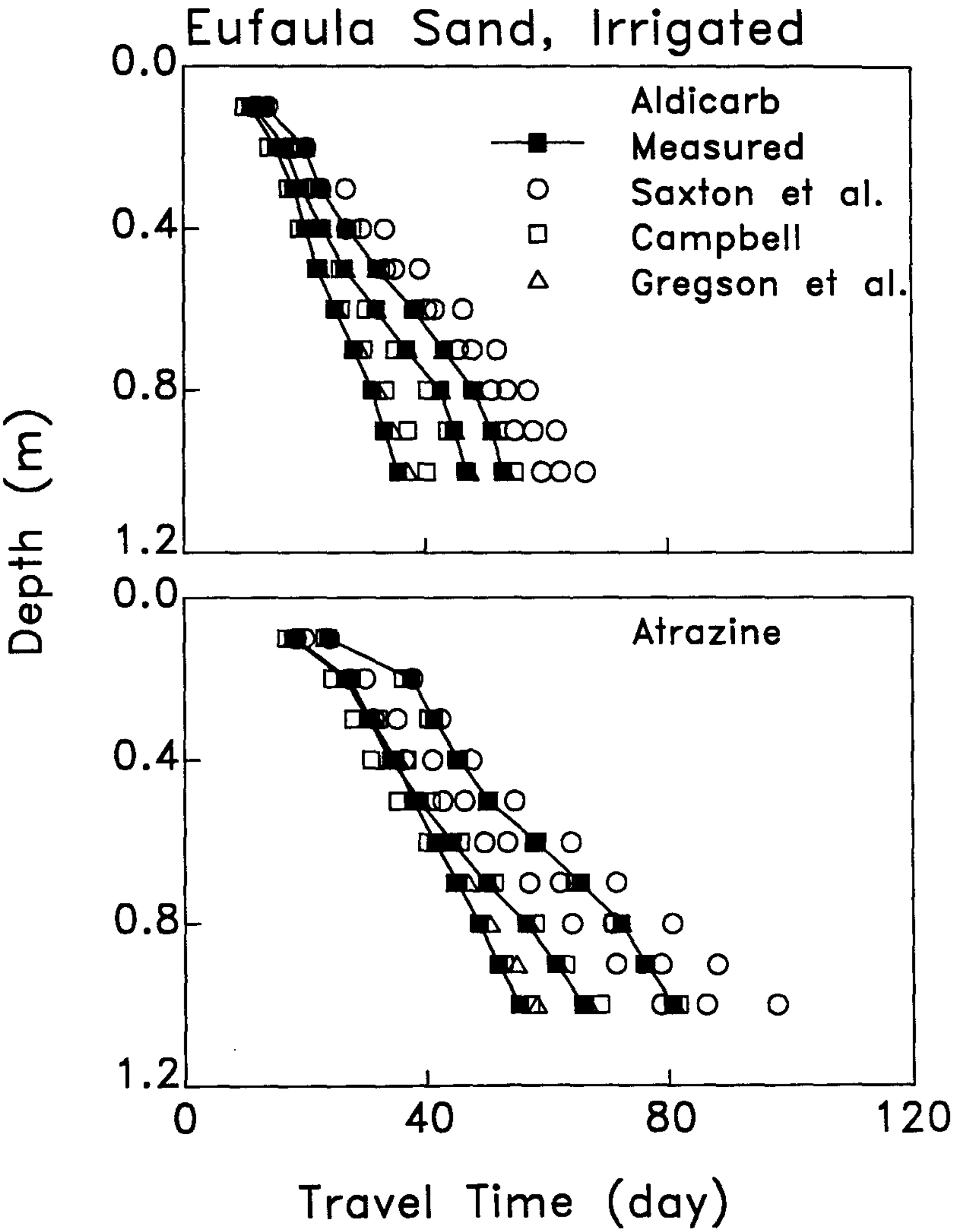

Figure 39. Depth of chemical as a function of travel time as predicted by CMLS for measured and estimated parameters at three sites of Eufaula sand.

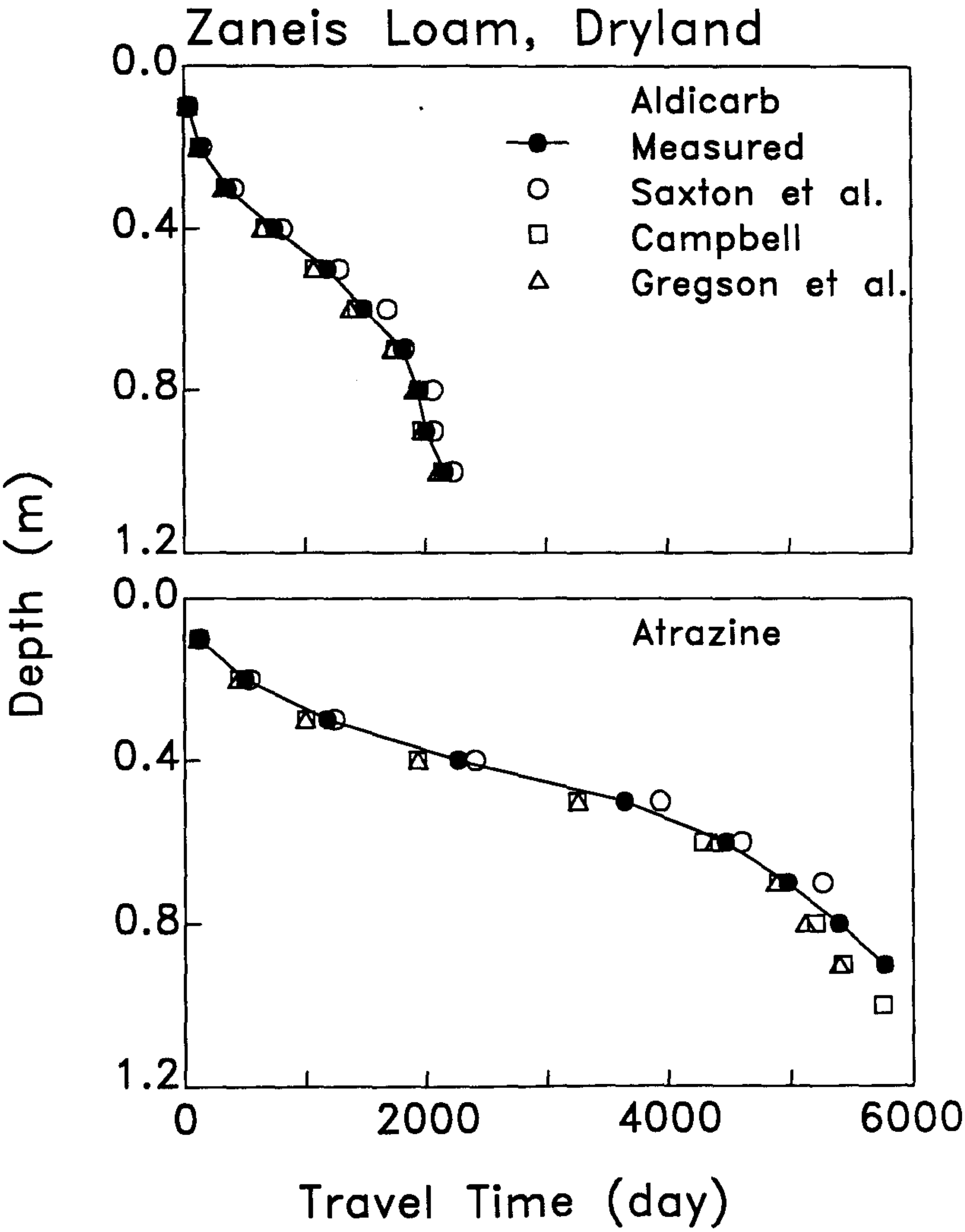

Figure 40. Depth of chemical as a function of travel time as predicted by CMLS for measured and estimated parameters for Zaneis loam.

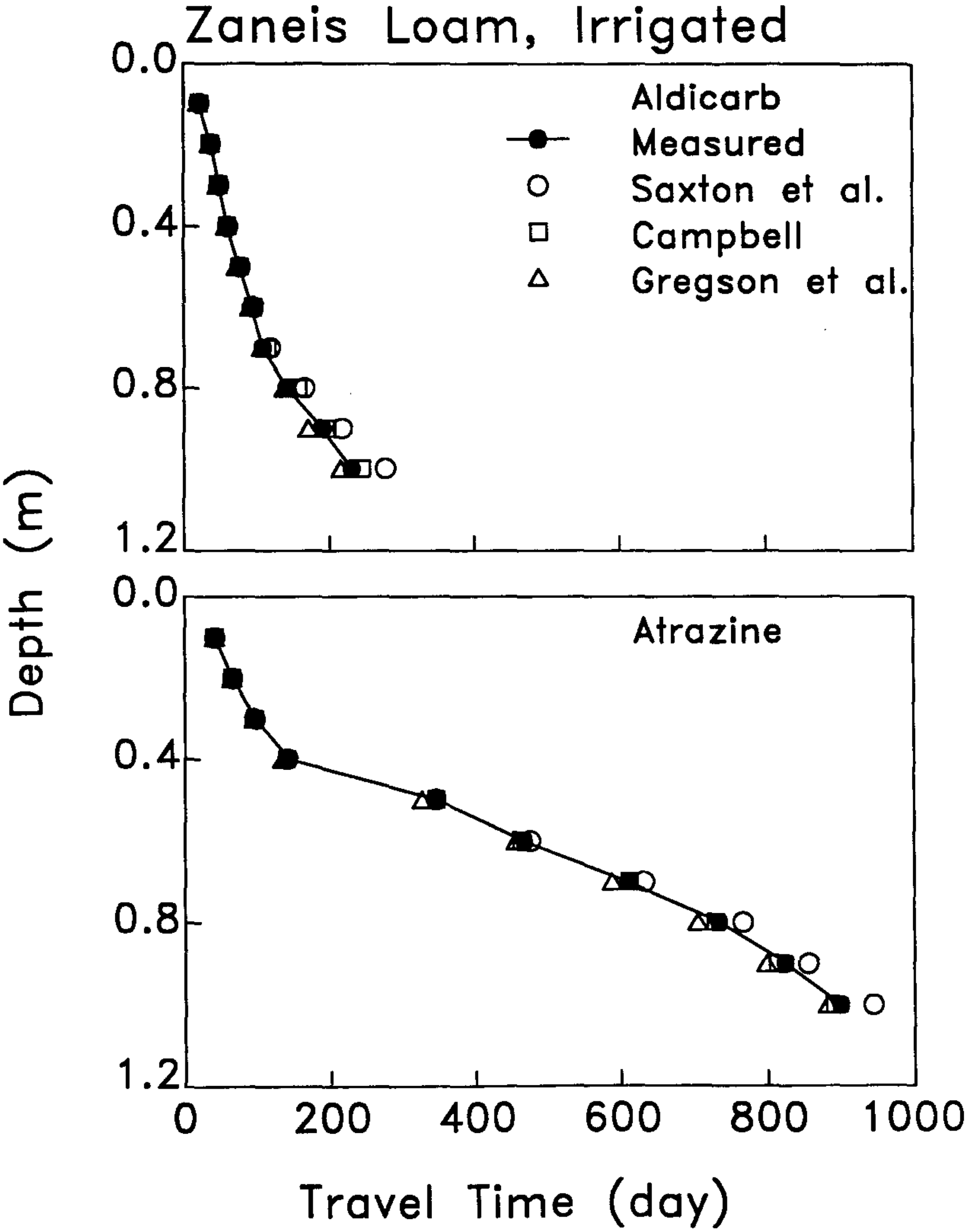

Figure 41. Depth of chemical as a function of travel time as predicted by CMLS for measured and estimated parameters for Zaneis loam.

sequences for the site in Caddo County Oklahoma. It was also of interest to examine the distribution of simulated depths of movement using measured data and estimated parameters. If the estimation techniques are able to reproduce the distributions obtained with measured parameters, the estimation techniques could be considered adequate for predictive purposes. Those results are presented for aldicarb in Figures 42 to 51. The distributions for the measured parameters and the estimated values are very similar. Once again, Gregson's method usually provides the best agreement followed closely by Campbell's. The largest differences exist for Eufaula soil where Saxton's method greatly underestimates the depth of penetration. The same observations were made from results for atrazine which are not shown. These results are very encouraging in that they suggest that estimated parameters based on Campbell's and Gregson's methods can be used to estimate the probability of a chemical passing a specified depth in a certain period of time. More analyses of these results are underway to determine whether this agreement will persist to greater depths and times.

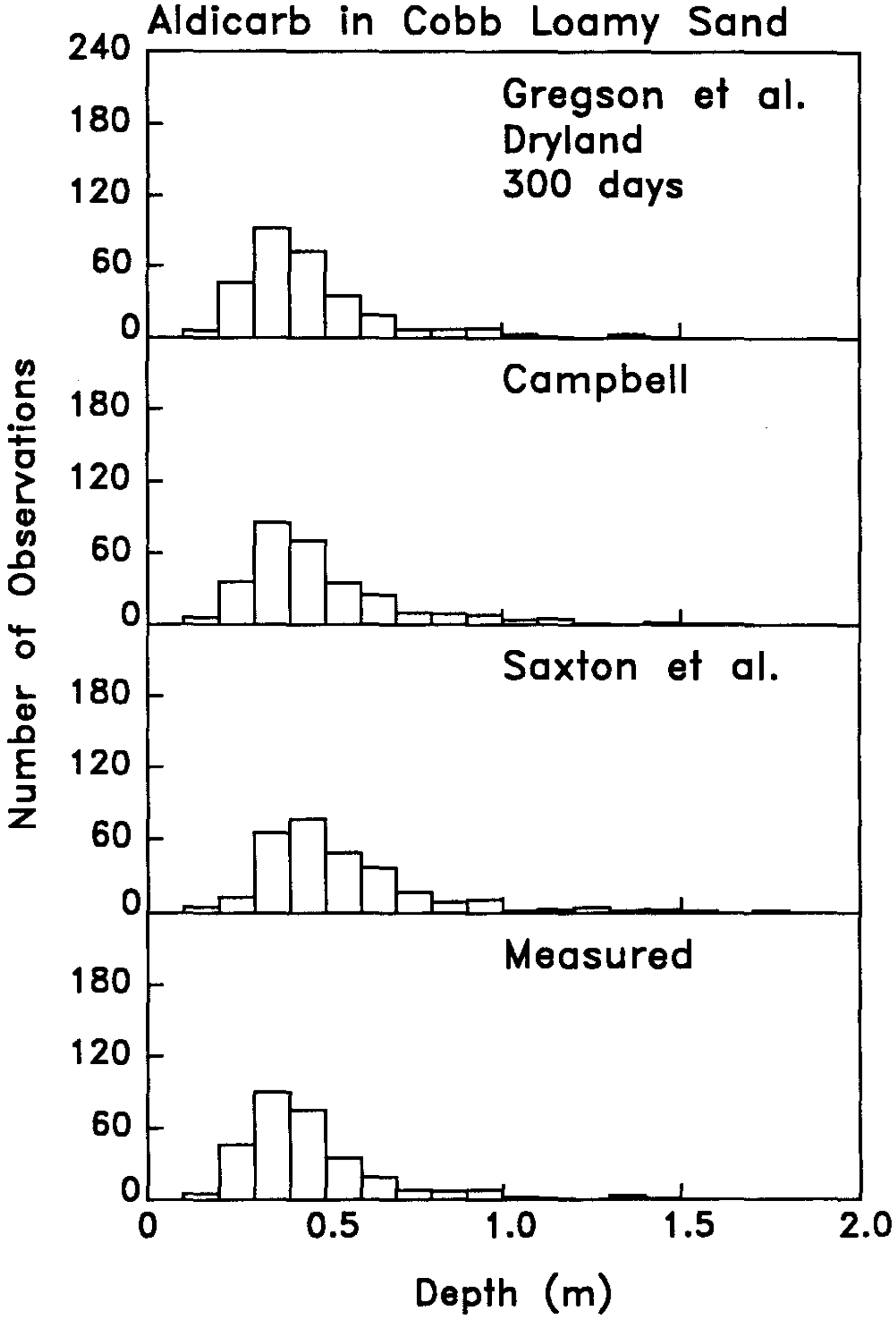

Figure 42. Distribution of depth of aldicarb 300 days after application on a Cobb loamy sand using measured and estimated parameters in the CMLS model under dryland conditions.

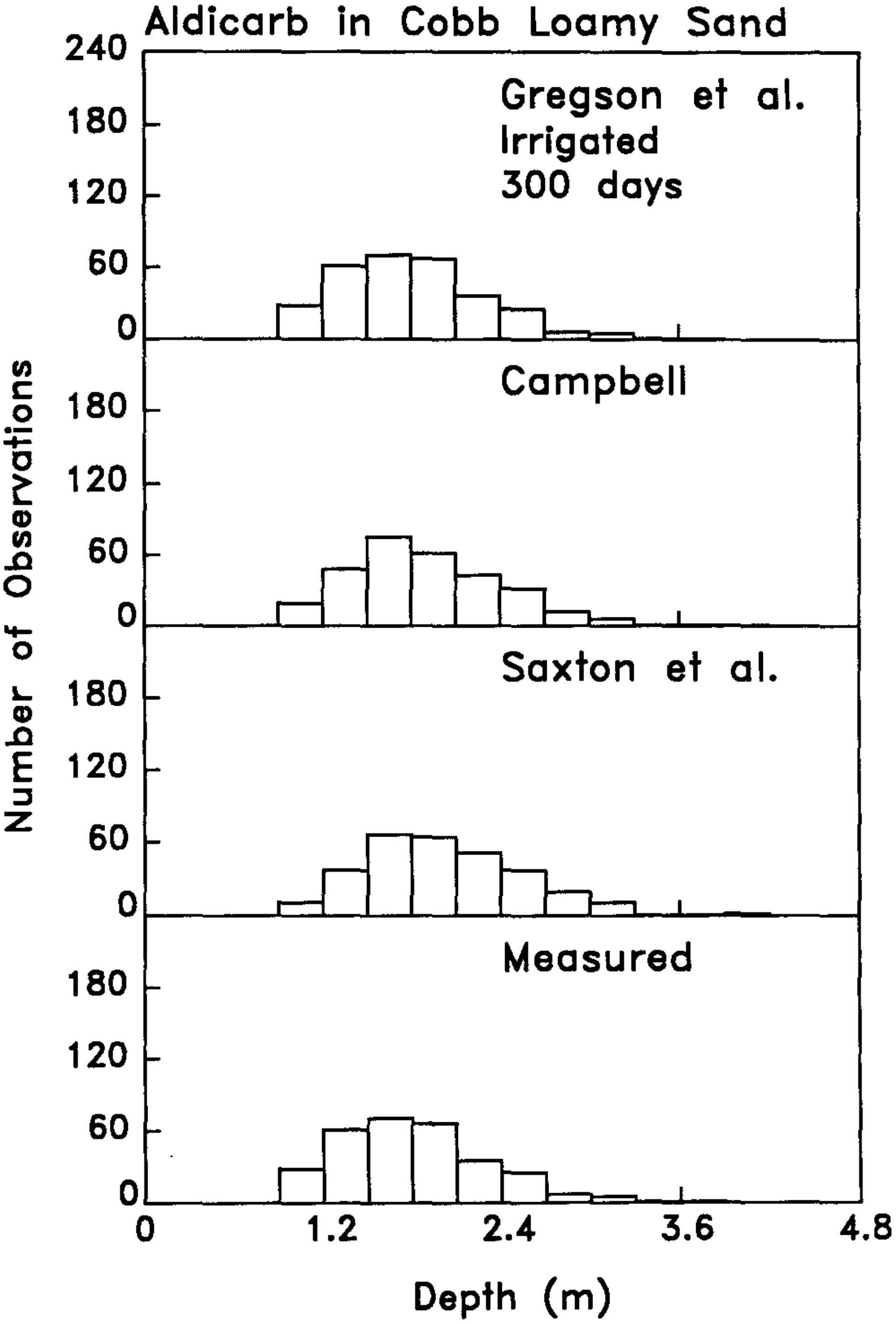

Figure 43. Distribution of depth of aldicarb 300 days after application on a Cobb loamy sand using measured and estimated parameters in the CMLS model under irrigated conditions.

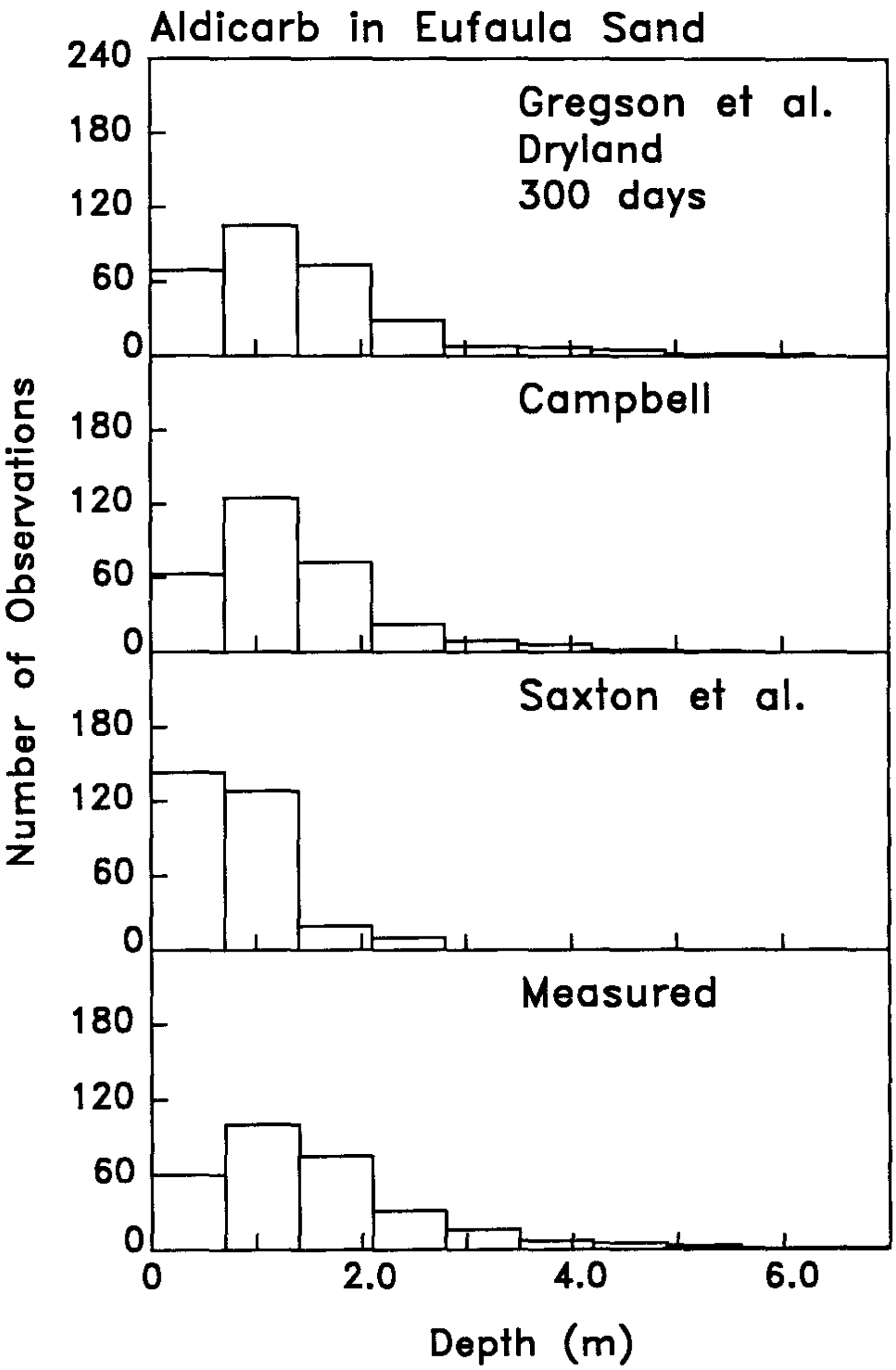

Figure 44. Distribution of depth of aldicarb 300 days after application on a Eufaula sand using measured and estimated parameters in the CMLS model under dryland conditions.

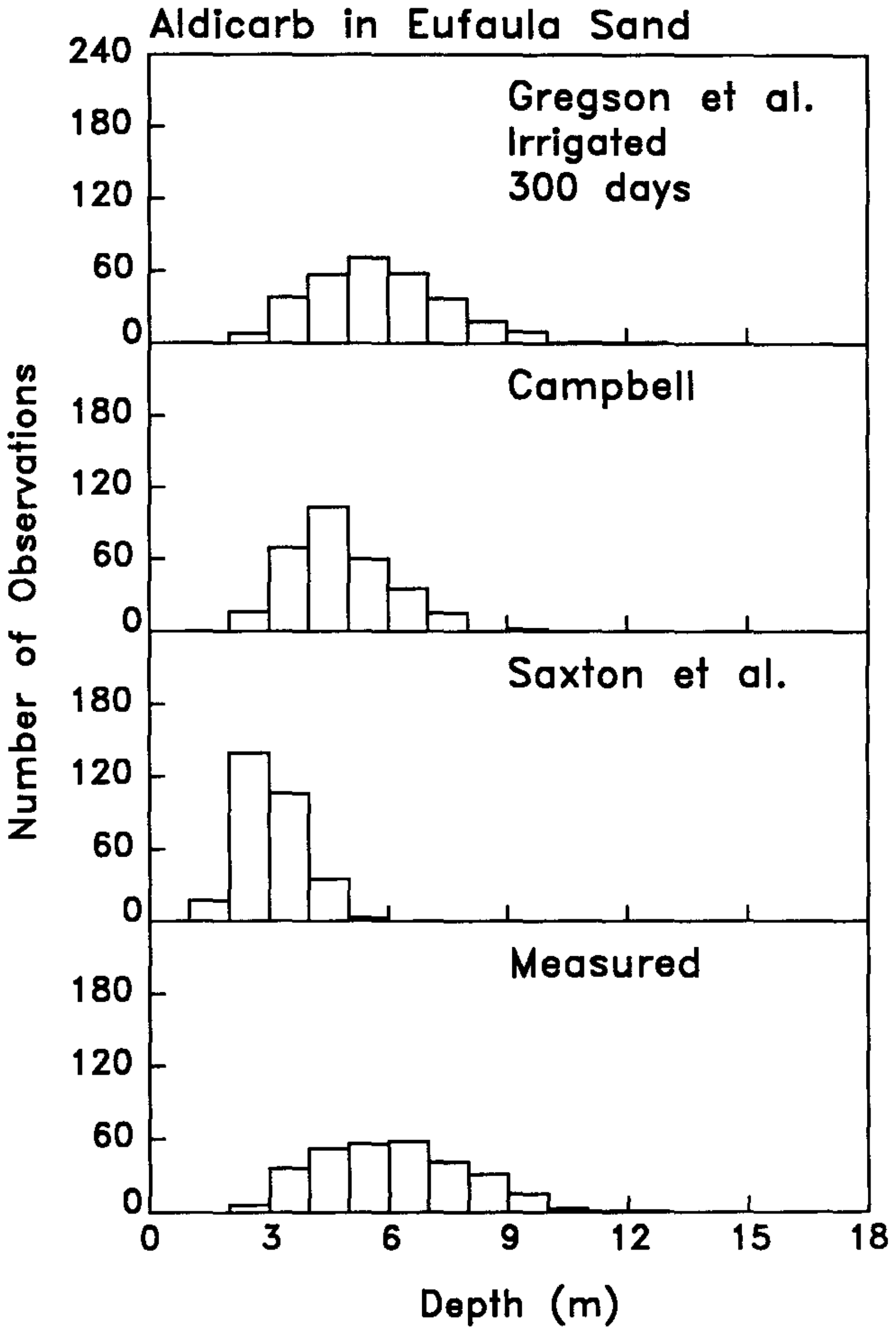

Figure 45. Distribution of depth of aldicarb 300 days after application on a Eufaula sand using measured and estimated parameters in the CMLS model under irrigated conditions.

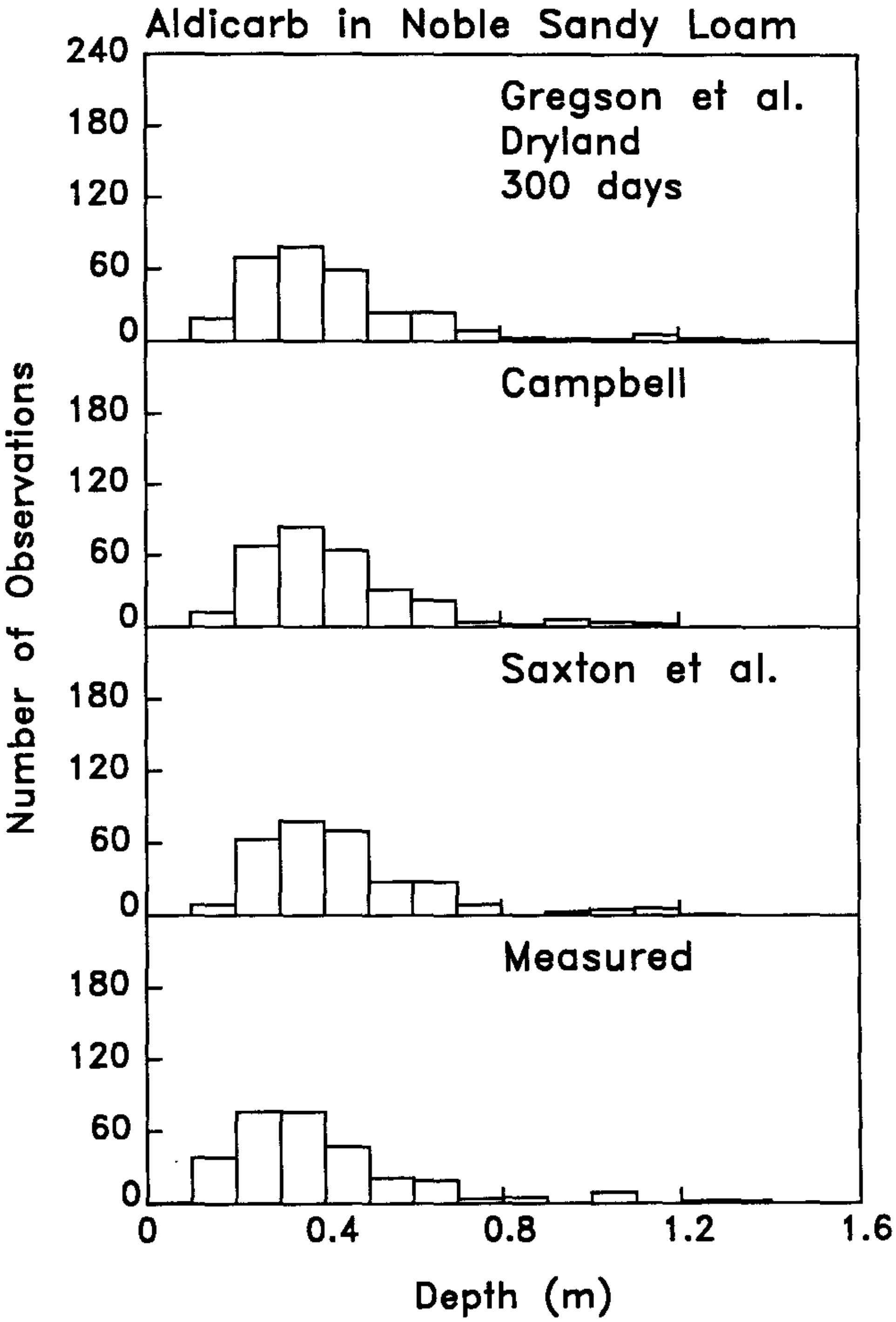

Figure 46. Distribution of depth of aldicarb 300 days after application on a Noble sandy loam using measured and estimated parameters in the CMLS model under dryland conditions.

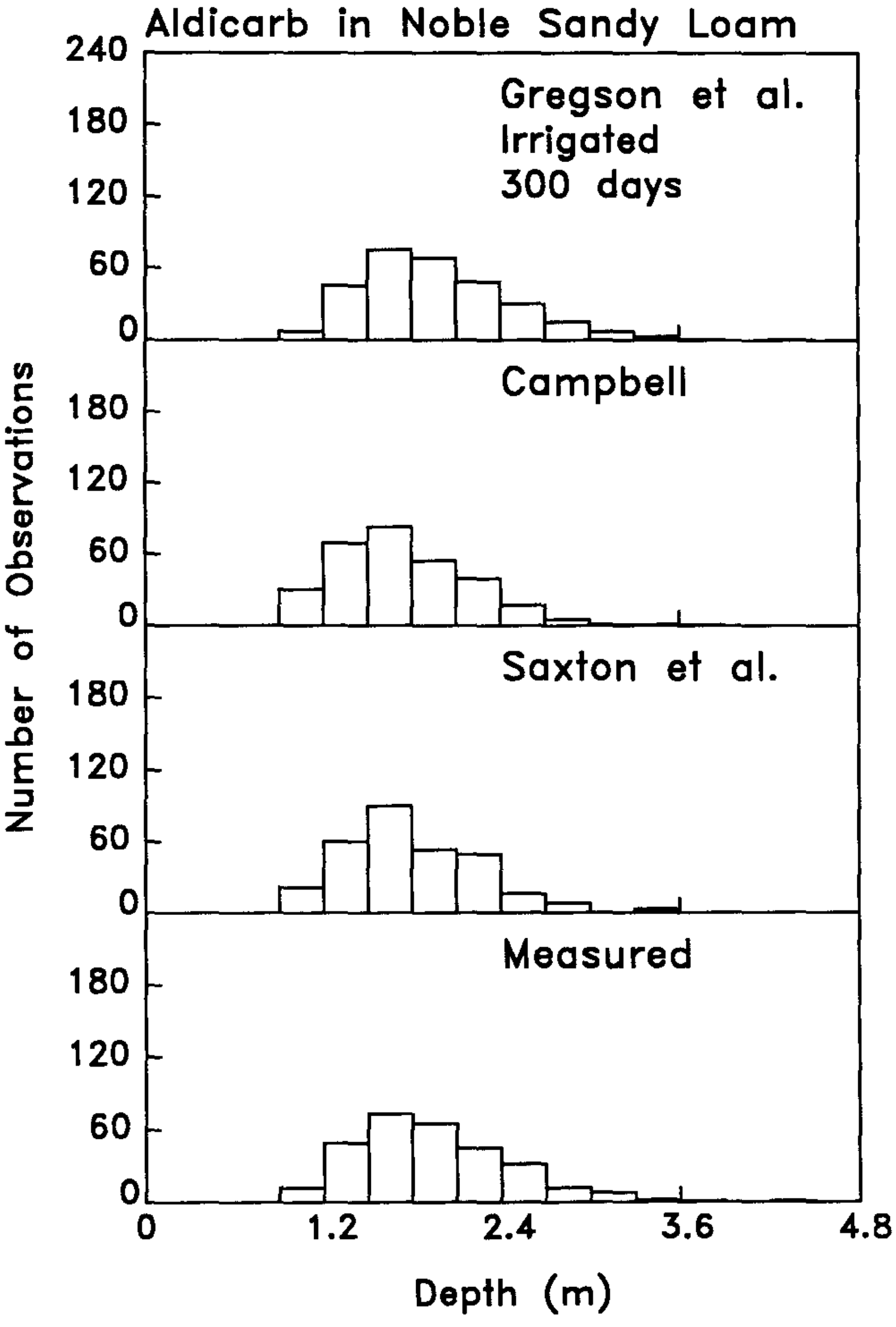

Figure 47. Distribution of depth of aldicarb 300 days after application on a Noble sandy loam using measured and estimated parameters in the CMLS model under irrigated conditions.

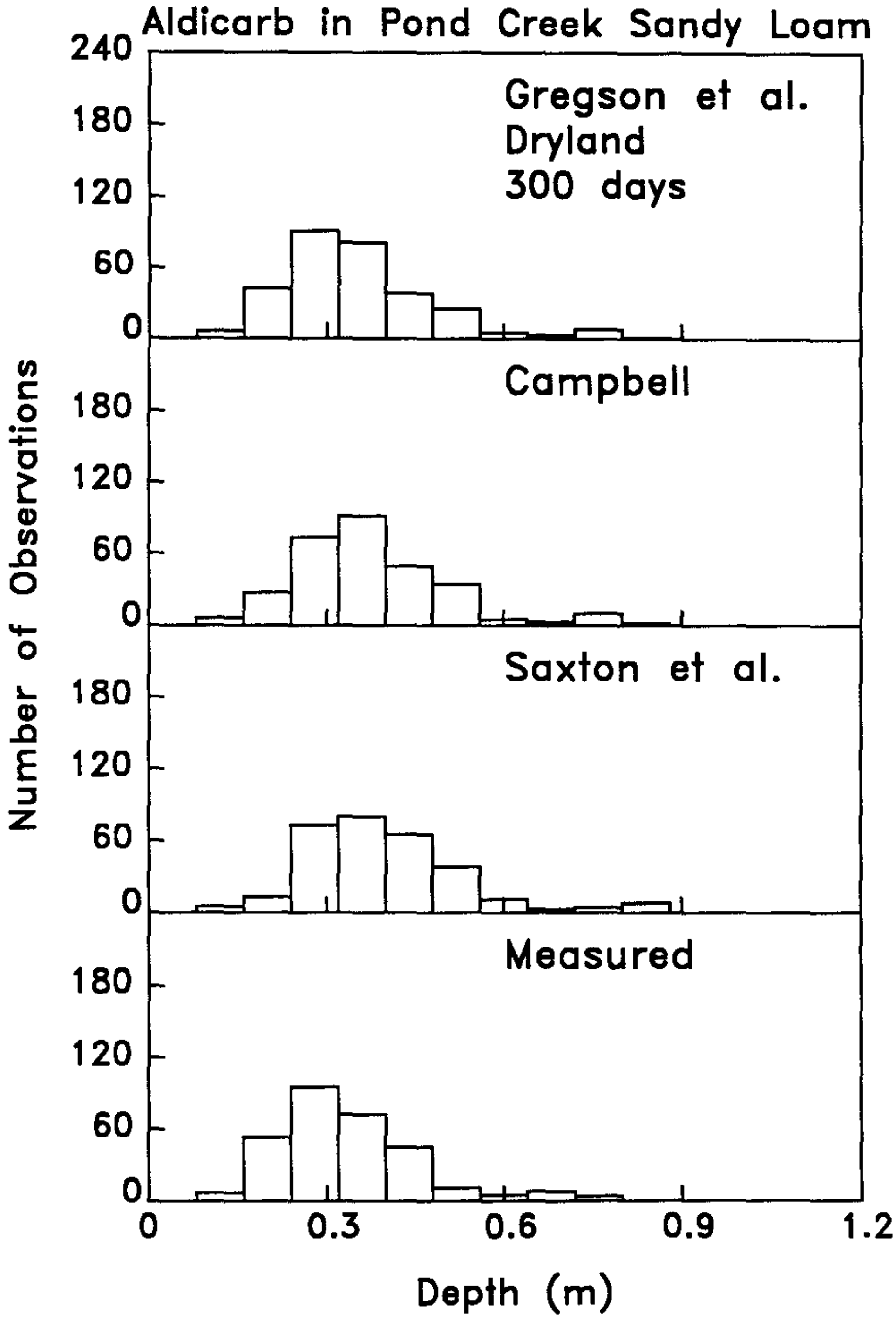

Figure 48. Distribution of depth of aldicarb 300 days after application on a Pond Creek sandy loam using measured and estimated parameters in the CMLS model under dryland conditions.

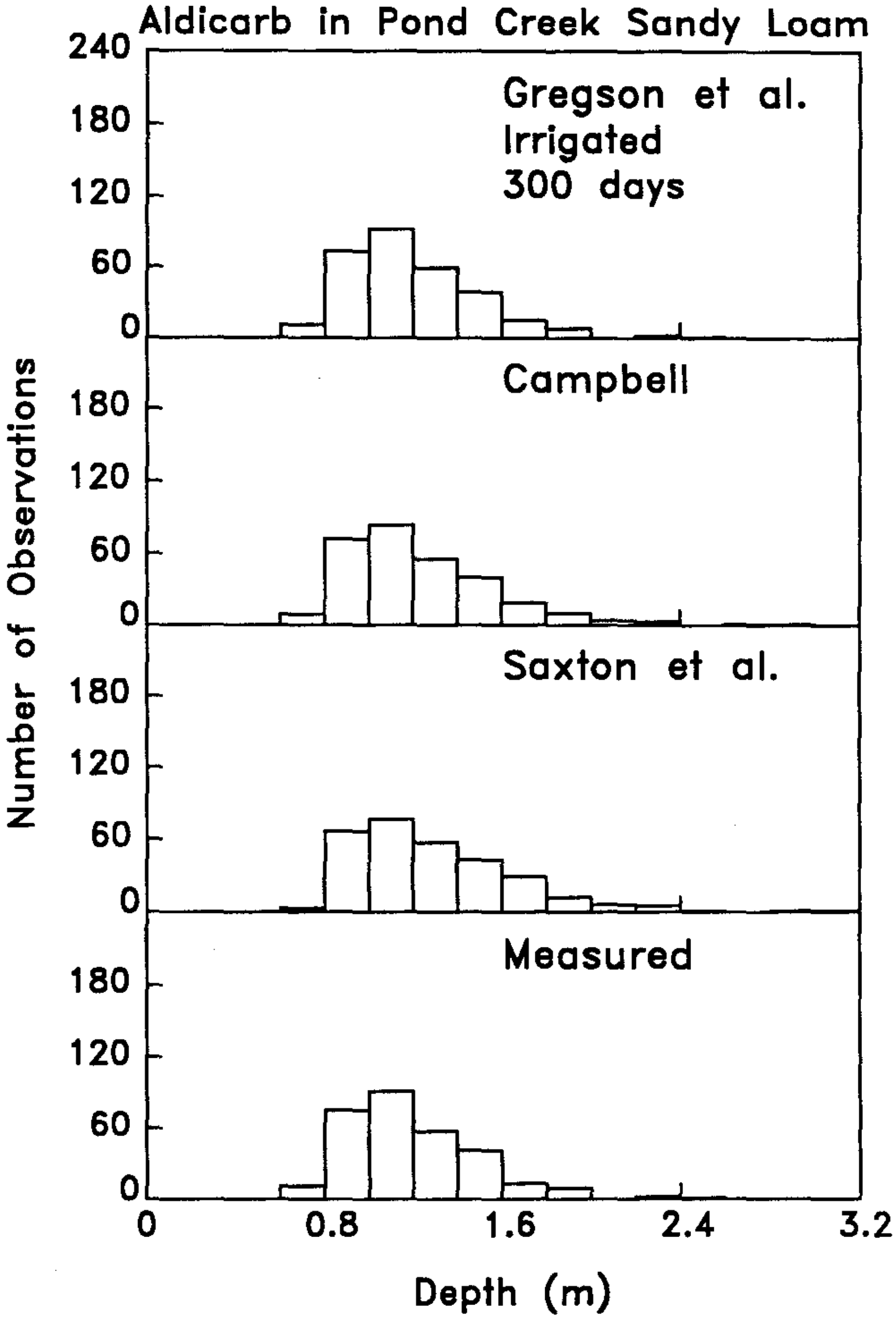

Figure 49. Distribution of depth of aldicarb 300 days after application on a Pond Creek sandy loam using measured and estimated parameters in the CMLS model under irrigated conditions.

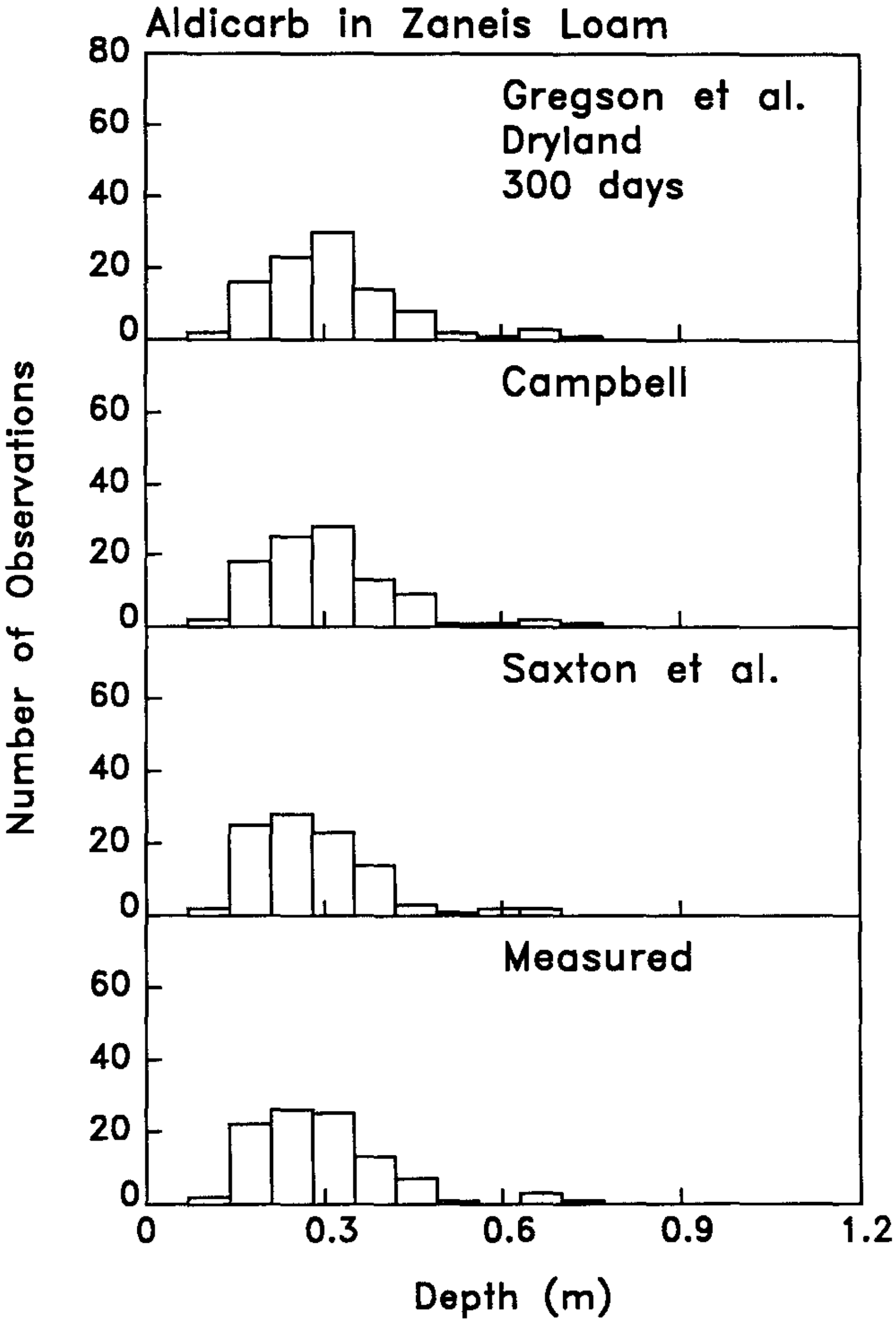

Figure 50. Distribution of depth of aldicarb 300 days after application on a Zaneis loam using measured and estimated parameters in the CMLS model under dryland conditions.

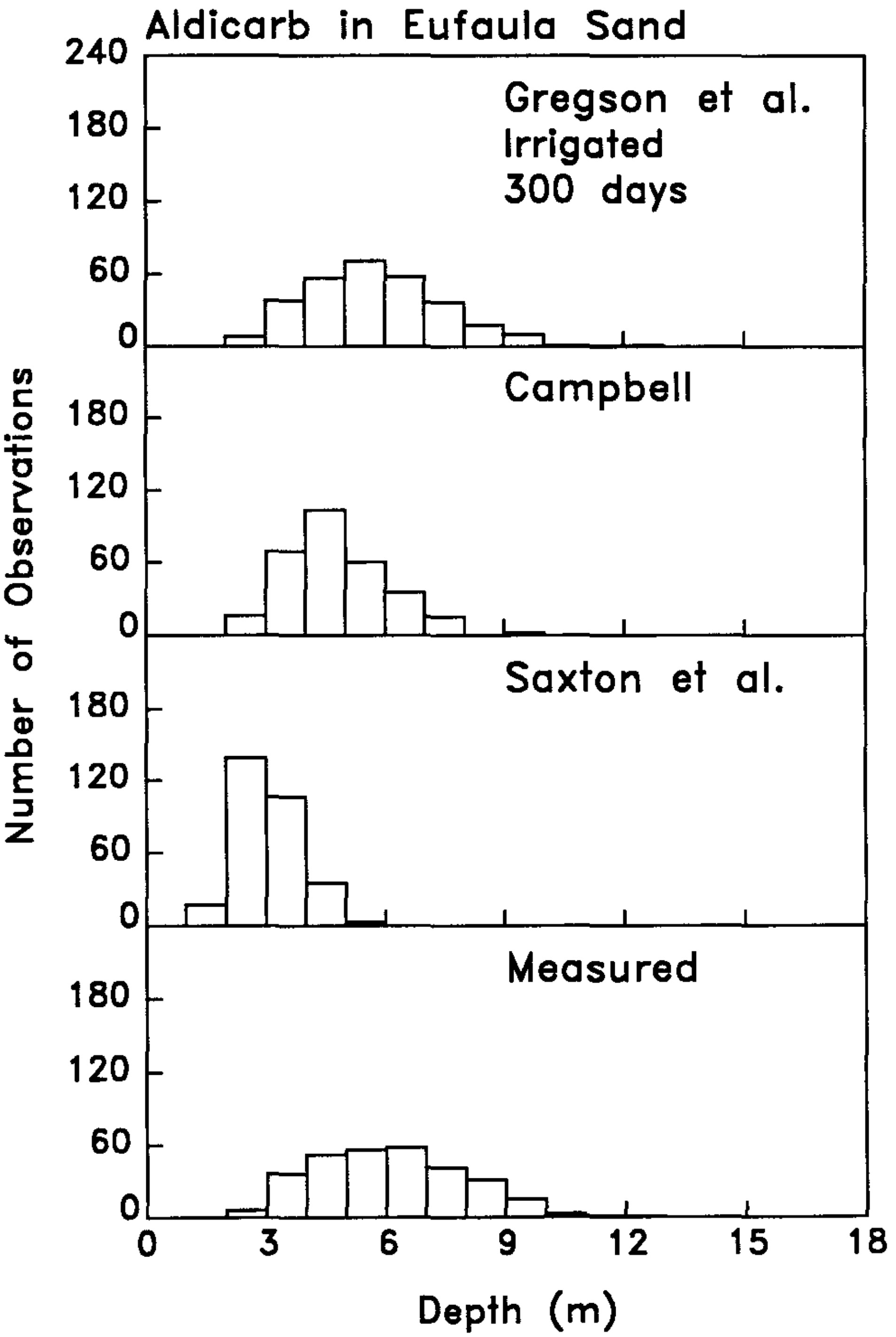

Figure 51. Distribution of depth of aldicarb 300 days after application on a Zaneis loam using measured and estimated parameters in the CMLS model under irrigated conditions.

CONCLUSIONS

The regression model of Campbell (1985) predicted water characteristic curves using the soil particle size distribution and bulk density more reliably than did the regression method of Saxton et al (1986) which does not use bulk density. The method of Gregson et al (1987) provided the best estimates overall. That model requires one measured water content at a particular tension and the bulk density of the soil. All three methods performed best for tensions above 10 kPa.

Both Campbell's and Gregson's methods appear to provide good estimates of chemical movement in unsaturated soils when combined with the CMLS model and when natural variability within a soil series is considered. These results indicate that these estimation techniques can be used for screening agricultural chemical management systems on different soils. Therefore, work on the state-wide AGCHEMS system for evaluating agricultural chemicals can proceed without waiting for time consuming and expensive field sampling and experimental measurement of water characteristics. Soil textural data available in the soil survey can be used to estimate the needed hydraulic properties.

Although the estimates performed well when spatial variability of the soil series is considered, they may not be satisfactory for detailed analysis of water and chemical movement at a particular small site.

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