QUANTIFYING WHEEL-TRACK EFFECTS ON SOIL HYDRAULIC PROPERTIES FOR AGRICULTURAL SYSTEMS MODELING

L. R. Ahuja[1], J. G. Benjamin[2], G. H. Dunn[1], L. Ma[1], T. R. Green[1] and G. A. Peterson[3]
[1]USDA-ARS, Great Plains Systems Research Unit, Fort Collins, CO, USA
email: Ahuja@gpsr.colostate.edu
[2]USDA-ARS, Central Great Plains Resources Management Research, Akron, CO, USA
[3]Colorado State University, Dept. of Soil and Crop Sciences, Fort Collins, CO, USA

Abstract

We measured soil hydraulic properties on intact soil cores from wheel track and no-wheel track areas of four soil types, after long-term no-till or reduced-till crop rotations in semiarid eastern Colorado. The soil texture varied from sandy loam to silt loam. The results showed a large variability but no consistent differences in water retention curves and hydraulic conductivity (K_{sat}) between track and no-track areas. However, all water retention and K_{sat} data could be quantified by essentially universal models that require only soil bulk density and 33-kPa water content. For water retention data from three field soils in the literature where wheel track effects were significant, we present a simple model to derive retention curves for track areas from curves of the no-track areas. This is presented as a topic for further research. The K_{sat} data for these soils were consistent with the general K_{sat}-effective porosity relationship developed previously.

Introduction

Wheel-track compaction is thought to increase soil bulk density, decrease porosity, and change the size and shape of voids or pores (e.g., Warkentin, 1971). The changes in total porosity and pore size distribution change the water storage and transmission properties of the soil. These latter properties are expressed in the two generally accepted soil hydraulic properties: (1) the soil water retention curve, i.e., the soil water content as a function of matric potential (or suction); and (2) the soil hydraulic conductivity function, i.e., the soil hydraulic conductivity as a function of soil water content or suction. The changes in these hydraulic properties directly affect the amount of soil water in the root zone by changing the magnitude of rain or irrigation water infiltration into the soil, as well as the redistribution and storage of this water in the soil profile. The wheel track compaction of the surface soil could markedly decrease water infiltration into a soil.

The extent of wheel track compaction, including whether there will be a significant compaction at all, depends, of course, on the equipment used from planting to harvesting operation. But it also depends upon the soil type and particularly upon the soil moisture regime of the area, landscape position, and year (Lindstrom and Voorhees, 1995). Wetting and drying cycles and freezing and thawing processes may alleviate some of the wheel compaction. Based on these principles, we would not expect severe compaction problems in the semi-arid Central Great Plains on sandy loam to loam soils. However, under the new no-till management practices the farmers have expressed concerns about the wheel track compaction in the long term. At the USDA-ARS, Central Great Plains Experimental Station, studies have been underway to evaluate such compaction problems, including any changes in the soil hydraulic properties after several years of wheel tracks.

A number of investigators have presented the effects of wheel tracks versus no wheel tracks on the soil hydraulic properties in the laboratory or field (Croney and Colemen, 1954; Hill and Sumner, 1967; Culley et. al., 1987; Gupta et al., 1989; Benjamin et. al., 1990; Hill and Meza-Montalo, 1990; Lindstrom and Voorhees, 1995). The effects varied from study to study, depending upon the prevailing conditions, and have been interpreted only qualitatively. Hills and Sumner (1967) measured the soil water retention curve between 0.1 bar and 15 bars suction for a variety of soils artificially compacted to various bulk densities. Their results showed that the changes in water retention curves due to compaction varied by textural class. Benjamin et al. (1990) presented more complete water retention curves and K_{sat} data for wheel track and no-track areas under practical field conditions for three different soil types. We need more field data of this type to develop better scientific understanding and quantitative methods for describing the changes in soil hydraulic properties caused by wheel tracks and other management practices.

Objectives of this study were: (1) evaluate the effect of wheel track compaction, if any, on the soil water retention and hydraulic conductivity of a number of soils, under a variety of crop rotations and management, in the Central Great Plains of the U.S.; and (2) quantify the observed results using simple, and sound, practical approaches.

Experimental Data Description

Evaluation of the effects of wheel tracks versus no tracks were done in selected plots of two longterm field studies of alternative crop rotations on two sites in eastern Colorado, USA. Mean annual precipitation is about 35 cm at each location. At Sterling, Colorado, crop rotations of increasing cropping intensity and duration (e.g., wheat-fallow, wheat-corn-fallow, wheat-corn-millet-fallow) are being tested under no-till and residue conditions for the last 13 years. Each rotation treatment runs downslope through a topographic sequence of summit, sideslope, and toeslope soils. The soil surface texture varies from sandy loam at the summit to sandy clay loam in the toeslope. We took four intact soil cores, 7.5 cm diameter by 7.5 cm long, from wheel-track areas, and four from the no- track areas of each of the three soils in the toposequence in the wheat-fallow rotation plots (two replications). At Akron, Colorado, a similar crop rotation study has been conducted for the last 7 years on just one soil type (mostly silt loam), but under both no-till and sweep plow tillage management. There, intact cores were taken from wheel-track and no-track areas of the wheat-fallow rotations under both no-till and sweep plow treatments.

Saturated hydraulic conductivity (K_{sat}) of all the soil cores was determined by the constant-head technique. The water retention curves were determined by using the pressure chamber and pressure plate approaches.

Theoretical Constructs

The One-Parameter Model For Water Retention Curves:
We will refer to this model based on the work of Gregson *et al.* (1987) as the GHM model. This model is based on the log-log linear form of the soil water retention curve (Brooks and Corey, 1964) in the matric potential range below the air-entry value. We have modified the GHM model to include the residual water content, θ_r, where $\psi(\theta)$ is expressed as

$$\ln|\psi| = a + b \ln(\theta-\theta_r) \quad (1)$$

where a and b are, respectively, the intercept and slope of the log-log linear relationship. Gregson *et al.* (1987) found that Equation (1), with $\theta_r = 0$, provided a good fit to several sets of data for Australian and British soils. More interestingly, they found that the values of the calculated parameters a and b for the different data sets of British, as well as Australian soils, had a strong linear relation (r^2=0.99). These a versus b relationships for all different data sets merged nicely into one common relationship:

$$a = p + qb \quad (2)$$

In other words, the constants p and q were approximately the same for all soils.

Substituting Equation (2) into Equation (1) yields a one-parameter model:

$$\ln|\psi| = p + b\,[\ln(\theta-\theta_r) + q] \quad (3)$$

where p and q are determined from regional datasets.

Equation (3) can then be used to estimate the entire $\psi(\theta)$ relationship below the air-entry value of ψ, simply from one measured value on the $\psi(\theta)$ curve. The known (ψ,θ) value is used to determine the only unknown parameter, b, in Equation (3). In our case we used the values of soil water content at -33 kPa. The known or bulk-density estimated θ_s value caps off the $\psi(\theta)$ curve and enables determination of the air-entry value. Equations (1-3) allow the spectrum of water retention curves to be brought together or scaled (Ahuja and Williams, 1991) or estimated from the knowledge of soil bulk density and 33-kPa water content (Williams and Ahuja, 1992).

K_{sat} as a Function of Effective Porosity:

Ahuja *et al.* [1984, 1989] showed that a modified Kozeny-Carman equation of the form

$$K_{sat} = B_1 \phi_e^n \tag{4}$$

is applicable to a wide range of soils from the southern region of the U.S., Hawaii and Arizona. Here ϕ_e is an effective porosity, calculated as the saturated water content (θ_s) minus the water content at 33 kPa matric suction. Even though the coefficients of Eq. (4), fitted to the data, varied slightly with soil type, Eq. (4) fitted to K_s data for nine different soil series had an r^2 as good as for individual soil series. In other words, Eq. (4) exhibited a degree of universality. In fact, the coefficients, B_1 and n obtained from the above fit of Eq. (4) to data for nine soils, estimated K_{sat} with acceptable accuracy for several soils from Korea [Ahuja *et al.*, 1989] and a variety of soils from Indiana [Franzmeir, 1991]. Messing [1989] presented data for some Norwegian soils for which Eq. (4) fit the data for individual soils well, although the coefficients varied slightly with soil type. Some of these soils had high clay contents and likely exhibited shrink-swell behavior, which could possibly affect the values of the fitted coefficients.

Results and Discussion

The average soil water retention curves measured for each of the three soils along the toposequence (summit, sideslope, toeslope) at Sterling are shown in Fig. 1 for Replication 1, and in Fig. 2 for Replication 2. There is a great deal of variability between the two replications, and there is no consistent trend among soils for wheel-track vs. no-track results. Aggregated results for wheel-track vs. no-track are shown in Fig. 3. Overall, there are no consistent differences in the water retention between wheel-track and no-track data. The average soil bulk density for all wheel-track cores was 1.36g cm^{-3}, versus 1.33g cm^{-3} for no-track cores, with variances of 0.0049 and 0.0087, respectively. Despite the apparently small difference, the mean values of bulk density are different at the p=0.086 significance level (91% confidence level).

The overall average soil water retention results for the Akron soil are presented in Fig. 4. Again, there is no significant difference in the water retention due to wheel tracks versus no tracks. The mean soil bulk density was 1.45g cm^{-3} for the wheel track cores and 1.39 g cm^{-3} for no-track cores, with variances of 0.0056 and 0.0049, respectively. Here, the mean values of bulk density are different (only) at the p=0.34 significance level. There were no significant differences due to tillage or crop effect either. The individual water retention curves were, however, as variable as for the Sterling data in Fig. 1 and 2.

In a separate study, Benjamin (1999, personal communication) has shown that in spite of large differences among the individual soil cores, the water retention data for all Akron cores were described extremely well by the one-parameter model. The constants a and b, Eq. (1) fitted to individual curves were very strongly correlated with each other (r^2 = 0.93), and parameters p and q, Eq. (2), derived from the data were similar to the values reported by Ahuja and Williams (1991) for the textural range. Thus, the water retention curve for any soil core can be estimated if its 33-KPa soil water content and soil bulk density are known. This provides a simple method to estimate wheel-track effects on the water retention curve.

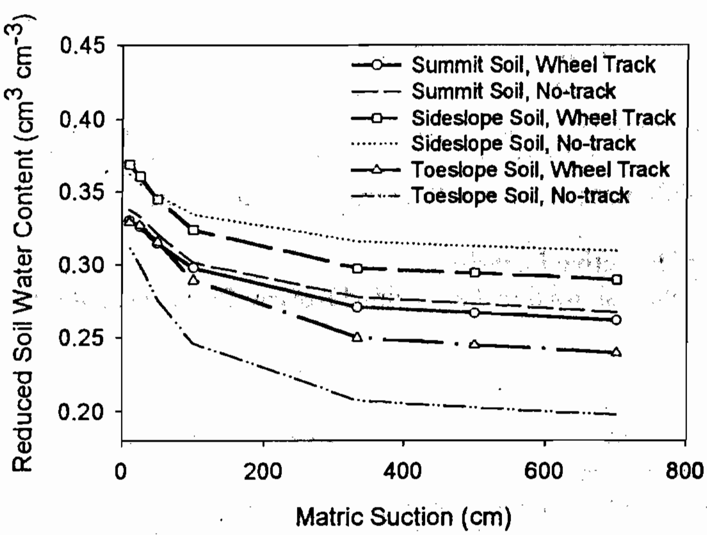

Figure 1. Soil water retention curves for wheel-track and no-track areas of Summit, Sideslope, and Toeslope soils at Sterling, Colorado, Replication 1. The field is no-till with wheat-fallow cropping.

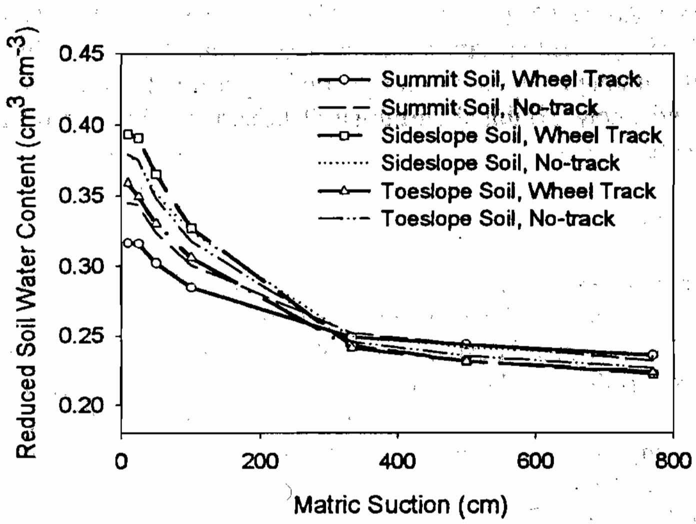

Figure 2. Soil water retention curves for wheel-track and no-track areas of Summit, Sideslope, and Toeslope soils at Sterling, Colorado, Replication 2. The field is no-till with wheat-fallow cropping.

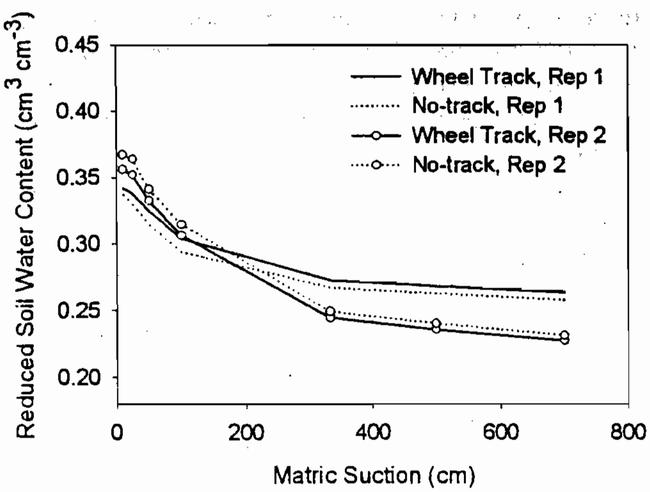

Figure 3. Soil water retention curves for wheel-track and no-track areas averaged over all the slopes as shown in Figures 1 and 2. The field is no-till with wheat-fallow cropping.

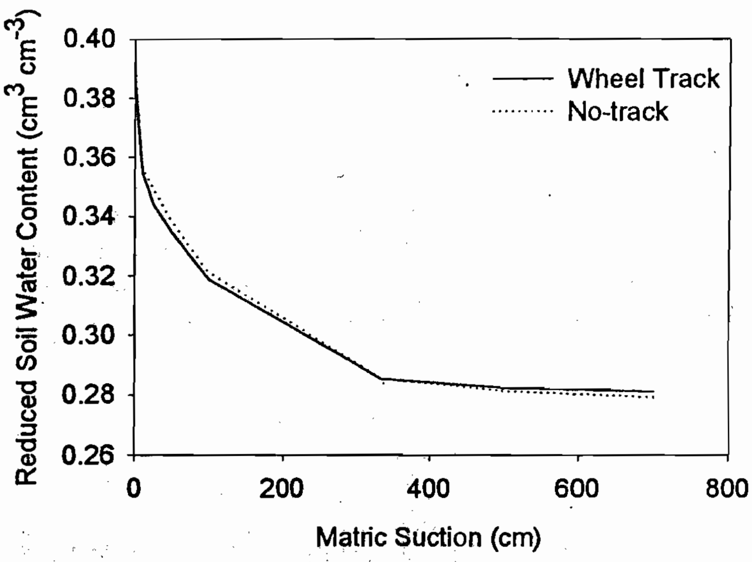

Figure 4. Soil water retention curves for wheel-track and no-track areas of Akron soil averaged over both till and no-till. The field is cropped with wheat-fallow.

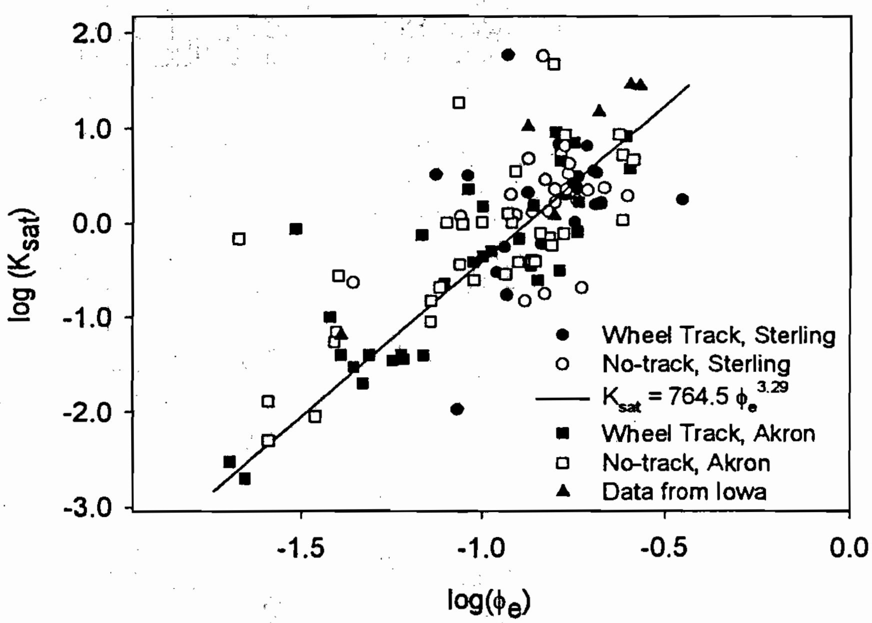

Figure 5. Saturated hydraulic conductivity (K_{sat}, cm hr-1) versus effective soil porosity for the two Colorado soils and the three Iowa soils in comparison to the general relationship (solid line) of Ahuja *et al.* (1989) for nine other soils.

The K_{sat} data for the two sites are plotted in Fig. 5 along with data from an Iowa study (Benjamin et al. 1990), as a function of effective porosity on a log-log scale. There is a large variability in the data for Sterling, but no apparent differences between wheel-track and no-track results. For Akron, the wheel-track K_{sat} data appear to be only slightly smaller than those for no-track. However, the differences are practically insignificant. It is interesting that in both sites, the K_{sat} data are described quite well by the general relationship obtained earlier (Ahuja *et al.*, 1989) for nine other, totally unrelated soils. This shows that the general relationship derived earlier is close to being universal for soils that do not swell or compact in a special way by some local conditions.

Since the data from our current studies showed no consistent effect of wheel tracks on soil hydraulic properties, we decided to analyze the field data for three soils from Iowa, reported by Benjamin *et al.* (1990), where significant effects were found. The measured water retention curves for wheel track and no-track interrows, along with the results of our analysis are shown in Fig. 6. To estimate the wheel track curve from that of no track, we utilized two observations from the data: (1) one value of water retention at 100 kPa for the tracked area curve was assumed known; and (2) assuming that at 1500 kPa suction the soil water is present primarily as thin films around the particles and not in pores or necks, the volumetric water content at this suction for the tracked soil was equal to water content in no-track sample times the ratio of their bulk densities. Based on Eqs. (1) and (2) our estimates of the tracked area Brooks-Corey type curve for the three soils are reasonably good.

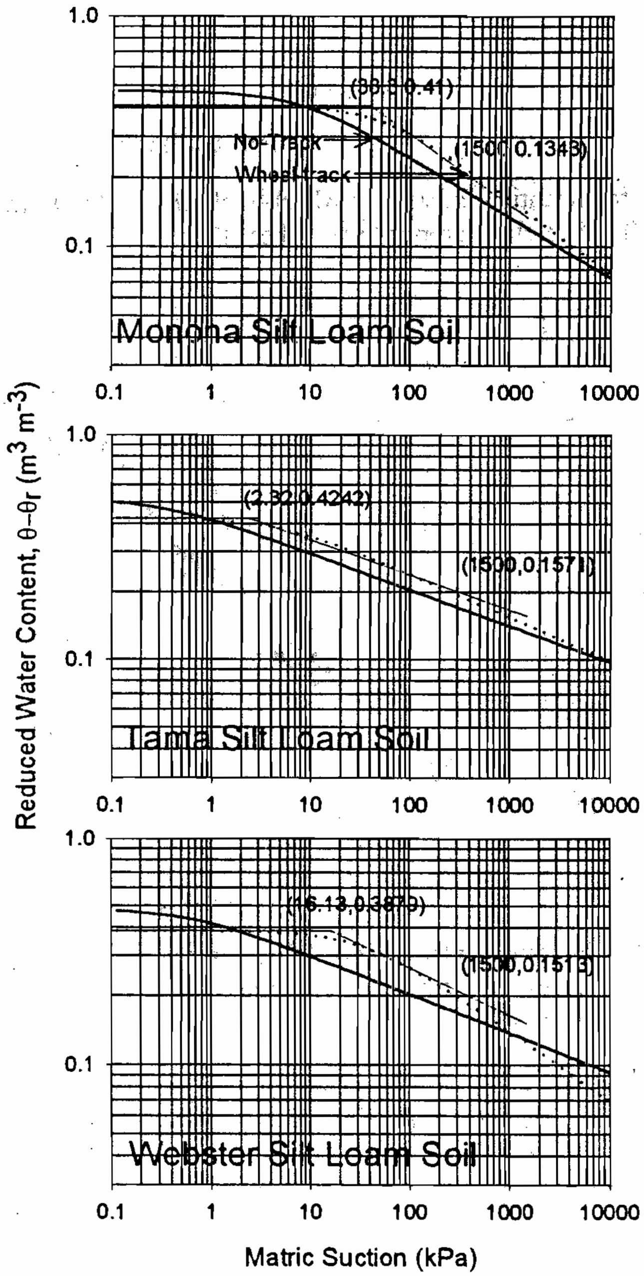

Figure 6. Soil retention curves for the three Iowa soils with estimated slopes and air entry values based on estimated soil water contents at 1500 kPa suction and known water contents at 100 kPa. Solid curves are for no-track interrows; dotted curves for wheel-track interrows, and solid lines are estimates of the track curve based on Eqs. (1) and (2).

For the data of Benjamin *et al.* (1990), we also explored the changes in slope of the log-log curves between 100 and 1500 kPa suctions as a function of the soil bulk density. For all three soils and for both wheel-track and no-track interrow curves (Fig. 6), as well as additional no-track row curves (not shown in Fig. 6), the slope versus bulk density is shown in Fig. 7. There is a good bit of scatter, but r^2=0.58. We then obtained the slope from this fitted function for each wheel-track curve using the known bulk density, and used this slope value instead of the one known value from the water retention curve, with the calculated 1500 kPa water content, to estimate the wheel-track curve. The estimates were slightly worse but comparable to those shown in Fig. 6. This approach should be investigated further, since it does away with having to measure one value of water retention (e.g., 100 kPa). The slope-bulk density relationship, such as shown in Fig. 7, may have to be expressed on a relative basis for a given soil, i.e., the change in slope of wheel-track soil relative to that of the no-track soil as a function of bulk density.

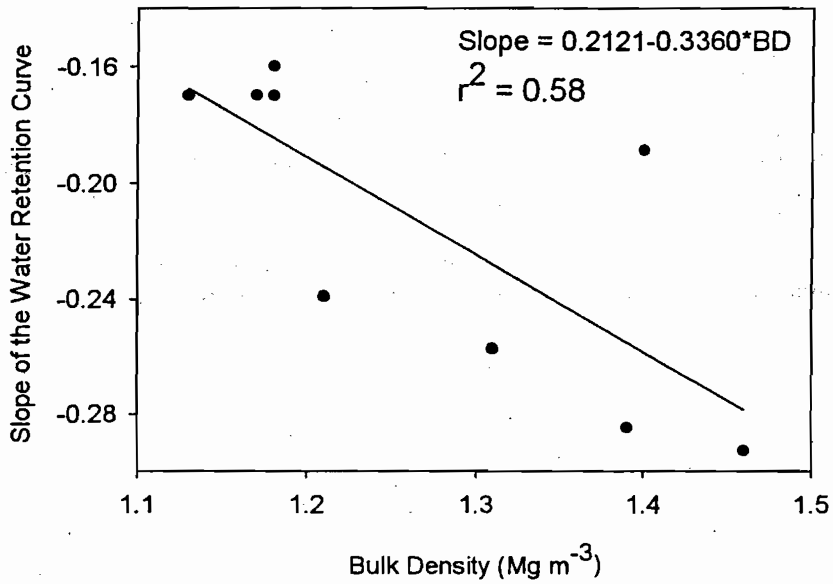

Figure 7. Fitted slopes versus soil bulk density from the water retention curves in Figure 6. Slopes were estimated from the log-log soil water retention curves between 100 kPa and 1500 kPa of matric suction.

Benjamin et al. (1990) also gave measured K_{sat} values for wheel-track and no-track areas of two of the above soils. We plotted these values as a function of the effective porosity Eq. (4), and found that they were consistent with the other data around the general relationship in Fig 5.

Conclusions

The results indicate that under the semi-arid conditions and sandy loam to silt loam soils of the Central Great Plains of the U.S., wheel tracks did not cause a significant effect on soil hydraulic parameters overall. Nonetheless, the spectrum of field soil hydraulic properties could be estimated from measurements of soil bulk density and 33-KPa (~1/3 bar) soil water content values by using two simple models. For water retention curves of three soils from the literature where wheel track effects were significant, we present a simple model to derive curves for track areas from those of the no-track areas, for further research. The K_{sat} data for these soils were consistent with the general K_{sat}-φ_e relationship.

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