Least Limiting Water Range: Traffic and Long-term Tillage Influences in a Webster Soil

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ABSTRACT

Rooting is a continuous response to the soil physical environment, but root responses in the field are sufficiently complex to require a least limiting approach. Rooting limitations of available water, soil aeration, and penetration resistance are linked into a least limiting water range (LLWR) as a function of bulk density (ρ_b). The LLWR concept and associated measurements were used to evaluate the impact of tillage and tracking on root and hydrologic environment at two depths in a poorly drained clay loam: (i) the 5- to 10-cm depth in nontracked and tracked interrows of three long-term tillage treatments (chisel plow, CH; moldboard plow, MB; and no tillage, NT); and (ii) a plow pan at 25- to 30-cm depth. Soil shrinkage, ρ_b, saturated hydraulic conductivity, water retention characteristic (WRC), and penetration resistance characteristic (PRC) were all measured in undisturbed soil cores (5 cm long by 5 cm in diameter). Both the WRC and PRC included ρ_b as an independent variable. Linearized fits of the WRC and PRC, with $R^2 > 0.70$, were sensitive to tracking and to CH vs. MB tillage; compaction in the plow pan and tracking in the NT reduced by 75% the impact of ρ_b on the PRC. Tracking reduced the LLWR as much as 0.04 to 0.06 $m^3\ m^{-3}$ in CH and NT treatments, but the reduction in the MB treatment was <0.02 $m^3\ m^{-3}$. Penetration resistance was more limiting than the wilting point in the NT treatment and the plow pan, but not in treatments receiving annual tillage. Aeration was more limiting than available water in the NT and plow pan than in the MB and CH. The LLWR portrayed a major soil structural impact on physical control of rooting. Soil hydraulic properties associated with the LLWR explained a compaction and drainage problem with conservation tillage that can be linked to shallow penetration of tillage tools in this poorly drained soil.

Root environment is often controlled by long-term tillage management. This environment can be impacted by soil organic matter accumulations as related to depth of incorporating crop residue (Allmaras et al., 1988; Karlen et al., 1994), soil structural properties as related to frequency and intensity of fragmentation (Voorhees and Lindstrom, 1984; Dexter, 1988), and rooting patterns especially related to row and interrow positions, soil depth, and traffic intensity (Kaspar et al., 1991, 1995; Liebig et al., 1993). Root environments above the undisturbed subsoil are usually associated with or controlled by soil physical factors, and most often only one or two of these factors are field measured. Consequently, better methods are needed to assess tillage effects on root environment at a time when reduced and conservation tillage places more emphasis on seedbed management.

The soil physical environment surrounding a root is characterized by soil water content, aeration, temperature, and mechanical (penetration resistance) factors (Hamblin, 1985; Letey, 1985; Boone et al., 1986; Goss et al., 1989), all of which are related to texture, structure, aggregation, aggregate stability, bulk density, and pore-size distribution. Oxygen diffusion to the root approaches zero at about 10% air-filled porosity (Currie, 1984; Smucker and Erickson, 1989), although soil structure can significantly influence this diffusion rate (Grable and Siemer, 1968). Root growth is mechanically impeded at a penetrometer resistance of 2 MPa, but this limit is also highly sensitive to soil structure (Hamblin, 1985; Allmaras and Logsdon, 1990). The limits of available water for root growth and function are variable; however, da Silva et al. (1994) selected −0.01 to −1.5 MPa matric potential for the surface layer of medium-textured soils. Because soil water is required for root development and nutrition and is distinctly interrelated with each of the other factors, it is the primary in situ factor controlling root growth. Other controlling factors are temperature, nutrients localized around the root, and photosynthate translocated from the plant shoot.

The four soil physical factors may interact to influence root growth and function, although it is difficult to determine when a factor is most limiting. Voorhees et al. (1975) observed primary root elongation to be most sensitive to aeration at low mechanical resistance levels, whereas resistance and aeration effects on root growth were indistinguishable at high resistance levels. When isolated effects of mechanical resistance, low temperature, oxygen stress, and water stress were all examined together, optimal conditions for corn (*Zea mays* L.) root elongation in a medium-textured soil were 0.24 to 0.27 $m^3\ m^{-3}$ for volumetric water and <1.22 g cm^{-3} for bulk density (Logsdon et al., 1987). These conditions removed mechanical resistance, water stress, and oxygen stress limitations on corn root growth. Thus, a range of soil structure for root growth is logically represented by a series of soil water contents and bulk densities related to limiting values of the soil physical factors.

Letey (1985) introduced a *nonlimiting water range* (NLWR) to describe a water-content range in which crop growth is not restricted by limitations related to available soil water, aeration, and mechanical resistance. Water contents associated with field capacity and wilting point defined the upper and lower limits, respectively. The upper and lower limits of the NLWR were further reduced by poor aeration or high mechanical resistance in some soils (Letey, 1985), which suggests root-growth limitations in a stagewise fashion.

Because root growth varies in a continuous manner

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within some threshold of the limiting environmental factor (Allmaras and Logsdon, 1990), the NLWR concept was improved (da Silva et al., 1994) to stress that plant response to varying water content is least limited inside of a range and most limited outside of the same range. This *least limiting water range* (LLWR) concept of de Silva et al. (1994) characterizes a single range in water content wherein available water, soil aeration, and mechanical resistance may impose significant limitations on root growth and function at each bulk density. Although tested as an index of soil structure for rooting in a coarse-textured and a moderately fine-textured soil (da Silva et al., 1994), further evaluation of the LLWR is needed when soil management may change soil structure.

This study used the LLWR concept and measurements to differentiate the LLWR response to soil structural characteristics of the 5- to 10-cm layer in the interrow of three long-term tillage systems (CH, MB, and NT) with and without the normal traffic that occurs during secondary tillage, planting, and harvest. The LLWR was used also to characterize rooting environment in the plow pan at a 25- to 30-cm depth beneath the experimental area. Both historical moldboard plowing and recent traffic have developed the plow pan. Our specific objectives were to: (i) test the LLWR on a soil high in clay and moderately high in shrink–swell; (ii) examine the influence of long-term tillage, with and without wheel traffic, on the LLWR. In a third objective, saturated hydraulic conductivity and air-entry pressure were used to characterize hydrologic responses to the tillage and traffic treatments in a poorly drained soil used for corn and soybean [*Glycine max* (L.) Merr.] production. The choice of tillage treatments includes conventional (MB) and conservation (CH and NT) tillage systems.

MATERIALS AND METHODS

Field Experiment

A long-term tillage experiment was established in 1985 on a poorly drained Webster clay loam (fine, loamy, mixed, mesic Typic Haplaquoll) at the Southern Experiment Station, Waseca, MN. Six treatments, each characterized by a tillage and wheel traffic combination (Table 1), were repeated for 9 yr in a corn–soybean sequence, continuous soybean, and continuous corn. A split-block design was used with two replications of primary tillage as main plots and four replications of crop sequence as the subplots. Subplot size was eight 76-cm rows, each 16 m long. Tillages were CH, MB, and NT. The CH and MB treatments were initiated in the fall, and included secondary tillage (tandem disk and spring-tooth cultivator) in the spring before planting — NT had neither primary nor secondary tillage. The wheel traffic types consisted of: nontracked (nt), where no traffic occurred on the interrow; and tracked (t), where traffic occurred on the interrow during secondary tillage and planting. Tractor size was about 85 kW. The field plots did not have postplant cultivation, but controlled wheel traffic was used occasionally during postplant herbicide application. Four-row harvest equipment used the same controlled tracking as during secondary tillage.

In late July 1992, soil cores (2-cm increments to 50-cm depth) were taken in the corn–soybean sequence (soybean year) to measure soil bulk density as a function of soil depth for both the row and tracked interrow of the three tillage treatments. A composite of 15 cores (1.8-cm diameter) was taken separately from each of two replications using the sampling procedure of Logsdon et al. (1990).

Table 1. Treatment combinations, symbols, and selected properties of the Webster clay loam.†

Primary tillage	Interrow traffic	Treatment symbols	Carbon	K_{sat}‡	ρ_b§	Air-entry pressure
			g kg^{-1}	μm s^{-1}	g cm^{-3}	kPa
Chisel	nontracked	CHnt	40.7	3.64a¶	1.08	1.66
	tracked	CHt		0.01cd	1.28	2.74
Moldboard	nontracked	MBnt	32.7	0.21b	1.20	2.20
	tracked	MBt		0.04c	1.29	2.78
No-till	nontracked	NTnt	39.1	0.02cd	1.30	2.92
	tracked	NTt		0.003d	1.40	3.85
Plow pan	–	–	24.7	0.01cd	1.48	4.54
Standard error#			0.2	–	0.02	–

† Textural composition in 5- to 10-cm layer is 331 347, and 322 g kg^{-1} of clay, silt, and sand, respectively; respective composition in the 25- to 30-cm layer is 319, 344, and 337 g kg^{-1}.
‡ Saturated hydraulic conductivity.
§ Bulk density at field moisture (approximately −33 kPa water potential).
¶ Geometric means followed by the same letter are not different ($P < 0.05$) using the Student–Newman–Keuls test.
# Standard error for C has 9 df; that for ρ_b has 14 df.

Prior to corn harvest in late September 1994, undisturbed soil cores (5 cm long by 5 cm in diameter) were randomly sampled in the corn–soybean sequence at the midpoint within the nontracked and tracked interrows. A total of 90 cores (15 cores per treatment) was collected from the 5- to 10-cm depth when the soil was at a field water content near the lower plastic limit. In April 1996, a set of 30 randomly selected cores was taken from a distinct plow pan at the 25- to 30-cm depth in the experimental site — again field water content was near the lower plastic limit.

All undisturbed cores were wrapped in plastic film and stored at 4°C pending laboratory measurements.

Laboratory Measurements

A series of measurements was made on each undisturbed soil core to measure saturated hydraulic conductivity (K_{sat}), WRC, and PRC related to soil water content (θ_v). The undisturbed soil core was retained in the original brass ring (1.6-mm wall thickness) throughout the measurements. Deaerated distilled water (with $CaCl_2$ and thymol added to retain a natural ionic strength and suppress microbial activity) was used to saturate each soil core for several days before K_{sat} was measured with the falling-head method (Klute and Dirksen, 1986). After completing K_{sat} measurements, each core was placed into a Tempe pressure cell to extract water at pressures (ψ) of 1, 10, 20, 30, 40, 60, and 80 kPa (Soil Moisture Equipment Corp., 1986) to generate a WRC. When not subjected to a measurement, the cores were wrapped in plastic film and maintained at 4°C to prevent drying.

After finishing the Tempe cell measurements for outflow at ψ up to 80 kPa, the 15 soil cores from each tillage × tracking treatment were split into five groups of three cores and randomly assigned to ψ of 3, 30, 100, 300, or 1500 kPa. Cores in the 3 and 30 kPa groups were resaturated and equilibrated in Tempe cells; cores in the 100, 300, and 1500 kPa groups were equilibrated on pressure plates. After this equilibration, a second WRC was generated, and the cores again stored in plastic film at 4°C for a 1-wk minimum to ensure water equilibration throughout the soil core before making penetration resistance measurements.

Penetration resistance (PR) was measured using a cone penetrometer with a semi-included cone angle of 36° and a 9.62-mm^2 basal area — the shaft was 3 mm in diameter, and a sleeve was used to reduce stem friction. The cone penetrometer, mounted on an Instron[1] testing machine (Instron Corp., Canton, MA), was advanced three times into each core at a constant velocity of 2 mm min^{-1} with PR in megapascals recorded every 3 s. Observed PR values corresponding to the 0.5- to 4.5-cm distance through the core were integrated across that 4-cm band for each penetration. The cores were then oven dried to determine bulk density (ρ_b) and θ_v.

After oven drying, soil samples were taken from at least 10 cores of each tillage treatment to determine particle-size distribution (pipette method, Gee and Bauder, 1986) and organic C (dry combustion method, Nelson and Sommers, 1982).

Air-entry pressure was calculated (Rawls and Brakensiek, 1985) using measured textural composition and ρ_b. Rather than a smooth WRC during initial desaturation, air-entry pressure can be considered as a Haines jump when air enters an interior pore (Corey, 1986).

The Webster clay loam has moderate shrink–swell, which was accounted for in all measurements and calculations. A measured COLE (coefficient of linear expansion) of 0.065 was used for the soil cores from the 5- to 10-cm surface layer (Kassa, 1992). Because the undisturbed soil cores were sampled when field water content was near the lower plastic limit, we assumed cores to be 5 cm long at the field-moist −33 kPa water potential. We designated ψ as a pressure for ease of calculation and extended the swell–shrink estimate from the reference ρ_b measured at ψ = 33 kPa. Three-dimensional swelling between ψ = 33 kPa and saturation, and three-dimensional shrinkage was assumed between ψ = 33 kPa and oven dry using the standard COLE relation:

$$\rho_{33} = \rho_{od}/(\text{COLE} + 1)^3 \quad [1]$$

where ρ_{33} and ρ_{od} occur at ψ = 33 kPa and oven dry, respectively. Expanded core lengths were measured immediately after K_{sat} and were used to compute a saturation ρ_{sat}. For pressures between saturation and ψ = 33 kPa, ρ_i was estimated as:

$$\rho_i = \rho_{33} - [(\rho_{33} - \rho_{sat})/(\theta_{g\text{-}sat} - \theta_{g\text{-}33})](\theta_{g\text{-}i} - \theta_{g\text{-}33}) \quad [2]$$

where $\theta_{g\text{-}sat}$, $\theta_{g\text{-}33}$, and $\theta_{g\text{-}i}$ are gravimetric water contents at saturation, at ψ = 33 kPa, and at corresponding equilibrated pressure between saturation and ψ = 33 kPa, respectively.

For all measured pressures greater than ψ = 33 kPa, ρ_{ii} was estimated:

$$\rho_{ii} = \rho_{od} - [(\rho_{od} - \rho_{33})/\theta_{g\text{-}33}]\ \theta_{g\text{-}ii} \quad [3]$$

where $\theta_{g\text{-}ii}$ is gravimetric water content corresponding to equilibrated pressure larger than ψ = 33 kPa.

A COLE value had not been measured for the 25- to 30-cm plow pan layer. Instead, three separate core length measurements at field moist, saturation, and oven dry were made on the soil cores to directly calculate the volumes needed to estimate ρ_{33}, ρ_{sat}, and ρ_{od}. Equations [2] and [3] were then used to estimate ρ_b in the plow pan soil across the whole range of water contents from saturation to oven dry.

Combining Measurements and Statistics

For each of the six treatments, two separate functional relations involving θ_v, ψ, ρ_b, and PR were developed using multiple linear regression and associated statistical tests (Jandel Scientific, 1992). In the first relation, θ_v, ρ_b, and ψ measurements were fitted to a model (Ross et al., 1991; da Silva et al., 1994):

$$\theta_v = \exp(a + b\rho_b)\psi^c \quad [4]$$

or the linearized form

$$\ln\theta_v = a + b\rho_b + c\ \ln\psi \quad [5]$$

where a, b, and c are constants.

In the second relation, PR, θ_v, and ρ_b measurements were fitted to a model (Busscher, 1990; da Silva et al., 1994):

$$\text{PR} = d\theta_v^e\ \rho_b^f \quad [6]$$

or the linearized form

$$\ln\text{PR} = d + e\ \ln\theta_v + f\ \ln\rho_b \quad [7]$$

where PR has units of megapascals and d, e, and f are constants.

Constructing the Least Limiting Water Range

A LLWR (for each treatment) related to field capacity (θ_{fc}), wilting point (θ_{wp}), a limiting penetration resistance (θ_{pr}), and a limiting air-filled porosity (θ_{afp}) was constructed using the working Eq. [5] and [7]. Limiting values were: −0.01 MPa matric potential for field capacity (Haise et al., 1955), −1.5 MPa matric potential for wilting point (Richards and Weaver, 1944), 2 MPa for PR (Taylor et al., 1966), and 10% for air-filled porosity (Grable and Siemer, 1968). The equation $\theta_{v\text{-}sat} - 0.1$ or $(1 - \rho_b/\rho_s) - 0.1$ was used to calculate θ_{afp} for each treatment, where the mean particle density (ρ_s) is 2.65 g cm^{-3}.

Within the characteristic range of ρ_b for each treatment, the LLWR is the range between the upper and lower limit of θ_v. The upper limit is defined by either θ_{fc} or θ_{afp}, whereas the lower limit is defined by either θ_{wp} or θ_{pr}.

RESULTS AND DISCUSSION

Bulk Density: Field Measurements to Guide Least LimitingWater Range Inference

As a function of soil depth, ρ_b obtained from cores (2 cm long and 18 mm in diameter) shows sensitivity of this soil to long-term tillage and controlled traffic (Fig. 1); plotted symbols in the upper 30 cm are means of two individual ρ_b estimates within each of the six treatments sampled, and each individual estimate is derived from a composite sample of 15 cores. Tillage implements did not penetrate more than 30 cm; therefore, ρ_b plotted below 30 cm are means of the estimated ρ_b across three tillage treatments for both the row and tracked interrow. Although not shown, ρ_b measured in the nontracked interrow in July 1994 using 7.5-cm increments provided estimates of 1.20, 1.22, and 1.27 g cm^{-3} for the CH, MB, and NT treatments in the 5- to 10-cm layer — these are nearly the same as in the row (Fig. 1) and reveal the adverse impact of interrow tracking. In the 5- to 10-cm layer, where tillage and tracking effects are most evident, the ρ_b for MB and CH treatments are similar but much less than for NT in all three positions (Fig. 1).

The core ρ_b (Table 1) for the CHt and MBt treatments are interspersed between the lower values of the CHnt and MBnt treatments and the higher values of the NT

[1] Names are necessary to report factually on available data; however, the University of Minnesota and USDA-ARS neither guarantees nor warrants the standard of the product, and the use of the name by University of Minnesota or USDA-ARS implies no approval of the product to the exclusion of others that may also be suitable.

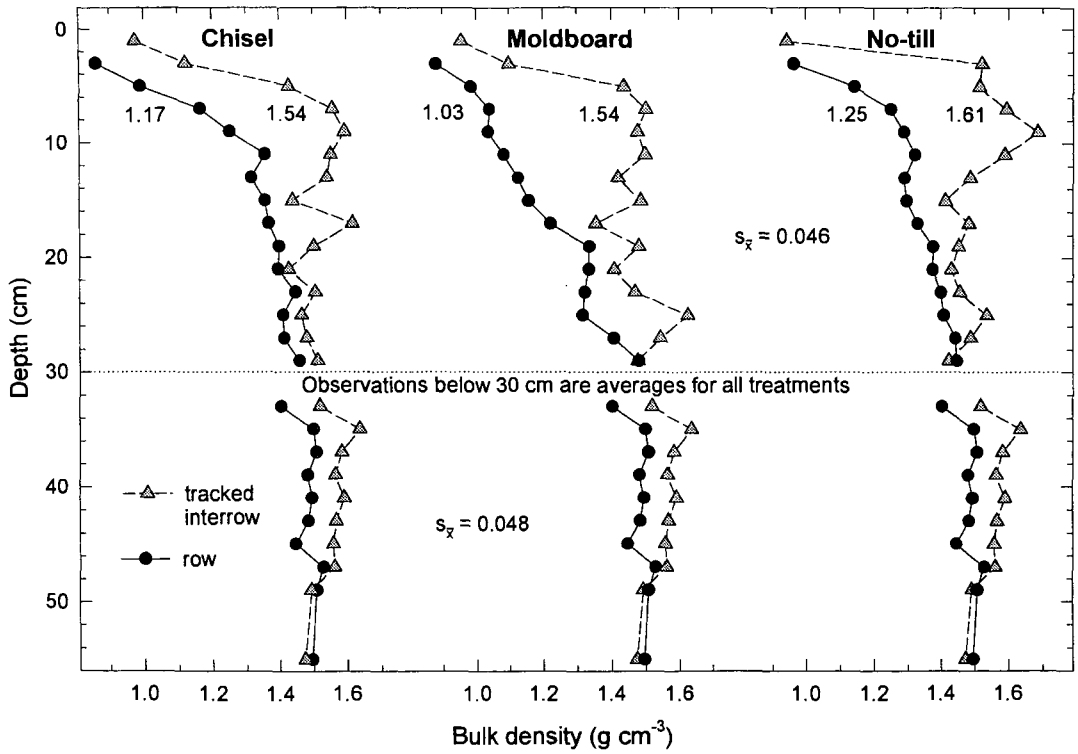

Fig. 1. Profiles of bulk density (ρ_b) under the row and in a tracked interrow as related to long-term tillage and traffic treatments on a Webster clay loam. Standard error of the mean, $s^{\bar{x}}$, was derived from the root mean square error between duplicate measures of ρ_b. Values of ρ_b integrated over the 5- to 10-cm depth are shown to the left of the curves.

treatments. Higher ρ_b for the tracked interrow were measured with the field method (Fig. 1) than with the larger 5-cm-diameter cores (Table 1). Field measurements (Fig. 1) are necessary, however, to guide inferences derived from the larger cores and selected depths used for LLWR.

All three tillage treatments exhibited distinct compaction to a depth of 46 cm caused by controlled traffic (Fig. 1) — ρ_b in the 15- to 30-cm depth of the nontracked interrow (not shown) were nearest to the row measurements of Fig. 1. This compaction due to controlled traffic was an accumulation during the first 7 yr of the experiment and agrees with heavy-axle load compaction of a Webster subsoil (Voorhees et al., 1986). The mean ρ_b of 1.48 g cm^{-3} from cores taken in the plow pan is consistent with measurements in Fig. 1 that range near 1.5 g cm^{-3} at the 25- to 30-cm depth.

Soil Properties Measured in Undisturbed Five-centimeter Soil Cores

Differences in residue return and incorporation are reflected by the significantly ($P < 0.05$) different C contents in the CH and MB treatments (Table 1). The C content in the MB treatment represents a long-term composition in the 0- to 30-cm layer before the experiment, while that in the CH treatment reflects an increased accumulation in the upper 12 cm because residue was not incorporated below this maximum depth of tillage as suggested by field ρ_b (Fig. 1). A significantly ($P < 0.05$) larger C content in the NT treatment than MB portrays an organic matter increase in the surface layer while annual tillage did not occur for 9 yr; however, the significantly ($P < 0.05$) less C accumulation in the NT treatment than in the CH treatment within the upper 10 cm is not the usual reported situation (Schomberg et al., 1994).

The K_{sat} in the surface layer had three distinct ranges: a high value (3.64 μm s^{-1}) in the CHnt interrow; a much reduced but medium value (0.21 μm s^{-1}) in the MBnt interrow; and very low values ($\leq$0.04 μm s^{-1}) in the NTnt and all tracked interrows. These K_{sat} values are inversely related to ρ_b of the undisturbed cores (Table 1), and there is heteroscedasticity (not shown) in that the spread among K_{sat} is greater at the lower values of ρ_b. Heteroscedasticity is also more prevalent within treatments that have a smaller mean ρ_b. Apparently pore connectivity and size distribution are influencing water flow more at the lower ρ_b. The K_{sat} in the plow pan was nearly equal to that in the NTnt and tracked interrow treatments of the surface layer. Air-entry pressures in the surface layer, calculated from measured textural composition and ρ_b in Table 1, displayed four groups with an interval of about 0.5 kPa (Table 1): the lowest value in CHnt with an increased value in the MBnt treatment; larger values for the CHt, MBt, and NTnt; and the highest values for NTt and the plow pan. Air-entry values in the latter two groups are indicative of an undesirable environment for air entry and drainage.

Least Limiting Water Range: Working Equations

Least-squares fits of the WRC and PR (the working equations) in Tables 2, 3, and 4 include ρ_b measurements

Table 2. Least-squares fit of the relation $\ln\theta_v = a + b\rho_b + c \ln\psi$ with extraction pressure ψ ranging from 3 to 1500 kPa.

Treatment	Coefficient a	b	c	R^2	s_{yx}
CHnt	−1.626	0.867	−0.079	0.91	0.053
CHt	−1.240	0.454	−0.055	0.84	0.051
MBnt	−1.325	0.516	−0.081	0.96	0.036
MBt	−1.002	0.254	−0.077	0.92	0.055
NTnt	−2.155	1.172	−0.064	0.96	0.022
NTt	−1.005	0.230	−0.043	0.90	0.031
Plow pan	−1.050	0.256	−0.070	0.72	0.096
Mean standard error†	0.295	0.229	0.006	–	–

† 12 df.

Table 4. Least-squares fit of the relation $\ln PR = d + e \ln\theta_v + f \ln\rho_b$.

Treatment	Coefficient d	e	f	R^2	s_{yx}
CHnt	−3.965	−2.933	5.684	0.93	0.186
CHt	−3.481	−2.679	4.716	0.94	0.137
MBnt	−4.106	−2.772	4.726	0.96	0.138
MBt	−3.773	−2.358	5.418	0.89	0.205
NTnt	−3.036	−2.373	4.314	0.88	0.140
NTt	−1.986	−2.526	0.789	0.72	0.165
Plow pan	−1.844	−2.062	0.768	0.73	0.230
mean standard error†	0.383	0.363	1.147	–	–

† 12 df.

as an input variable. These least-squares fits had $R^2 \geq 70\%$ in the surface layer treatments and ranging from 61 to 73% in the plow pan treatment. The regression standard error ($s_{y,x}$) has units of the linearized equations. Two separate fits of the WRC (Eq. [5]) were made (Tables 2 and 3) to measure θ_v response to two different ranges of ψ and associated sensitivity to ρ_b.

In all six comparisons, tracking reduced the absolute value of $\partial \ln\theta_v/\partial \ln\psi$ (the c coefficient), even though ρ_b was included in the WRC (Tables 2 and 3). The mean reduced absolute c coefficient due to tracking (0.016 and 0.020, respectively, in Tables 2 and 3) was significantly ($P < 0.01$) greater than zero. Tracking reduced the magnitude of the b coefficient in all comparisons; these mean differences of 0.539 (Table 2) and 0.328 (Table 3) were significantly ($P < 0.01$) greater than zero. These reductions in the b coefficient due to tracking are relatively larger than the reductions of total porosity, which may partially explain the smaller effect of ψ on θ_v in the tracked soil.

The b coefficient in the plow pan was negative when the WRC was measured with Tempe cells only (Table 3), compared with the positive b coefficient when measured across the wider range of ψ (Table 2). When $\psi = 1$ the combination $a + b\rho_b$ predicts an identical θ_v. We cannot explain such a different set of parameters in Tables 2 and 3, except to note that da Silva et al. (1994) also obtained a negative coefficient of ρ_b in a silt loam that had $\rho_b = 1.47$ g cm^{-3}.

The WRC was also sensitive to tillage in the absence of traffic. The c coefficients did not distinguish CHnt from MBnt, but their mean had a significantly ($P < 0.05$) larger absolute value than that observed for the NTnt treatment (Tables 2 and 3). The b coefficient for CHnt was always larger than for MBnt, but the difference of these b coefficients from that of the NTnt treatment as related to ρ_b changes was better defined when predicting the WRC using the data with ψ ranging from 1 to 80 kPa (Table 3).

Table 3. Least-squares fit of the relation $\ln\theta_v = a + b\rho_b + c \ln\psi$ with extraction pressure ψ ranging from 1 to 80 kPa.

Treatment	Coefficient a	b	c	R^2	s_{yx}
CHnt	−1.413	0.671	−0.078	0.93	0.032
CHt	−1.042	0.311	−0.049	0.73	0.044
MBnt	−1.431	0.613	−0.079	0.92	0.035
MBt	−1.189	0.365	−0.062	0.78	0.046
NTnt	−1.284	0.475	−0.044	0.73	0.036
NTt	−0.974	0.199	−0.029	0.70	0.026
Plow pan	−0.089	−0.386	−0.050	0.61	0.059
Mean standard error†	0.112	0.085	0.009	–	–

† 102 df.

Both θ_v and ρ_b controlled PR (Table 4). The plow pan had the largest PR as indicated by the smallest d, but tracking in all tillage treatments increased PR. All e coefficients were negative and significantly ($P < 0.01$) <0, indicating an inverse relationship between θ_v and PR. Although not statistically significant, the e coefficient in the CH and MB treatments indicates a smaller PR response to θ_v change for the tracked than the nontracked treatment. Tracking in the NT treatment had only a small effect of θ_v on PR. Such a response would be expected if tracking had less effect on pore-size distribution in the NT treatment. The positive f coefficients were consistent with an increase in PR as ρ_b increased, but the coefficients were in two distinct and significantly ($P < 0.05$) different groups, one for NTt and the plow pan and another for all other treatments.

Fitted relationships for all six treatments in Fig. 2 show that treatments change the $\ln\theta_v$ response to $\ln\psi$ (parameters in Table 2 were used with ρ_b matched to ψ as related to soil swelling). Treatments with a higher ρ_b and air-entry pressure show a θ_v at $\psi < 3$ kPa, consistent with a significant Haines jump during initial desaturation. A display of $\ln PR$ response to $\ln\theta_v$ at the mean ρ_b (Table 1) is shown in Fig. 3 for the six treatments. Tracking increased θ_v for all three tillage systems (Fig. 2). The significantly greater effect of tracking on θ_v in the CH than MB system might be expected by the lower ρ_b in the CHnt than MBnt treatment (Table 1) — PR in the CHt treatment was also much higher than in the MBt treatment (Fig. 3). The higher organic C content in the CH treatment (Table 1) did not prevent traffic-induced compaction as suggested by many studies (Soane, 1990) — the lower ρ_b in the CHnt than in the MBnt treatment may also relate to bridging between aggregates produced by fresh crop residue in the CH treatment and not present in the MB treatment (Allmaras et al., 1996). Two related factors that most likely explain more compaction in the CH treatment are: the thinner tilled layer (0–12 cm) of low ρ_b in the CH treatment, compared with a thicker tilled layer (0–30 cm) of low ρ_b in the MB treatment (Fig. 1), and the larger clod size and consequent resistance to crushing in the MB treatment as demonstrated by Hadas and Wolf (1984).

Traffic increased θ_v in the NT treatment at a given ψ

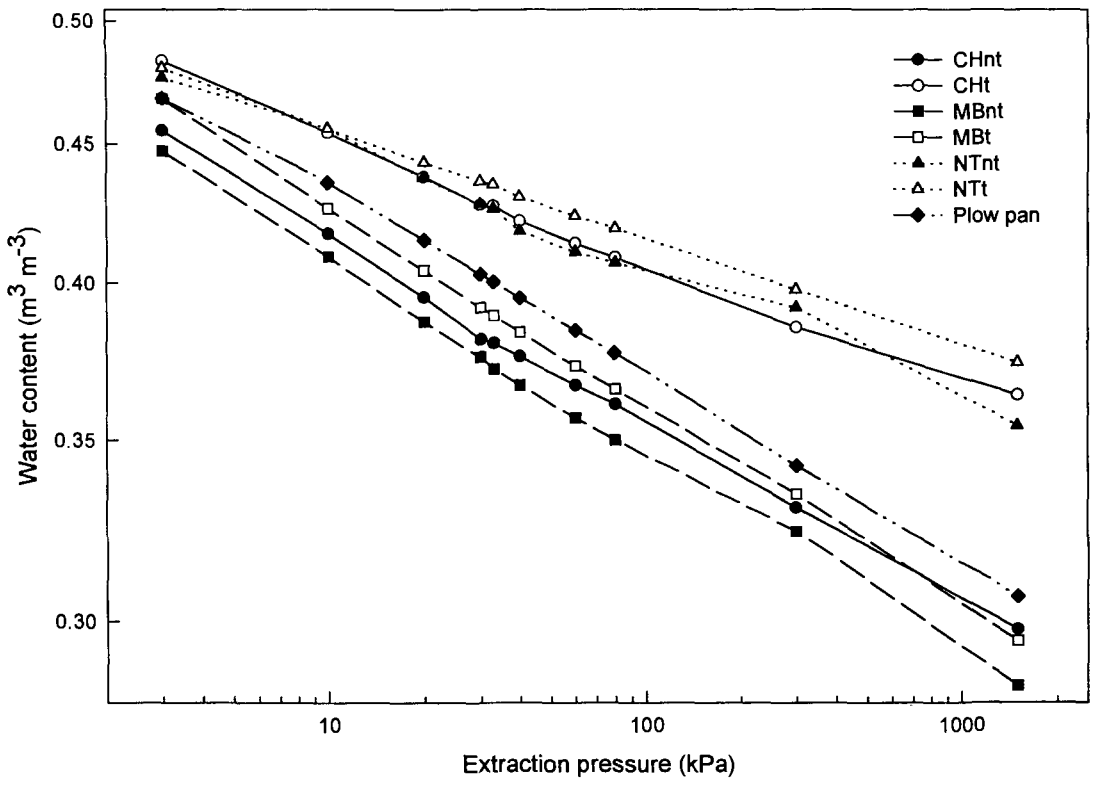

Fig. 2. Predicted soil water content (θ_v) response to extraction pressure for the long-term tillage and traffic treatments and plow pan in a Webster clay loam. Curves predicted using Eq. [5] with bulk density matched to θ_v.

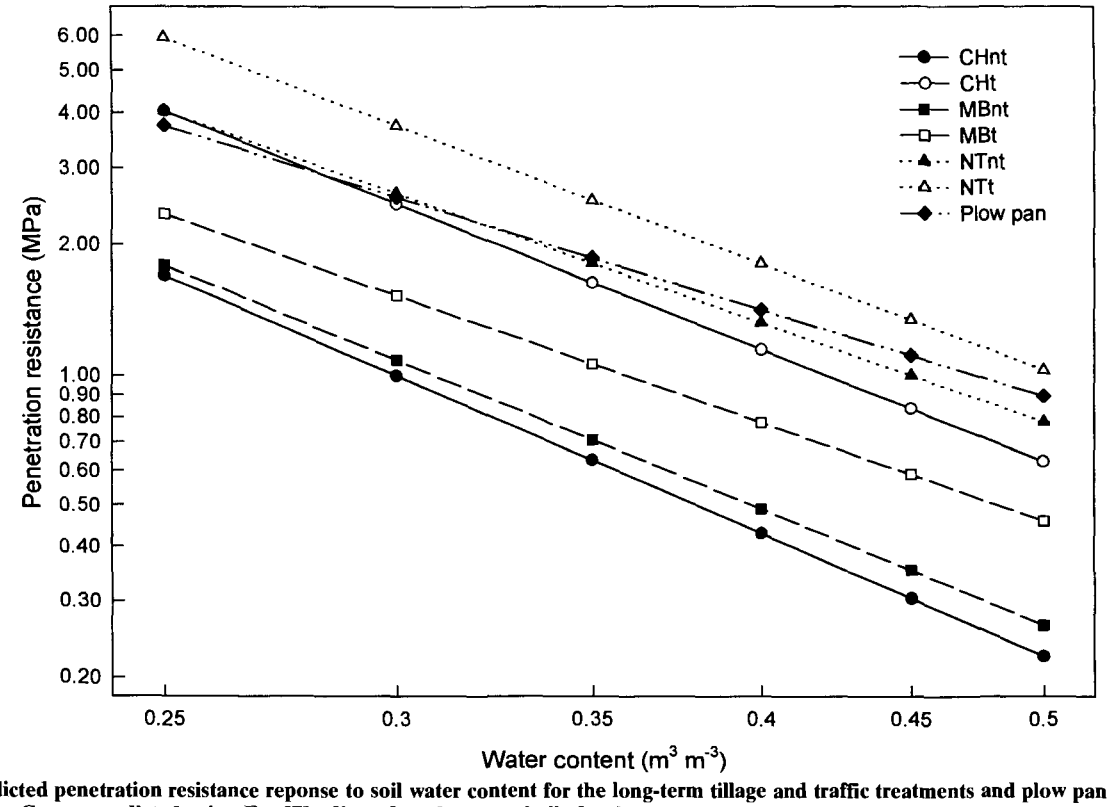

Fig. 3. Predicted penetration resistance reponse to soil water content for the long-term tillage and traffic treatments and plow pan in a Webster clay loam. Curves predicted using Eq. [7] adjusted to the mean bulk density.

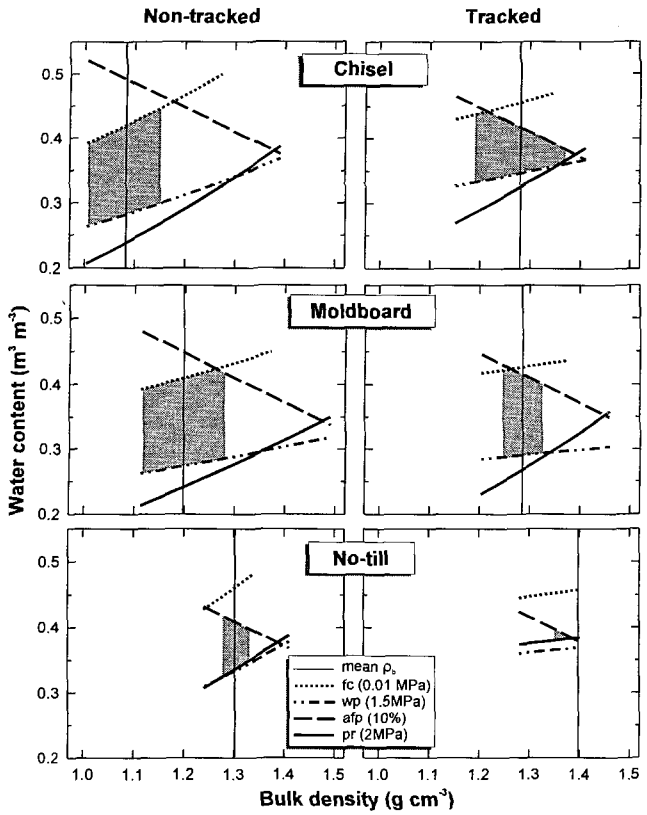

Fig. 4. Relationships between water content (θ_v) and bulk density (ρ_b) for the six long-term tillage and traffic treatments in a Webster clay loam. Values of θ_v predicted at critical values of root growth relating to field capacity (fc), wilting point (wp), air-filled porosity (afp), and penetration resistance (pr). The true least limiting water range is represented by the shaded area corresponding to the ρ_b range for the treatment.

(Fig. 2) — this 9-yr effect was produced without annual fragmentation. An increased PR due to tracking over and above the high PR for the NTnt treatment confirms the long-term effect of compaction even though there was freeze–thaw and wetting and drying. The close proximity of the NTnt and CHt curves for PR emphasizes a susceptibility to damaging wheel traffic under the CH tillage system, while the difference between the PR curves of MBt and NTnt indicates a relatively lower soil strength in the MB system when tracked.

Although the fitted relationship between $\ln\theta_v$ and $\ln\psi$ for the plow pan is not unlike that of the surface tillage and tracking treatments (Fig. 2), θ_v has less influence on PR (Fig. 3). This response may be related to the absence of repeated fragmentation and recompaction in the plow pan.

Least Limiting Water Range: Tillage and Traffic Effects

The four limiting water contents, θ_{fc}, θ_{wp}, θ_{afp}, and θ_{pr}, all as a function of ρ_b, comprise the LLWR for the six tillage and traffic treatments (Fig. 4) and the plow pan treatment (Fig. 5). Parameters from Tables 2 and 4 were used in Eq. [5] and [7] to construct the LLWR. Shading extends over 66% of the variation about the observed mean ρ_b except at the ρ_b where the upper and lower

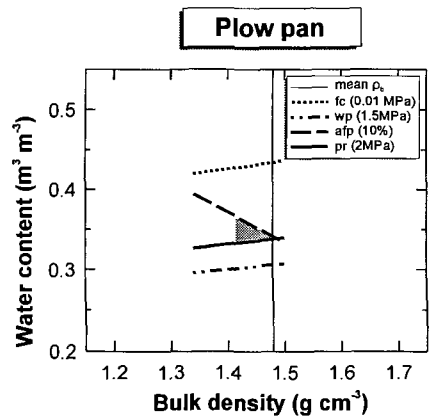

Fig. 5. Relationship between soil water content (θ_v) and bulk density (ρ_b) for the plow pan layer underlying the six long-term tillage and traffic treatments in a Webster clay loam. Values of θ_v predicted at critical values of root growth relating to field capacity (fc), wilting point (wp), air-filled porosity (afp), and penetration resistance (pr). The true least limiting water range is represented by the shaded area corresponding to field-measured ρ_b.

limits on θ_v converge — a thin vertical line depicts the mean ρ_b as presented in Table 1.

The four factors in the LLWR are limiting differently as related to tillage and traffic treatments. The θ_{fc} line forms the upper limit of the rooting environment in the CHnt and MBnt treatments, while θ_{afp} forms all of the upper limit in the NTnt and NTt treatments and most of the upper limit in CHt and MBt treatments (Fig. 4). The θ_{pr} line forms the lower limit only in the NT treatments — θ_{wp} forms the lower limit for rooting environment in all other surface treatments (Fig. 4). Irrespective of tillage treatment and tracking, the θ_{afp} and θ_{pr} lines generally show a steeper slope than the θ_{fc} and θ_{wp} lines, which demonstrates that the LLWR has a stronger response to soil structure than indicated by the response to available water. Da Silva et al. (1994) concluded similarly. More constraint by θ_{afp} and θ_{pr} on LLWR in the plow pan (Fig. 5) than in the surface layer treatments has significance because θ_v would fluctuate less during the growing season in the plow pan than at the surface. A corollary is reduced early growth and rooting advance only when there is an unusually dry or wet period during this critical period for root development in a compacted layer (Hamblin, 1985).

In contrast to the results of da Silva et al. (1994), Fig. 4 always shows an increasing θ_{fc} and θ_{wp} as ρ_b increases, θ_{pr} functions less as the lower limit of the root environment, and the ρ_b range is much lower, even in the NTnt and all tracked treatments. Both of the soils used by da Silva et al. (1994) have a coarser texture than the Webster soil (Table 1).

Plant rooting within the six tillage and tracking treatments and within the plow pan will be more or less restricted depending on the magnitude of change in θ_v within the LLWR and how the θ_v range changes as ρ_b changes (Fig. 6). The LLWR for each treatment has its largest value at the left of Fig. 4 and 5 and a zero value on the right where the limits on θ_v intersect. Tracking drastically reduces the LLWR in the CH and NT treatments, but no effect of tracking is apparent in the MB

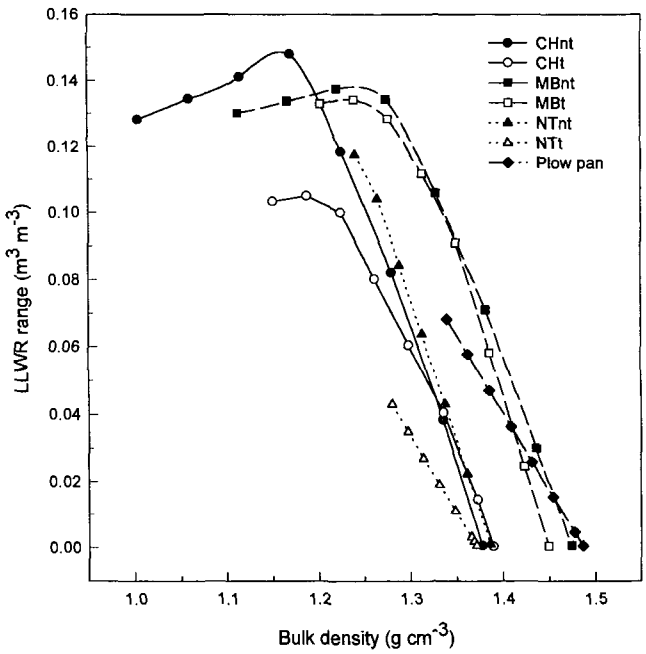

Fig. 6. Magnitude of the least limiting water range (LLWR) in Fig. 4 and 5 as related to increasing bulk density for each of the six tillage and traffic treatments and for the plow pan.

treatment. The CHnt, CHt, MBnt, and MBt treatments displayed similar curves in that each LLWR increases up to a certain ρ_b, at which it then decreases as ρ_b increases, the rate of decrease ultimately increases as ρ_b increases. The NTnt, NTt, and plow pan treatments display sharply declining LLWR with increasing ρ_b, but the relationship between LLWR and ρ_b for these treatments is always negative (Fig. 6).

The seven curves are displaced horizontally from each other depending on the observed ρ_b values for each treatment (Fig. 6). The wide LLWR and ρ_b range for the CH and MB treatments suggests a hospitable environment for rooting, whereas the narrow LLWR and ρ_b range for the NTt and plow pan treatments indicates a highly restrictive environment. The NTnt treatment tends to have a wide LLWR, but its narrow range in ρ_b ($\approx$0.15 g cm^{-3}) would make it appear much less hospitable for rooting than in the CH and MB treatments.

Da Silva et al. (1994) evaluated LLWR sensitivity to various assumptions about air-filled porosity (10–15%), critical soil mechanical resistance (2–5 MPa), and the upper limit of available water (−0.005 to −0.033 MPa matric potential). Their projected sensitivities as a function of bulk density had a magnitude similar to that produced by the different tillage and traffic treatments in Fig. 4 and 5. This is strong evidence for the impact of soil structure on the fundamental processes of aeration, available soil water, and mechanical resistance that interact to constrain root environment.

Plant Response to Treatments Evaluated with Least Limiting Water Range

Soils of the Webster series are widely used for corn and soybean production in the northern Corn Belt. They are typically imperfectly to poorly drained (most are tile drained), highly susceptible to compaction, and sensitive to tillage systems. Numerous studies (Bauder et al., 1985; Culley et al., 1987; Allmaras et al., 1991; Iragavarapu and Randall, 1995) have noted adverse corn and soybean growth under all NT methods in these soils, especially when wheel traffic was not controlled. Failure to control wheel traffic has increased ρ_b and reduced corn rooting in the upper 30 cm of soil when reduced tillage systems are used in these soils (Bauder et al., 1985; Kaspar et al., 1991, 1995). Rooting failure in the interrow was noted in our study whenever there was interrow traffic — rooting failure was noted also in the interrow of both NTnt and NTt.

Control of wheel traffic has allowed CH and ridge-till systems to gain considerable acceptance over NT. Yet these systems, with annual tillage only above 10 cm, often present management problems associated with internal drainage as well as root environment because the shallow depth of tillage tool penetration fails to reduce ρ_b in the 10- to 30-cm depth. Reduction of ρ_b in the whole Ap layer would be achieved with the MB system, but other problems are introduced by deeply incorporated crop residue (Allmaras et al., 1996). Post-plant cultivation in all forms of tillage management would reduce the adverse ρ_b effects of wheel traffic in the 5- to 10-cm layer (Fig. 1, Table 1).

SUMMARY AND CONCLUSIONS

Constraints on root environment in a poorly drained Webster clay loam were evaluated as related to three long-term tillage systems and controlled traffic (non-tracked and tracked interrows) for production of soybean and corn. Soil depths evaluated were the 5- to 10-cm layer and the 25- to 30-cm layer corresponding to a traditional plow pan. Fundamental relations derived from WRC and PRC measurements on undisturbed soil cores were used to construct a LLWR.

Field-measured ρ_b showed soil compaction in all three tillage treatments to a 46-cm depth caused by 7 yr of controlled traffic. A significantly lower ρ_b within the 10- to 30-cm depth under MB than NT and CH systems was apparent in the nontracked interrows. Tracking obliterated these tillage treatment effects throughout the 0- to 30-cm depth.

The changing LLWR with tillage and traffic treatments demonstrates that soil structure can have a significant control on root environment. The upper bound of the LLWR was determined by θ_{fc} in the nontracked treatments with annual cultivation while θ_{afp} served as the constraint in the NTnt treatment, the plow pan, and where there was tracking — θ_{wp} served as the lower bound, except in the plow pan and the NT treatments, where θ_{pr} was limiting.

Three groups of K_{sat}, and potential for infiltration, were observed: two groups with annual tillage and no traffic, nominally 3 μm s^{-1} in the CHnt treatment and 0.2 μm s^{-1} in the MBnt treatment. The third group, with $K_{sat} \leq 0.04$ μm s^{-1}, was found in NT or any tracking treatment.

The MB treatment tolerated traffic more than the

CH treatment, as noted in LLWR and K_{sat}. Although the CH treatment has great conservation appeal because of the much higher C content in the surface 10 cm, the low tolerance to tracking and the reduced tillage depth are both problematic (compaction and internal drainage) for adoption of conservation tillage systems in poorly drained soils of the northern Corn Belt.

APPENDIX

LLWR	least limiting water range
CH	chisel plow
MB	moldboard plow
NT	no tillage
WRC	water retention characteristic
PRC	penetration resistance characteristic
t, nt	tracked, nontracked
ρ_b	bulk density, g cm^{-3}
ψ	extraction pressure, kPa
K_{sat}	saturated hydraulic conductivity, μm s^{-1}
θ_v	soil water content, m^3 m^{-3}
PR	penetration resistance, MPa
θ_{fc}, θ_{wp}, θ_{pr}, θ_{afp}	soil water content, m^3 m^{-3} corresponding to field capacity, wilting point, 2 MPa penetration resistance, and 10% air-filled porosity
ρ_{33}, ρ_{od}, ρ_{sat}	bulk density, g cm^{-3}, at 33 kPa extraction pressure, oven dry, and saturation
ρ_i, ρ_{ii}	estimated bulk density at extraction pressures below and above 33 kPa
$\theta_{g\text{-}sat}$, $\theta_{g\text{-}33}$, $\theta_{g\text{-}i}$, $\theta_{g\text{-}ii}$	water content, kg^3 kg^{-3}, at saturation, 33 kPa extraction pressure, and at extraction pressures below and above 33 kPa

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