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Quantifying effects of soil conditions on plant growth and crop production

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Abstract

Soil management decisions often are aimed at improving or maintaining the soil in a productive condition. Several indicators have been used to denote changes in the soil by various management practices, but changes in bulk density is the most commonly reported factor. Bulk density, in and of itself, gives little insight on the underlying soil environment that affects plant growth. We investigated using the Least Limiting Water Range (LLWR) to evaluate changes in the soil caused by soil management. The LLWR combines limitations to root growth caused by water holding capacity, soil strength and soil aeration into a single number that can be used to determine soil physical improvement or degradation. The LLWR appeared to be a good indicator of plant productivity when the full potential of water holding capacity on available water can be realized, such as with wheat (*Triticum aestivum*, L.) grown in a no-till system when the wheat followed a fallow period. A regression of wheat yield to LLWR gave an r^2 of 0.76. The LLWR was a poorer indicator of plant productivity when conditions such as low total water availability limited the expression of the potential soil status on crop production. Dryland corn (*Zea mays*, L.) yields were more poorly correlated with LLWR ($r^2 = 0.18$), indicating that, under dryland conditions, in-season factors relating to water infiltration may be more important to corn production than water holding capacity. An improved method to evaluate in-season soil environmental dynamics was made by using Water Stress Day (WSD). The WSD was calculated by summing the differences of actual water contents in the field from the limits identified by the LLWR during the growing season. A regression of irrigated corn yield with LLWR as the soil indicator of the soil environment resulted in an r^2 of 0.002. A regression of the same yield data with WSD as the indicator of the soil environment resulted in an r^2 of 0.60. We concluded that the LLWR can be a useful measure of management effects on soil potential productivity. Soil management practices that maximize the LLWR can maximize the potential of a soil for crop production. Knowledge of the LLWR for a soil can help the farm manager optimize growing conditions by helping schedule irrigation and for making tillage decisions. The WSD, calculated from the LLWR and in-season water dynamics, allows us to evaluate changes in the

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soil caused by differing soil management practices and identify critical periods of stress on the plant that can reduce production.

Keywords: Soil–plant relationships; Soil productivity; Water availability; Corn; Wheat; Crop rotation

1. Introduction

One of the primary interests of agriculturalists is the use of soil as a medium for plant production. Many of our crop management decisions are aimed at improving the soil to maximize production of food and fiber. Farmers recognize that the soil physical condition will affect crop production and they are interested in maintaining the productive capability of the soil.

Farmers voice a recurring concern with the issue of soil compaction in no-till crop management systems. Some of the questions are: (1) How do I identify a compaction problem on my farm? (2) Do I need periodic tillage to cure a compaction problem with no-till farming systems? (3) How often do I need to till? (4) How deep should I till? and (5) How much yield do I lose from excessive compaction? These are common questions asked by farmers in many regions of the country.

Over the years much energy and intellectual talent has been spent on studying the effects of tillage and other soil management practices on plant productivity. Several indicators have been used to show changes in the soil condition caused by soil management, but changes in bulk density is probably the most commonly used indicator. Bulk density has the advantage of being relatively easy to measure and often has a good correlation with plant growth and yield. Many times, though, we find a very poor correlation between bulk density and crop yield. Bulk density alone lacks an interpretation that tells us why the plant responds to a specific soil condition. Therefore, we continue the search for a soil indicator or indicators that have physical meaning related to the soil environment and that give us insight on how to better manage our soils.

A method that could prove useful as a means to evaluate changes in the soil is the Least Limiting Water Range (LLWR). Some researchers have proposed using this technique to combine several soil environmental factors that affect plant growth into one factor that could then be used to evaluate changes in the soil condition. Letey (1985) described the need to combine soil environmental factors because of the interactions of soil water, aeration, and strength as bulk density changes. da Silva et al. (1994) further refined the concept and coined the term “Least Limiting Water Range”.

The LLWR combines soil water holding capacity, soil strength and soil aeration into one factor to describe soil suitability for plant growth. The LLWR is the range of water contents that are not considered to pose a restriction to root development and growth. The LLWR changes with changes in soil bulk density as different factors such as aeration or strength become limiting. The LLWR is likely to vary with soil depth or soil horizon. It would be helpful for many soil management decisions to have knowledge of the LLWR within the root zone. The objective of this paper is to demonstrate the use of the LLWR for making soil management decisions.

2. Materials and methods

To construct the LLWR for a particular soil, knowledge of field capacity, wilting point, air-filled porosity and soil strength are needed for the range of bulk densities likely to occur in the field. In this paper we have defined field capacity as the water content at − 33-kPa water potential, the wilting point as the water content at − 1500-kPa water potential, the aeration limitation as 10% air-filled porosity, and the strength limitation as 2-MPa cone penetrometer resistance. These criteria have also been used by da Silva et al. (1994) and Betz et al. (1998).

Data to determine the LLWR for a Weld loam (fine, smectitic, mesic Aridic Paleustolls) were collected from the Alternative Crop Rotation (ACR) experiment that was started in 1990 at the Central Great Plains Research Station at Akron, Colorado. The experiment consists of three replications of several rotations of crops suited for dryland crop production in the central Great Plains. Each phase of each rotation occurs each year. Crops included in the rotations are wheat (*Triticum aestivum* L.), abbreviated W, corn (*Zea mays* L.), abbreviated C, sunflower (*Helianthus annus* L.), abbreviated S, and proso millet (*Panicum miliaceum* L.), abbreviated M. More detail about the experimental design and crop management techniques can be found in Anderson et al. (1999) and Bowman et al. (1999). We selected the wheat and corn plots from the WF, WCF, WCSF, WCM rotations in the experiment.

Soil cores were taken from each plot in 1997 to determine field capacity. Cores were taken before corn planting in late April from the corn plots and immediately after wheat harvest in July from the wheat plots. Sampling was conducted with a Giddings[1] hydraulic probe that used aluminum sleeves to contain the undisturbed soil sample. Soil cores, 75-mm diam. by 75-mm long, were taken to a depth of 0.5 m. The cores were trimmed and placed in individual desorption cells and 33-kPa air pressure was applied to the chambers. Water outflow was measured daily until no more water was expelled from the core. The cores were then removed from the chamber and the gravimetric water content (θ_{g33}) was determined. The bulk density (ρ_b) of each core was determined and the volumetric water content at − 33 kPa (θ_{v33}) was calculated from θ_{g33} and ρ_b by

$$\theta_{v33} = \theta_{g33}\rho_b \tag{1}$$

To determine the wilting point, soil samples were taken from the same plots and depths as for determining field capacity. These samples were passed through a 2-mm sieve. The disturbed samples were then placed in small rubber rings on a 15-bar air-entry-value ceramic plate and placed in a high-pressure desorption chamber. A 1500-kPa air pressure was introduced into the chamber and the water outflow was monitored. When no more water was expelled from the chamber, the samples were removed and the gravimetric water content of each sample at − 1500 kPa (θ_{g1500}) was measured. The wilting point volumetric water content (θ_{v1500}) was then determined by

$$(\theta_{v1500}) = \theta_{g1500}\rho_b \tag{2}$$

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[1] Mention of specific brand names are for informational purposes only and do not denote an endorsement of that brand over other similar brands.

where ρ_b is the bulk density for the plot and position determined from the undisturbed cores used for θ_{v33} determinations.

Penetrometer readings from each plot were made with a recording penetrometer with a 12.5-mm diameter, 30° cone angle probe that was mounted on the Giddings hydraulic probe. The probe was inserted at approximately 40 mm/min to a depth of 0.5 m. The penetrometer recorded the average PR at 50-mm intervals. Immediately after taking the pentrometer reading, the penetrometer was removed and a 50-mm-diam. soil sampling tube was attached to the hydraulic probe. A soil sample was taken within 100 mm of the location for PR and the sample was cut into 50-mm sections to determine ρ_b and θ_g at the time of PR measurements. Eq. (1) was used to convert θ_g to θ_v. Samples were taken in both tracked and nontracked zones in each plot. Penetrometer measurements from the corn plots before planting gave penetration and water content data for the soil in a relatively wet condition and penetrometer measurements from the wheat plots after harvest gave penetration and water content data for the soil in a relatively dry condition. The PR measurements were plotted as a function of both ρ_b and θ_v. Using the function suggested by da Silva et al. (1994) and also used by Betz et al. (1998), the regression for PR was

$$\ln PR = 0.618 - 2.09 \ln\theta_v + 0.216 \ln\rho_b \qquad r^2 = 0.68 \tag{3}$$

Ten-percent air-filled porosity (ϵ_a) was calculated from the total porosity (ϵ_t) based on ρ_b measurements for each core by:

$$\epsilon_t = 1 - (\rho_b/\rho_s) \tag{4}$$

$$\epsilon_a = \epsilon_t - 0.1 \tag{5}$$

where ρ_s is the particle density of the soil solids, which we assumed to be 2.62 mg/m^3.

Field capacity (θ_{v33}), wilting point (θ_{v1500}), 10% air-filled porosity, and 2-MPa PR were plotted as a function of bulk density (Fig. 1) for each sampling depth. The LLWR is the crosshatched zone bounded by these functions where water holding capacity, aeration, and soil strength are not considered limiting to crop production. The water, air, and strength characteristics (and therefore the LLWR) changed with depth and soil horizon. These changes are evident in the A horizon at 0 to 10 cm, the Bt horizon at 10 to 20 cm and the Btk horizon below 30 cm.

Yield and ρ_b data were collected from a compaction and tillage experiment at the Akron research station on a Weld loam that started in 1997. Three compaction treatments and three tillage treatments were combined in a factorial design with three replications. The compaction treatments consisted of covering the entire soil surface with overlapping wheel tracks with 0, 2, or 8 passes of a 7000-kg tractor. The tracks were overlapped by 50% so that the entire soil surface received the same compaction amount within a treatment. The tillage treatments were no tillage, tillage with a chisel plow with 0.3-m shank spacing operated at a 20-cm depth, and tillage with the same chisel plow operated at a 30-cm depth. Compaction and tillage treatments were applied in the fall of 1997.

In the spring of 1998, the tilled plots were tilled once with a mulch treader to break any large clods and prepare a seed bed. No tillage was applied to the no-till plots. Corn was planted in the plots in early May. Neutron access tubes were inserted in each plot shortly

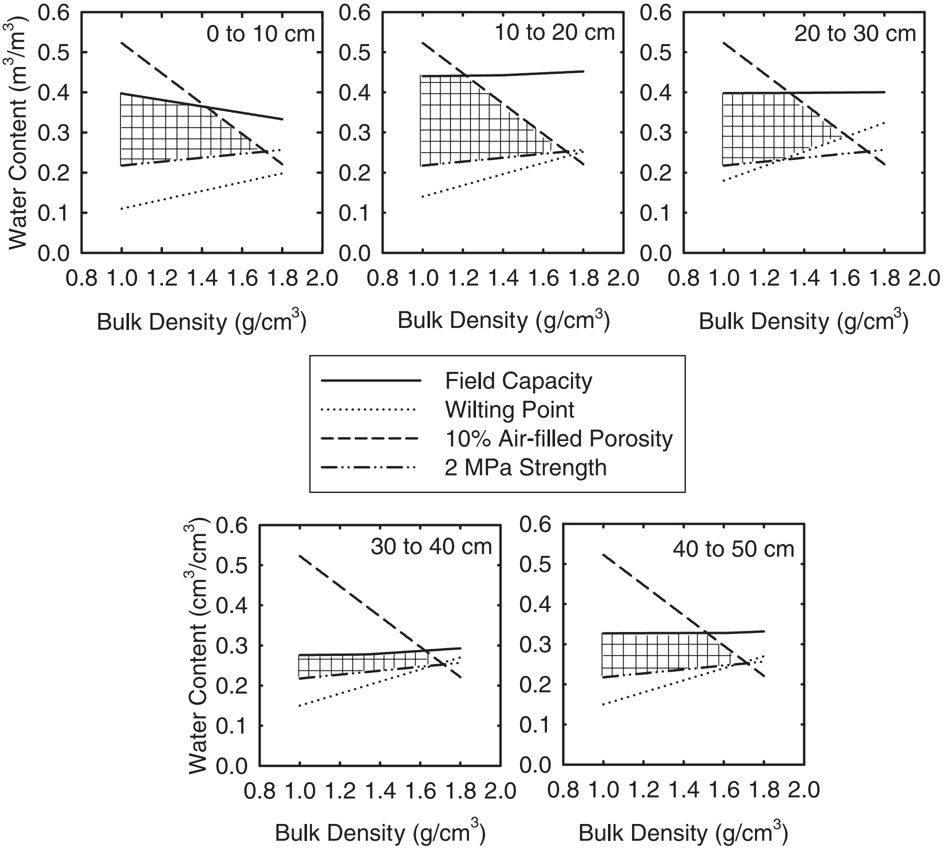

Fig. 1. Least Limiting Water Range with depth. ACR experiment, Weld loam, Akron, CO.

after planting. Irrigation was applied weekly to the plots during the growing season based on crop water needs calculated with the method of Nielsen and Hinkle (1996). Neutron readings were taken twice per week, once just before irrigation and once 2 days after irrigation, at 0.3-m intervals to at depth of 1.8 m. At the end of the growing season, soil samples were collected with the Giddings hydraulic probe, using 75-mm diam. by 75-mm long aluminum sleeves, to a depth of 0.5 m. Bulk density was measured on each core and the LLWR was determined for the samples using the relationships developed from the ACR study.

3. Results and discussion

Total 1996–1997 growing season precipitations for corn and wheat are shown in Table 1. Precipitation for wheat was 273.9 mm compared with the long-term average of 333.6 mm. Little rainfall or snowfall occurred during the winter of 1996–1997, particularly

Table 1
Monthly precipitation at Akron, CO; Fall, 1996 to Fall, 1997

Year	Month	Monthly precipitation (mm)	30-year average monthly precipitation (mm)
1996	September	86.4	35.6
1996	October	10.7	22.5
1996	November	0.3	15.2
1996	December	0.0	10.2
1997	January	9.8	9.3
1997	February	11.4	9.4
1997	March	0	28.9
1997	April	15.7	42.9
1997	May	61.9	81.9
1997	June	77.7	77.7
1997	July	27.7	70.3
1997	August	86.6	49.8
1997	September	22.8	35.6
1997	October	29.9	22.5

during the critical tillering period in the early spring. Total 1997 precipitation for corn was relatively normal with growing season precipitation of 306.6 mm compared with the long-term average of 337.8 mm.

Wheat yields versus LLWR for dryland wheat in 1997 is shown in Fig. 2. The actual yields for each plot were converted to relative yields (RY) within each rotation to remove

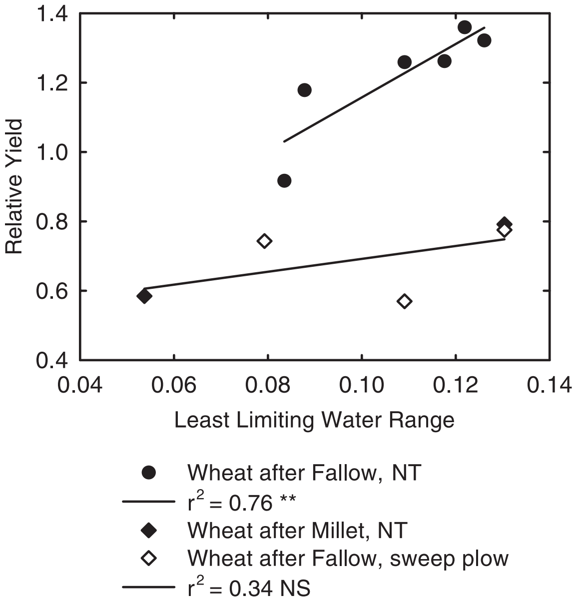

Fig. 2. Wheat (*T. aestivum*, L.) response to soil condition as measured by the LLWR. ACR experiment, Weld loam, Akron, CO, 1997. NS indicates that the slope of the regression is not significantly different from 0.0 at $p = 0.05$. (**) indicates that the slope of the regression is significantly different from 0.0 at $p = 0.01$.

rotation effects from the comparison between rotations. The relative yield was calculated by dividing the yield for a specific plot by the average of the plots within that rotation. For example, the RY for plot 1 in the WF, no-till is

$$\mathrm{RY_{wf1}} = \mathrm{Yield_{wf1}}/\mathrm{Yield_{wfavg}} \tag{6}$$

where $\mathrm{Yield_{wfavg}}$ is the average yield for all WF, no-till plots in 1997. The black circles indicate the wheat yields for wheat following fallow with no-till soil management. This includes wheat in the WF rotation and wheat in the WCF rotation. The correlation of wheat yield to the soil condition indicated by the LLWR is very good with an r^2 of 0.76. The diamonds indicate wheat yields for WF using sweep tillage or the wheat after millet in the WCM rotation. Wheat yields in WF sweep tillage and WCM no-till were always lower than the wheat yields after fallow using no-till. These rotations had lower initial water contents at the start of the growing season caused by drying of the soil by tillage or from having a crop immediately preceding the planting of wheat. The correlation of wheat yield with LLWR is worse for these rotations and the slope is less steep. The LLWR appears to be a good indicator of plant productivity when the full potential of available water can be realized, such as with W grown in a no-till system when the W follows a fallow period. The LLWR is a poorer indicator of plant productivity when conditions such as low total water availability limit the expression of the soil status on crop production.

Corn yields versus LLWR for dryland corn production are shown in Fig. 3. Again, the corn yields are presented as the yields relative to the rotation. Corn appears to be less sensitive to soil condition than wheat. All corn plots were following wheat in WCF,

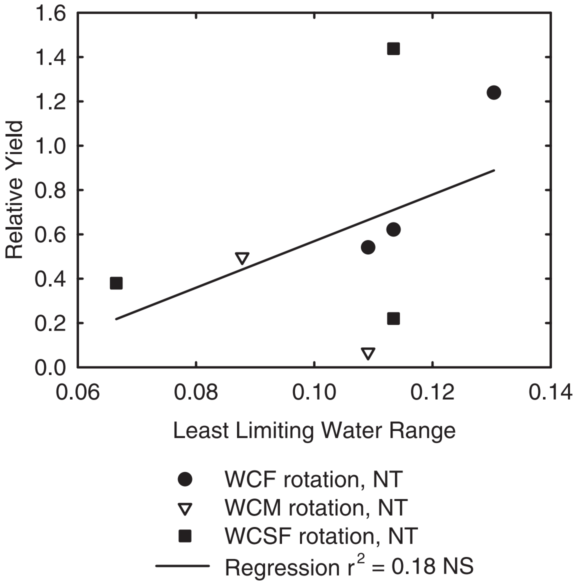

Fig. 3. Corn (*Z. mays*, L.) response to soil condition as measured by the LLWR. ACR experiment, Weld loam, Akron, CO, 1997. NS indicates that the slope of the regression is not significantly different from 0.0 at $p = 0.05$.

WCSF, and WCM rotations. All systems were no-till. The corn in the WCF rotation (indicated by the black circles) seemed to have a similar response to LLWR as the wheat in this rotation, but corn in the other rotations had little or no correlation to soil condition indicated by the LLWR. Nielsen et al. (1996) showed that yields of dryland corn grown in eastern Colorado are correlated with the rainfall received between July 15 and August 25 during the year. Because of the influence of current-season rainfall on corn yields, factors that influence the availability of rainfall such as infiltration capacity, surface residue cover or crusting may need to be considered to improve predictions of corn yield response to the soil environment.

An advantage to using the LLWR for identifying soil suitability for crop production is the ability to include in-season changes in the soil environment when analyzing soil management effects on crop production. Many times the correlation between crop response and a static soil measurement such as bulk density or LLWR is quite poor. We surmise that using the LLWR as a guideline to identify in-season water stress will improve crop yield predictions.

Fig. 4 shows the correlation between corn yield and both bulk density and LLWR for the compaction-tillage study in 1998. The distinct lack of correlation led us to believe that in-season water dynamics may play a large role in the determination of crop yields for irrigated corn production or for regions in the country that have greater rainfall than eastern Colorado.

Fig. 5 shows the water content changes of two plots from the compaction-tillage experiment measured during the growing season with a neutron moisture meter. Both of these plots had similar bulk density distributions and similar LLWRs in the root zone. The LLWR for each plot, as shown between the dashed upper water limit and the dotted lower water limit, is the average of the samples from the 0–300-mm depths. The upper graph shows that the plot had little water stress in the top 600 mm of soil for about half of the growing season and then the water content was such that a slight water stress occurred during the remainder of the growing season. The lower graph shows that this plot had water stress in the surface 300 mm from planting throughout the growing season and had water stress in the 300- to 600-mm depth after the middle of the growing season. The corn yields differed considerably between the two plots with the plot having less water stress yielding 11,700 kg/ha corn grain and the plot with more water stress yielding only 2700 kg/ha. This reenforces the need to use more than just a static soil property such as LLWR or BD to evaluate yield results for many experiments.

We have been examining methods to capture in-season water dynamics to better determine effects of soil condition on plant growth. We propose to use the term Water Stress Day (WSD) as a simple calculation that accounts for the amount of water stress the plant is subjected to during the growing season. Cumulative WSD is calculated by:

$$\mathrm{WSD} = \Sigma(\theta_\mathrm{d} - \theta_\mathrm{ll}) \times 100 \tag{7}$$

where θ_d is the daily water content of the soil and θ_ll is the lower limit of the LLWR for any day that $\theta_\mathrm{d} < \theta_\mathrm{ll}$. Otherwise $\mathrm{WSD} = 0$.

Fig. 6 shows the same yield data against WSD instead of BD or LLWR for each plot. We show a greatly improved correlation ($r^2 = 0.6$) between a measure of the soil

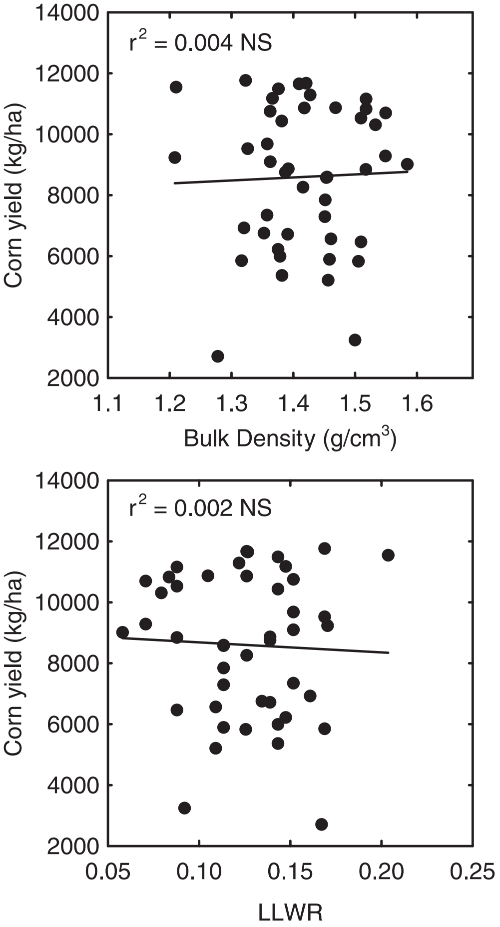

Fig. 4. Corn yield versus bulk density and LLWR. Compaction-tillage study, Weld loam, Akron, CO, 1998. NS indicates that the slope of the regression is not significantly different from 0.0 at $p = 0.05$.

environment and crop yield. Knowledge of the in-season water dynamics in addition to relatively static soil properties such as BD or LLWR can greatly improve our ability to predict crop yield or explain the resultant yields from various management practices.

Concepts such as LLWR or WSD can be used to improve soil management by farmers. For example, in irrigated crop production systems, knowledge of the LLWR for a soil can enable us to recommend the proper water content range needed to remove water availability, soil strength, and soil aeration from limiting crop production. Knowledge of the LLWR can also be used to recommend tillage operations and tillage depths when necessary to alleviate compaction problems. Using data such as that shown in Fig. 1, we could better determine the need for tillage and how deep to till. For example, if the bulk density in the A horizon (0 to 10 cm) was above about 1.4, we might consider using a tillage operation to decrease the BD. For BD less than 1.4, we see little improvement in the

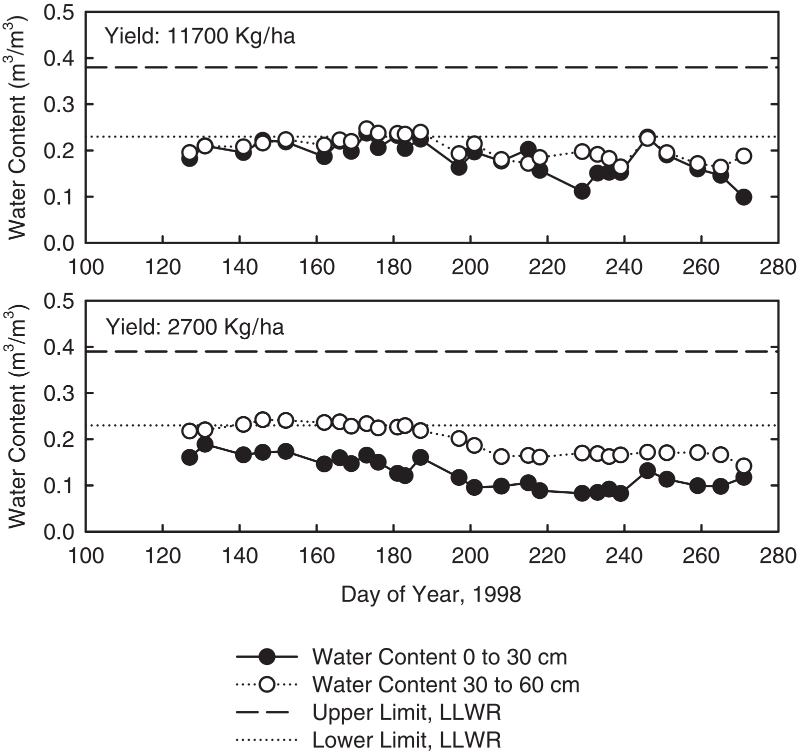

Fig. 5. Water content changes with time. Compaction-tillage study, Weld loam, Akron, CO, 1998. Water contents measured with neutron moisture meter.

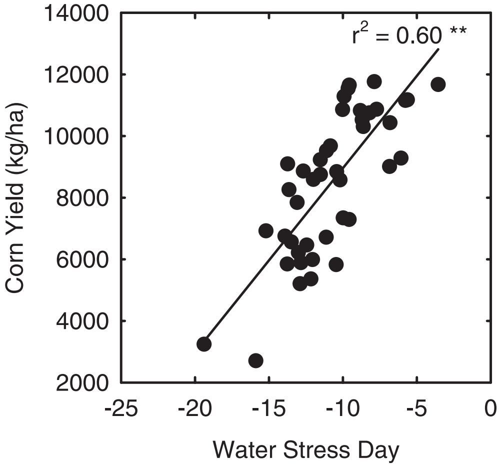

Fig. 6. Corn yield versus Water Stress Day. Compaction-tillage experiment, Weld loam, Akron, CO, 1998. (**) indicates that the slope of the regression is significantly different from 0.0 at $p = 0.01$.

LLWR and would predict little benefit to tillage. In the Bt horizon (10 to 30 cm), a bulk density above about 1.2 might warrant using tillage to reduce the BD. We also notice that tillage in the Btk horizon (below 30 cm) would likely be ineffective for improving the rooting environment since the LLWR does not change much with changes in BD at the deeper depths.

The data needed to construct the LLWR for a soil are extensive and time-consuming to accumulate. If we are to have widespread use of the LLWR for soil management decisions, we need some improvements in certain areas of technology. First, we need fast, accurate, and inexpensive methods to determine bulk density distributions across a field or landscape. We need the method to distinguish BD laterally and also with depth or by horizon. Knowledge of the BD distribution is needed to determine where to sample for water content and strength data. It also is necessary to know the BD distribution to determine the zones in a field where differential soil management practices can be applied. Second, we need a recording penetrometer that will simultaneously determine water content and penetration resistance to easily determine the soil strength characteristics of the soil. Prototypes of this technology are already in existence (Vas and Hopmans, 2001), so commercial versions may soon be available.

4. Conclusions

The Least Limiting Water Range can be a useful measure of management effects on soil potential productivity. Soil management practices that maximize the LLWR can maximize the potential of a soil for crop production. Knowledge of the LLWR for a soil can help the farm manager optimize growing conditions by helping schedule irrigation and for making tillage decisions. The WSD, calculated from the LLWR and in-season water dynamics, allows us to evaluate changes in the soil caused by differing soil management practices, and identify critical periods of stress on the plant that can reduce production.

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