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Limiting Water Range: A Case Study for Compacted Subsoils

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There is a need for improved knowledge of the limits to the available water range for root growth in the subsoil. The objective of this study was to recalculate the upper and lower limits of the least limiting water range (LLWR) concept by using respectively the air-filled porosity (ε_a) at which 0.005 of the relative gas diffusivity (D_s/D_o) is reached and readily available water (RAW). The refined upper limit estimates the variation in ε_a related to pore connectivity and the refined lower limit expresses the boundary at which plants suffer physiological water stress. This study was based on soil sampled in compaction trials on two sandy loam soils. Soil samples were taken from plots with no compaction (Control), and compaction with 78 kN (M8) and 58 kN (M6) wheel loads with multiple wheel passes. The soil cores were analyzed for ε_a, D_s/D_o, bulk density (ρ_b) and penetration resistance (PR). Heavy farm machinery impact of M8 and M6 led to subsoil compaction up to depth of 0.5 to 0.7 m for the soils under study. The subsoil structure was affected by compaction across depths with the decrease in ε_a (~33–46%) and D_s/D_o (~37–61%) and increase in ρ_b (~4–8%) and PR (~40–50%, at −100 hPa at 30-cm depth). The refined LLWR showed a wider water range compared to the original approach. We anticipate that the refined LLWR well reflects the limiting soil physical conditions for root growth for the studied soils, but validation by combined soil physical and plant growth measurements is needed.

Abbreviations: FC, field capacity; LLWR, least limiting water range; PR, penetration resistance; RAW, readily available water; WP, wilting point.

Core Ideas

- **Heavy traffic-induced compaction narrows LLWR in the subsoil.**
- **Air permeability at critical limit of gas diffusivity take in pore organization.**
- **Using readily available water as the lower limit represents a drought stress boundary.**

Subsoil compaction is a serious threat to soil structural quality because of its persistence (Berisso et al., 2012; Etana et al., 2013). The poor resilience of a compacted subsoil is the result of limited biological activity and physical processes that in the topsoil would allow the soil structure to recover (Håkansson and Reeder, 1994). The recovery process from subsoil compaction is very slow, and the restrictions in the subsoil to root growth and water and oxygen transport caused by compaction are assumed to persist for years, if not decades (Etana and Håkansson, 1994; Berisso et al., 2013; Schjønning et al., 2013). Fluctuations in water content are also found to be much smaller in compacted subsoil layers (Betz et al., 1998), regardless of changes in bulk density (ρ_b) (Benjamin et al., 2003). Consequently, the soil properties related to holding water content for root growth seem to remain constant over time for compacted subsoil layers.

The least limiting water range (LLWR) (da Silva et al., 1994), an improved concept after Letey (1958), is used as a soil physical index for evaluating the impact of soil management on root growth conditions. This LLWR approach integrates matric water pressure, soil resistance and air-filled porosity (ε_a) as factors associated with plant growth–factors that are all influenced by ρ_b. The calculation of LLWR involves the estimation of water content variation with ρ_b (θ_v) related to limiting values of the mentioned factors. The LLWR is then the water content

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range between an upper limit (smallest value of field capacity, θ_{FC}, and air-filled porosity, $\theta_{\varepsilon a}$) and a lower limit (largest value of wilting point, θ_{WP}, and penetration resistance, θ_{PR}) defined by the factors.

The LLWR has previously been used to quantify the impact of soil compaction on root growth conditions in the top 0.3 m (Betz et al., 1998; Chen et al., 2014). However, only a few studies have focused on deeper layers down to 0.5 m (Benjamin et al., 2003). They showed that the LLWR in the plow pan narrows when there is a strong restriction by ε_a and soil resistance. Changes in LLWR by agricultural practices depend on which factor is the upper and the lower limit that is restrictive. At the same time, the magnitude of change to the LLWR depends on the critical values set for the limits and these, in turn, depend on soil type (da Silva et al., 1994).

The LLWR concept, and especially the critical limits, has raised a concern by other authors. The upper limit proposed by da Silva et al. (1994) determined by FC and ε_a has been suggested to be instead determined by factors related to the oxygen consumption in the soil, the depth and total porosity of the soil, and the oxygen content and diffusion in the air (Mohammadi et al., 2010; Kadžienė et al., 2011; van Lier and Gubiani, 2015). Kadžienė et al. (2011) argued that the ε_a is a rough estimate of aeration status as it does not take soil pore organization into account. Other authors highlight that the tolerance periods of aeration stress vary depending on plant species (Håkansson and Lipiec, 2000) and some plants, depending on the soil type, can grow at <10% aeration porosity (McKenzie and McBratney, 2001; Siegel-Issem et al., 2005). For the lower limit, PR should be used with caution as an indicator of root growth restriction because plant response to mechanical impedance depends on many factors, such as soil structure characteristics and genotypic differences in root penetration capability (Bengough and Mullins, 1990; Whitmore and Whalley, 2009). Similarly, the use of WP for LLWR fails to consider the reduction in transpiration due to soil drying (Silva et al., 2015; van Lier and Gubiani, 2015). That is, WP can be considered as an ultimate limiting and not a least limiting factor. Therefore, in cases where PR becomes the lower limit, it can only hold true if it is higher than the water content at which water stress significantly limits root growth. Attempts to refine the calculations of the upper and lower limits of LLWR have been reported in some studies. Mohammadi et al. (2010) proposed a complex calculation of the upper limit of LLWR based on the soil moisture characteristic curve, air and hydraulic conductivity, plant root depth and oxygen consumption rate. A simpler approach was forwarded by Kadžienė et al. (2011). They proposed using the water content at a critical value of relative gas diffusivity (D_s/D_o) for root growth as a wet aeration limit instead of the water content at a fixed air-filled pore space value suggested by da Silva et al. (1994). For the lower limit, Silva et al. (2015) proposed to replace θ_{WP} with the critical soil water content where a reduction in stomata opening occurs. This approach represents the soil water state at which plants can extract water without reducing the maximum transpiration.

In the present study, the LLWR concept was evaluated using subsoil data from two sandy loam soils from northern Europe, that went from compacted to heavily compacted status after four consecutive years of realistic heavy farm traffic. We recalculate the upper limit and lower limit of the LLWR by the approaches proposed by Kadžienė et al. (2011) and Silva et al. (2015), respectively, and examined their applicability in relation to soil physical properties. It was hypothesized that heavy compaction would reduce the LLWR in the subsoil and that the refined LLWR upper and lower limit approaches would better reflect the growth conditions.

MATERIALS AND METHODS

Soil Description and Compaction Experiment

Traffic experiments were conducted at Aarslev and Taastrup sites in Denmark (55°18′18″ N, 10°26′52″ E, and 55°40′43″ N, 12°16′43″ E, respectively). The soils at both sites are sandy loam and derived from glacial tills of the Weichselian glaciation. Soil texture, soil organic matter content and a detailed description of the traffic experiments are provided by Schjønning et al. (2016).

Briefly, at both sites, the compaction treatments were applied during four consecutive years (2010–2013) at a soil water content near field capacity in the spring before seeding spring barley (*Hordeum vulgare* L.). The traffic treatments consisted of stresses applied using wheel-by-wheel passes across the plots and involving a range of wheel loads (29–117 kN), tire sizes (~0.30–0.96 m^2 tire-soil contact area), tire inflation pressures (150–300 kPa) and repeated wheel passes (1–5) in one traffic event. For this study, the most contrasting treatments regarding the effect of wheel loads on subsoil compaction (Schjønning et al., 2016) were selected: Control (no traffic) and traffic treatments conducted with 78 kN (M8, Aarslev) or 58 kN (M6, Taastrup) wheel loads on the middle and rear trailer axles, same range of tire inflation pressures (150–300 kPa at Aarslev, but 210–280 kPa at Taastrup) and multiple wheel passes (4–5) in one traffic event.

The Control and Trafficked treatments (M8 and M6) were established in a randomized complete block design with four replicates.

Soil Sampling

Undisturbed soil cores of 100 cm^3 (~3.5 cm length, ~6.1 cm diameter) were taken in spring 2015 and spring 2014 at Aarslev and Taastrup, respectively. Hence, soil cores were sampled respectively 2 yr and 1 yr after the fourth and final experimental traffic event at each site. Sampling was conducted within each experimental plot and for all four blocks at different depths. For the treatments selected in our study, only samples taken at 0.3, 0.5 and 0.7 m depths were considered. A total of 108 undisturbed soil samples per treatment per site were analyzed as follows.

Soil Physical Properties

The soil samples were saturated and then drained to −50 and −100 hPa on tension tables and to −300 and −1000 hPa matric potential in a pressure chamber. Soil samples from both sites were first analyzed for pore characteristics at −100 hPa, e.g., air permeability, air-filled porosity (ε_a) and relative gas diffusivity (D_s/D_o). Methodologies for the pore functioning analyses and results from the Aarslev site are described in Pulido-Moncada et al. (2019). Soil samples were then divided into four groups for penetration resistance (PR) measurements at different matric potentials (−50, −100, −300, and −1000 hPa). Soil PR for Aarslev samples was not measured at −1000 hPa. At both sites, two of the groups of samples were re-saturated after −300 hPa equilibration and were separately drained again to −50 and −100 hPa for further PR measurement. Samples were weighed at each matric potential before conducting the PR measurements.

The PR readings were made using a penetrometer probe with 1-mm basal diameter, a shaft diameter of 0.8 mm and 30° cone angle. The probe was driven five times into each soil sample at a penetration rate of 4 mm min^{-1} to 20-mm depth by an Instron loading frame. The data from the top 5-mm depth was not included in the analysis of the PR to avoid the noise of the top zone of the sample. The readings for each soil sample were averaged. After PR, the samples were oven-dried at 105°C to estimate soil dry bulk density (ρ_b).

Least Limiting Water Ranges

As described in da Silva et al. (1994), the LLWR is calculated by a functional relationship between water content and each of the following properties: water potential, PR, and aeration. The functional relationship between water content and water potential is fitted using Eq. [1] (Williams et al., 1989), and the functional relationship of PR, water content and ρ_b as given in Eq. [2] (Busscher and Sojka, 1987):

$$\theta = \exp\left(a + b\rho_b\right) \cdot \varphi^c \qquad [1]$$

where θ is the soil volumetric water content ($m^3\ m^{-3}$); φ is the matric potential; and a, b, and c are empirical parameters; and

$$PR = d \cdot \theta^e \cdot \rho_b{}^f \qquad [2]$$

where PR is the soil penetration resistance; θ is the soil volumetric water content; and d, e, and f are empirical parameters.

The LLWR was estimated for each ρ_b value by setting the critical limits of the soil physical variables as described in da Silva et al. (1994) and commonly used for Danish soils. The FC matric potential was set at −100 hPa and the permanent WP at −15000 hPa as the wet and dry limits for plant root growth, respectively. The PR value chosen as limiting for plant growth was 2.0 MPa (Taylor et al., 1966) and 10% was set as the limiting air-filled porosity (Wesseling and Van Wijk, 1957).

Variations in water content at field capacity (θ_{FC}) and permanent wilting point (θ_{WP}) with changes to ρ_b were calculated by applying Eq. [1]. The algebraic transformation of Eq. [2] calculates the variation with ρ_b of the water content at which PR is limiting for plant growth (θ_{PR}, 2.0 MPa).

The variation with ρ_b of the water content at the limiting air-filled porosity ($\theta_{\varepsilon a}$) was found from the ρ_b and particle density, Eq. [3] (da Silva et al., 1994):

$$\theta_{\varepsilon a} = \left(1 - \frac{\rho_b}{\rho_p}\right) - \varepsilon_a \qquad [3]$$

where ρ_p is the soil particle density (here assumed to be 2.65 Mg m^{-3}) and with a value for ε_a (air-filled porosity) of 0.1 $m^3\ m^{-3}$ (10%) as the critical limit of ε_a for plant growth as suggested by Wesseling and Van Wijk (1957).

Following da Silva et al. (1994), the upper limit of LLWR was equal to the value of either θ_{FC} or $\theta_{\varepsilon a}$, whichever was the smaller. The lower limit of LLWR was equal to θ_{WP} or θ_{PR}, whichever was the larger. The LLWR is the difference between the upper limit and the lower limit. The critical bulk density is the value derived when LLWR equals zero. The LLWR estimates were conducted using the spreadsheet software Microsoft Excel developed by Leão and Silva (2004).

Other Approaches for Estimating the Lower and Upper Limits of the Limiting Water Range

For the upper limit of LLWR, Kadžienė et al. (2011) proposed replacing the widely used critical limits for ε_a of 10% with ε_a limits estimated from the critical values of relative gas diffusivity of 0.005 to 0.02 (D_s/D_o) (Grable and Siemer, 1968) as an alternative and safer limit. Grable and Siemer (1968) summarized the critical values of relative gas diffusivity (D_s/D_o) for different crops that had been found to limit plant growth (e.g., 0.005 for tomatoes and ryegrass and 0.02 for maize). Low gas diffusivities (D_s/D_o < 0.02) were generally found for the tested subsoils in the present study and D_s/D_o = 0.005 was therefore selected as the critical level. It was estimated using the power law model (Eq. [4]) as suggested by Kadžienė et al. (2011):

$$D_s/D_o = \alpha \cdot \varepsilon_a{}^{\beta} \qquad [4]$$

where α and β are empirical parameters.

Incorporating Eq. [4] into Eq. [3], the variation with ρ_b of the water content at the limiting D_s/D_o can be found by applying Eq. [5]:

$$\theta_{\varepsilon a,\,0.005} = \left(1 - \frac{\rho_b}{\rho_p}\right) - \left(\frac{D_s/D_o}{\alpha}\right)^{1/\beta} \qquad [5]$$

In another study, Silva et al. (2015) introduced the use of a critical moisture content (assigned the symbol θ^*) as the lower limit of LLWR based on the definition of readily available water (RAW) (see Eq. [6–7]) (Doorenbos and Kassam, 1979). The readily available soil water is hence defined as the average fraction of total available soil water that can be extracted by plant roots without suffering water stress (actual transpiration rate falling to less than the maximum transpiration rate) (Allen et al., 1998; Van den Berg and Driessen, 2002).

$$RAW = p \cdot TAW \qquad [6]$$

where p is the crop evapotranspiration depletion factor, and TAW is the total soil available water, which is defined as the water content between field capacity and permanent wilting point.

The inclusion of θ^* (here θ_{RAW}) in the LLWR concept was proposed by Silva et al. (2015) as follows:

$$RAW = \theta_{FC} - \theta_{RAW} \quad [7]$$

Replacing Eq. [5] and the TAW concept in Eq. [7], θ_{RAW} is calculated by Eq. [8]:

$$\theta_{RAW} = \theta_{FC} - p \cdot (\theta_{FC} - \theta_{WP}) \quad [8]$$

For modeling and graphical visualization of LLWR, Silva et al. (2015) further replaced θ by θ_{RAW} (Eq. [8]) in the nonlinear form of Eq. [1]. However, the resulting model (Eq. [12] in Silva et al., 2015) did not fit our dataset well. Instead, Eq. [8] was applied to estimate the variation in water content at the limit for water stress by plant roots. The θ_{FC} and θ_{WP} were, in this case, the variation in water content with ρ_b calculated by Eq. [1] (assuming −100 and −15000 hPa for FC and PWP, respectively). We used a p-value of 0.55 as recommended for spring barley up to 1 m depth of soil exploration (Allen et al., 1998).

Statistical Analyses

A mixed model with compaction treatment as a fixed effect and block as well as treatment × block interaction as random effects was used to evaluate compaction effects on soil physical properties. The sampling spot effect nested within the experimental plot (treatment × block) was also treated as a random effect in the model. A t test was conducted to test for differences in the limiting factors and LLWR approaches. Pearson's correlation was conducted to test for associations among PR, water content and ρ_b. All tests were conducted at the 5% significance level. The analyses were performed using the statistical package SPSS (version 24, SPSS Inc., USA).

RESULTS

Effects of Subsoil Compaction on Soil Physical Properties

For the Aarslev soil, the publication by Pulido-Moncada et al. (2019) shows the effects of subsoil compaction on the degree of compactness and soil pores. Briefly, they found that soil ρ_b for Aarslev generally increased with traffic stress at 0.3 and 0.5 m depth ($P = 0.07$ and $P = 0.03$, respectively), with the largest values obtained at 0.3 m depth (mean of 1.77 Mg m^{-3}). No effect of compaction on ρ_b was observed at 0.7 m depth. Their results also indicated that the use of machinery with a wheel load of 78 kN significantly reduced air-filled porosity, ε_a, and gas diffusivity, D_s/D_o, up to 0.5 m depth (Table 1).

At Aarslev, the difference in PR between treatments was only significant at −50 and −100 hPa matric potential at 0.3 m depth ($P < 0.10$) (Fig. 1). The highest PR values for the M8 treatment were recorded at 0.3 m depth. For the Control treatment, mean and maximum values of PR at −100 hPa matric potential (field capacity) ranged from 1.88 to 2.37 MPa and from 3.60 to 4.69 MPa, respectively, across depths. For M8, PR ranged from 2.05 to 3.37 and from 2.61 to 6.61 MPa for the mean and maximum, respectively, across depths. Figure 1 shows that PR increases with decreasing matric potential as expected.

Table 1. Mean values of soil bulk density (ρ_b), air-filled pore space (ε_a), and relative diffusivity (D_s/D_o, in which D_s and D_o are the diffusion coefficients in soil and air, respectively) for the studied soils.

Site†	Depth	Treatment‡	ρ_b	ε_a	D_s/D_o
	m		Mg m^{-3}	m^3 m^{-3}	×1000
Aarslev	0.3	Control	1.68 A+§	0.136 A+	9.1 B
		M8	1.77 A	0.080 A	4.7 A
	0.5	Control	1.64 A	0.166 B	14.3 B
		M8	1.70 B	0.101 A	8.7 A
	0.7	Control	1.68 A	0.098 A	6.9 A
		M8	1.68 A	0.093 A	6.7 A
Taastrup	0.3	Control	1.63 A	0.112 B	9.8 B
		M6	1.76 B	0.060 A	4.1 A
	0.5	Control	1.57 A	0.157 B	20.3 B
		M6	1.65 B	0.094 A	11.9 A
	0.7	Control	1.61 A	0.124 B	15.6 B
		M6	1.67 B	0.083 A	9.8 A

† Data for site Aarslev were taken from Pulido-Moncada et al. (2019).

‡ Treatment labels indicate the number of wheel passes and the approximate maximum wheel load (M8 = multiple passes of 8 Mg load).

§ Values in a column followed by the same letter are not significantly different between treatments in the same depth ($P = 0.05$). Plus signs (+) indicate treatments were significantly different at $P = 0.10$.

For the Taastrup soil, the ρ_b estimated at the different depths varied significantly between treatments ($P < 0.01$), with higher values after traffic stress (Table 1). The highest values of ρ_b were found at 0.3 m depth for M6, with an average of 1.76 Mg m^{-3}. The M6 treatment showed detrimental effects of compaction on ε_a and D_s/D_o at all depths (Table 1). ε_a was reduced by 33 to 46%, and D_s/D_o by 37 to 58% across depths.

The PR results showed a similar picture for Taastrup as for Aarslev (Fig. 1). There was a significant treatment effect at each matric potential at 0.3 m depth ($P < 0.05$; at −100 hPa $P = 0.06$). The range in PR recorded in samples at −100 hPa matric potential across depths was from 2.0 to 2.4 and 2.7 to 4.0 MPa for mean and maximum values for the Control, respectively. For M6, mean PR values ranged from 2.1 to 3.5 MPa and maximum values from 2.7 to 6.4 MPa.

Effects of subsoil compaction on least limiting water range limits

For the Aarslev soils, the variation in water content with ρ_b at critical levels of FC and WP differed between treatments at all depths ($P < 0.05$), except for θ_{FC} at 0.5 m depth ($P = 0.28$). The θ_{FC} values decreased after traffic stress, with the opposite happening for θ_{WP}. The M8 treatment significantly reduced the $\theta_{\varepsilon a}$ 10% values at 0.3 and 0.5 m depth ($P < 0.05$), but not at 0.7 m depth (Fig. 2). For the Taastrup soil, traffic stress also had a significant effect on the θ_{FC} and θ_{WP} at all depths. The

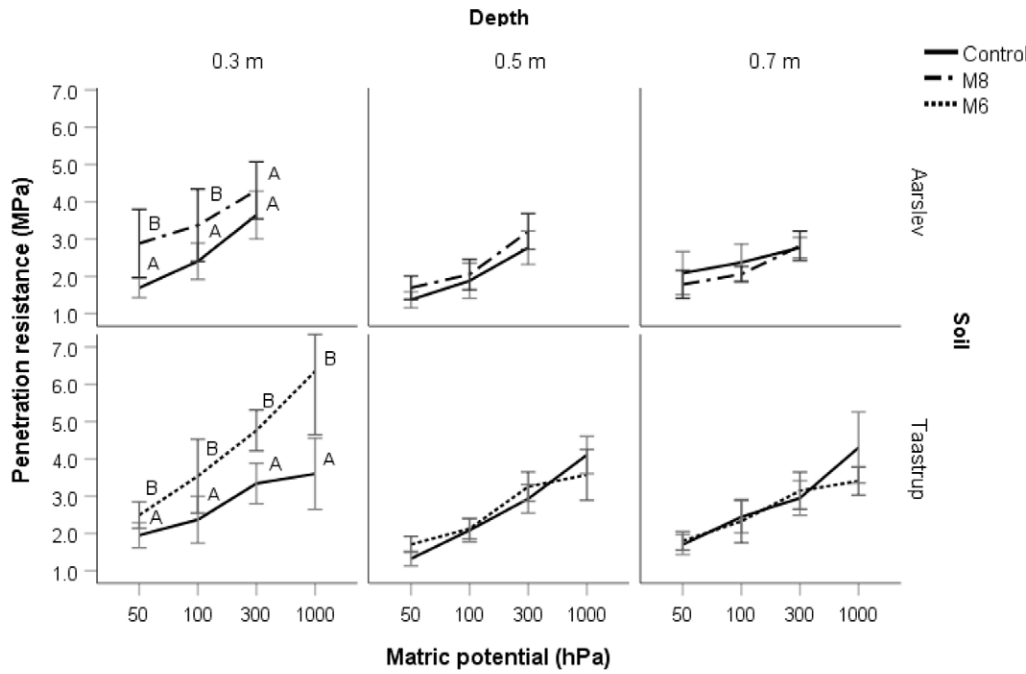

Fig. 1. Mean penetration resistance (MPa) measured with a cone micro-penetrometer at −50, −100, −300 and −1000 hPa matric potential for the Aarslev and Taastrup sites. Control undergoes no compaction treatment, and M8 and M6 are the compaction treatments with respectively 78 and 58 kN wheel loads and multiple passes. Error bars are ±2 standard errors.

θ_{FC} decreased after compaction at all depths ($P < 0.01$). For θ_{WP}, higher values were estimated for M6 at all depths ($P < 0.01$). A decrease in $\theta_{\varepsilon a}$ was also observed at 0.3, 0.5 and 0.7 m depth as a consequence of heavy traffic (Fig. 3).

For the Aarslev site at 0.3 m depth, PR was negatively related to water content ($P = 0.002$) and positively to soil ρ_b for the Control ($P = 0.03$). For M8, PR was not significantly ($P = 0.93$) related to water content (Fig. 4), but positively and significantly related to ρ_b ($P < 0.001$). At 0.5 m depth, for both Control and M8, a poor relationship was observed between PR and water content as well as ρ_b ($P = 0.09$ to 0.59). At 0.7 m depth, a positive and significant relationship existed between PR and ρ_b ($P = 0.005$ and $P = 0.007$, for Control and M8, respectively) whereas

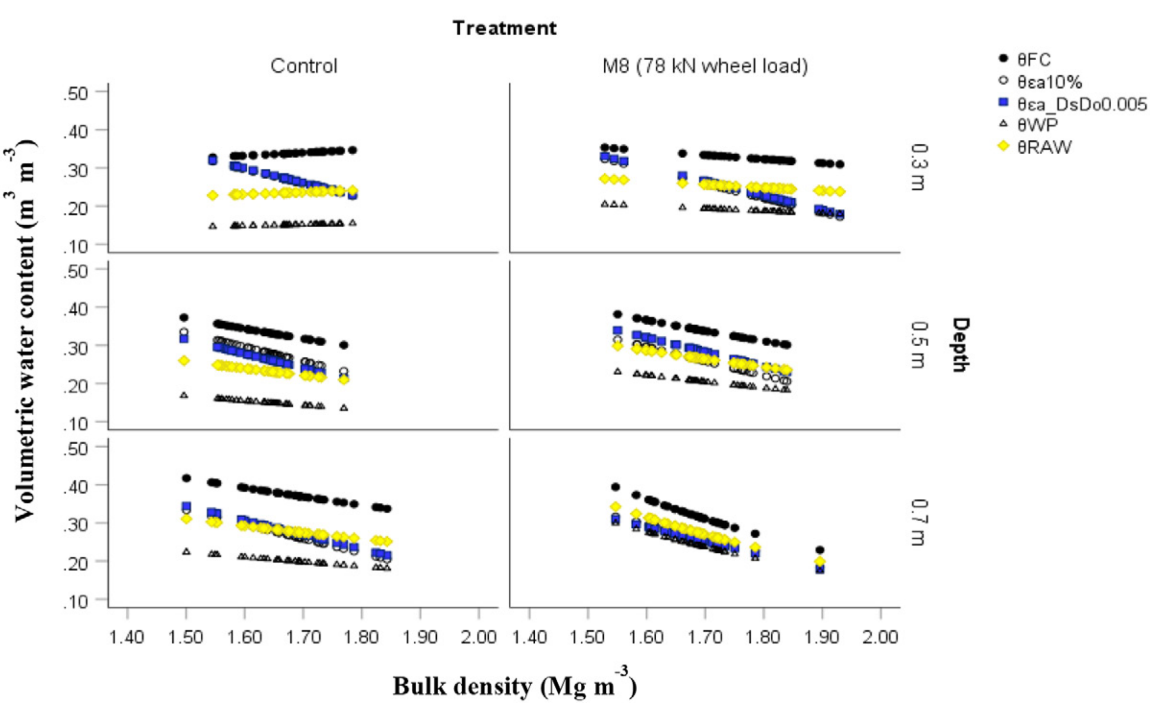

Fig. 2. Water content variation (θ_v) with soil bulk density at −100 hPa of field capacity (θ_{FC}), 10% of air-filled porosity ($\theta_{\varepsilon a,10\%}$), air-filled porosity at which gas diffusivity (D_s/D_0) reaches 0.005 ($\theta_{\varepsilon a,DsDo0.005}$), −15000 hPa wilting point (θ_{WP}) and critical moisture level based on the definition of readily available water (θ_{RAW}) for three depths at the Aarslev site.

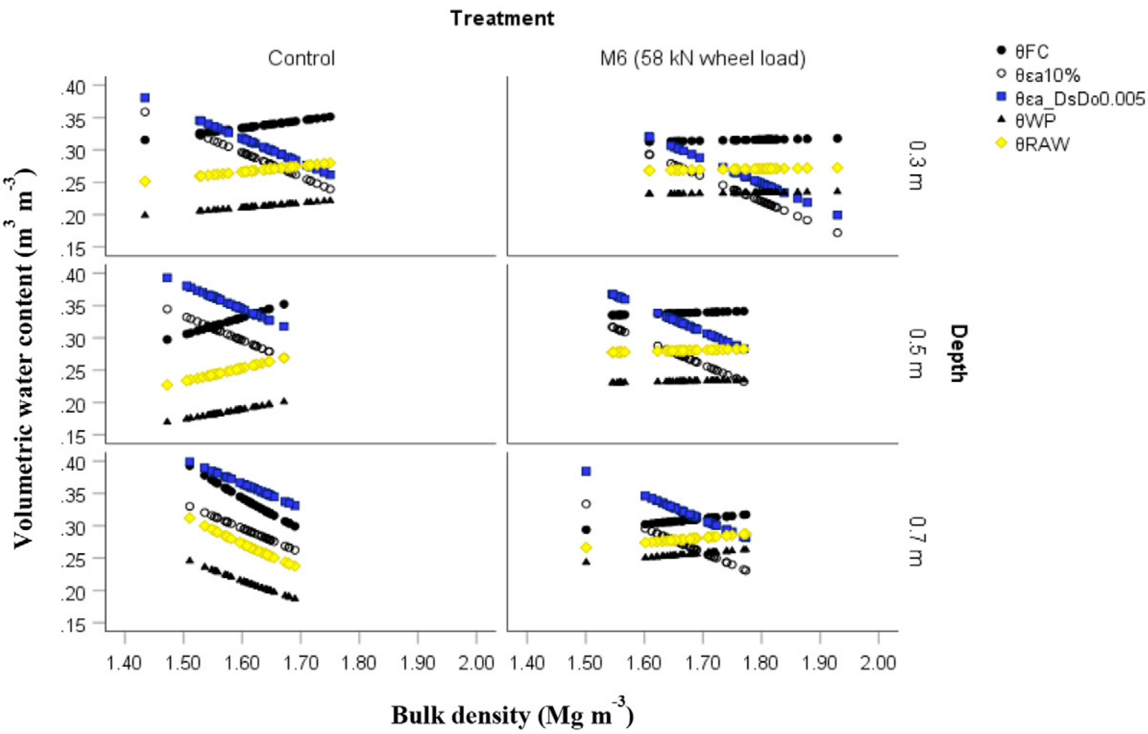

Fig. 3. Water content variation (θ_v) with soil bulk density at −100 hPa of field capacity (θ_{FC}), 10% of air-filled porosity ($\theta_{\varepsilon a10\%}$), air-filled porosity at which gas diffusivity (D_s/D_o) reaches 0.005 ($\theta_{\varepsilon a,DsDo0.005}$), −15000 hPa wilting point (θ_{WP}) and critical moisture level based on the definition of readily available water (θ_{RAW}) for three depths at the Taastrup site.

there was no significant correlation between PR and water content ($P = 0.72$ and $P = 0.28$, for Control and M8, respectively). Overall, the PR model poorly fitted the Aarslev dataset.

For the Taastrup site, PR was negatively related to water content for all treatments and at all depths ($P < 0.05$), except for M6 at 0.7 m depth ($P = 0.93$) (Fig. 4). A positive relationship between PR and ρ_b was found only for the Control at 0.3 m depth and for M6 at 0.3 and 0.5 m depths ($P < 0.05$).

Upper Limit Approach

As mentioned above, the upper limit established by the LLWR approach corresponds to the lowest value of θ_{FC} and $\theta_{\varepsilon a}$. In the present study, it is proposed to substitute θ_{FC} and $\theta_{\varepsilon a}$ with the air-filled porosity at $D_s/D_o = 0.005$, $\theta_{\varepsilon a,0.005}$ (Kadžienė et al., 2011).

For the Control at the Aarslev site, the $D_s/D_o = 0.005$ is reached at 10, 12, and 9% of ε_a at 0.3, 0.5 and 0.7 m depth, respectively, whereas 9, 8, and 11% of ε_a were obtained at $D_s/D_o = 0.005$ for the M8 treatment at similar depths. The $\theta_{\varepsilon a,0.005}$ variation with ρ_b was only different from $\theta_{\varepsilon a}$ 10% (v/v) at 0.5 m depth ($P < 0.01$) for both the Control and M8. The M8 treatment significantly reduced the $\theta_{\varepsilon a,0.005}$ at 0.3 and 0.7 m depth ($P < 0.001$), but increased at 0.5 m depth (Fig. 2).

For the Taastrup soil, values of critical ε_a estimated from $D_s/D_o = 0.005$ were lower than those observed for the Aarslev soil, e.g., 8, 5, and 3% for the Control and 7, 5, and 5% for M6 at 0.3, 0.5 and 0.7 m depth, respectively. The estimated $\theta_{\varepsilon a,0.005}$ was significantly higher than $\theta_{\varepsilon a}$ 10% (v/v) for both treatments and at all depths ($P < 0.01$). It was also significantly reduced by traffic stress ($P < 0.01$) (Fig. 3).

Lower Limit Approach

The use of the RAW concept as the lower limit to the water range represents a line in the plot halfway between θ_{FC} and θ_{WP} (Fig. 2 and 3). For the studied soil profiles at the Aarslev site, the critical water content based on the RAW (θ_{RAW}) significantly increased after traffic stress at 0.3 and 0.5 m depth ($P < 0.01$), but no differences were found at 0.7 m depth. For the Taastrup soil, differences between treatments for θ_{RAW} were evident only at 0.5 and 0.7 m depth, but not at 0.3 m.

Variation in Limiting Water Range

Results from the da Silva et al. (1994) approach using the PR model are shown in Fig. 5 and 6. According to this concept, PR will become the limiting factor in all cases. If the inconsistent relationship between PR and water content as a function of ρ_b is taken as a restricting factor for the applicability of the model, then the lower limit of the LLWR approach relies solely on θ_{WP}.

For the Aarslev site, when $\theta_{\varepsilon a}$ and θ_{FC} define the upper limit and θ_{WP} the lower limit, LLWR decreases as ρ_b increases, except for M8 at 0.7 m depth where it remains constant (Fig. 5). If θ_{WP} is replaced by θ_{RAW} as the lower limit, LLWR becomes close to zero for M8 at ρ_b of ~1.70 and 1.65 Mg m^{-3} at 0.3 and 0.5 m depth, respectively. For the Control, LLWR reached zero when ρ_b was ~1.78 and ~1.60 Mg m^{-3} at 0.3 and 0.7 m depth, respectively, whereas no critical ρ_b was found at 0.5 m depth. The

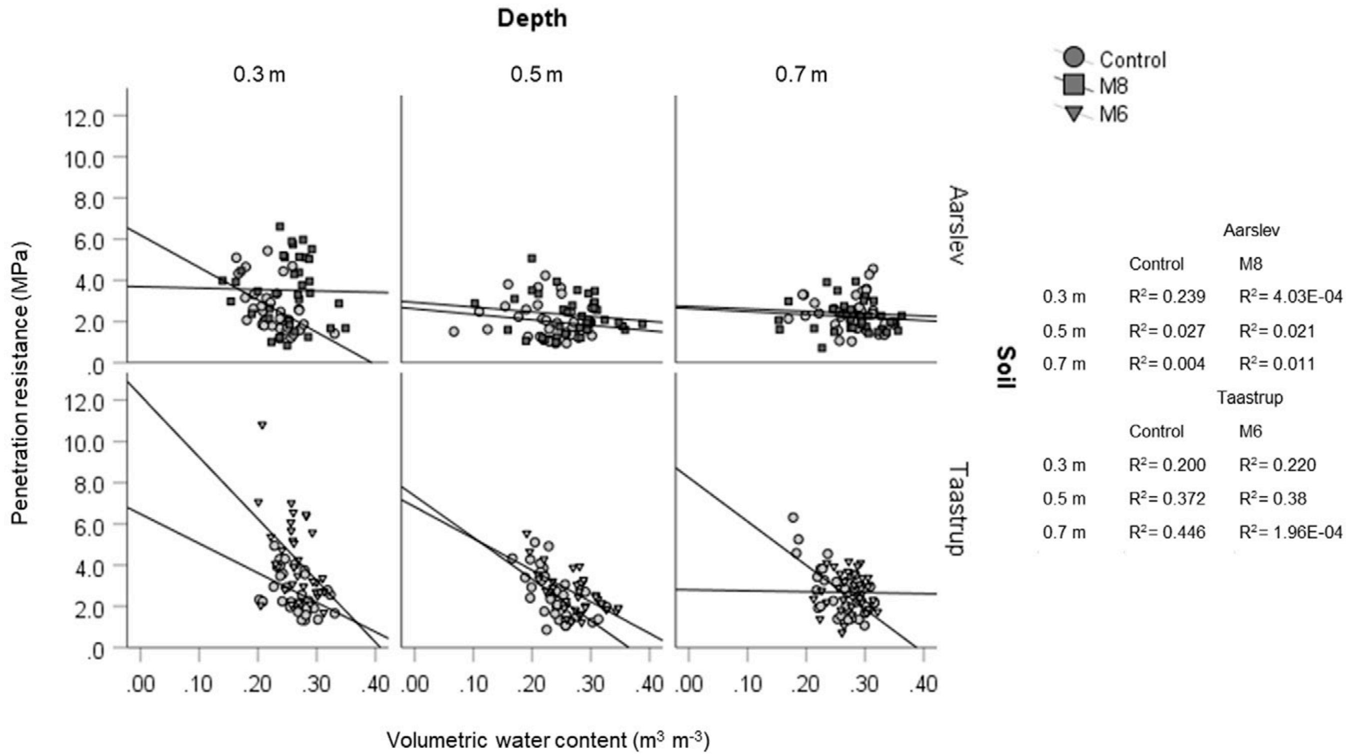

Fig. 4. Penetration resistance (MPa) vs. water content measured at different matric potentials for the Aarslev and Taastrup sites. Control undergoes no compaction treatment, and M8 and M6 are the compaction treatments with respectively 78 and 58 kN wheel loads and multiple passes.

LLWR estimated using θ_{RAW} was, as expected, considerably smaller than the LLWR when θ_{WP} was used as the lower limit

When $\theta_{\varepsilon a,0.005}$ is set as the upper limit and θ_{RAW} as the lower limit, the limiting water range followed a similar pattern as for the estimated LLWR when only the lower limit is set as θ_{RAW}, except at 0.5 m depth when higher values were recorded after traffic stress (Fig. 5).

For the Taastrup soil, the estimates of limiting water ranges based on the different upper and lower limits mentioned above are shown in Fig. 6. At 0.3 m depth, the results for LLWR using θ_{WP} as the lower limit and LLWR estimated from $\theta_{\varepsilon a,0.005}$ and θ_{RAW} were very similar for the M6 treatment. At 0.5 m depth, the LLWR estimated from $\theta_{\varepsilon a,0.005}$ and θ_{RAW} was very similar to the LLWR estimated with θ_{WP} as the lower limit for the Control and M6. The LLWR estimated from $\theta_{\varepsilon a,0.005}$ and θ_{RAW} at a ρ_b of ~1.75 Mg m^{-3} was zero at all depths. The results for the 0.7 m depth differed in that the limiting water range barely varied with ρ_b for the Control irrespective of the upper and lower limits used. For M6, the different LLWRs decreased with increases in ρ_b. In general, the refined LLWR resulted in a wider water range compared to the da Silva et al. (1994) original concept, except for Aarslev soil at 0.7 m depth.

DISCUSSION

Heavy Traffic Effects on LLWR and Subsoil Physical Parameters

Our LLWR results reflect the detrimental effects of heavy traffic on the soil physical parameters for both the studied soils. Heavy traffic reduced ε_a and D_s/D_o and increased ρ_b, resulting in a narrower LLWR. In general, the refined LLWR was sensitive to the impact of heavy traffic on the subsoil structure.

It appears that the LLWR concept using as the upper limit the ε_a at which 0.005 of D_s/D_o is reached establishes a wider range of water in compacted subsoil compared to the use of the water content at 10% air-filled pore space (M8 and M6 in Fig. 5 and 6). This suggests that after multiple passes of heavy machinery, subsoil layers that reach a severely compacted status are characterized by low ε_a values but still retain some well-connected pores (because of diffusivity). As expected, a remarkable decrease in LLWR took place when RAW was set as the lower limit rather than WP. The use of the refined LLWR approach for the sandy loam subsoils revealed that the LLWR narrows after compaction up to 0.7 m depth, and the conductive pore space and stomatal function were restricted when ρ_b exceeded 1.75 Mg m^{-3}.

Refined Upper Limit Approach

The 10% ε_a upper limit used by several authors for LLWR calculation is based on Wesseling and Van Wijk (1957) who showed that at 10% ε_a oxygen diffusion approaches zero. This was supported by Grable and Siemer (1968) who further concluded that 12 to 15% ε_a is a safer range limit. However, in a study conducted on a Vertisol under a cotton plantation, McKenzie and McBratney (2001) found that the oxygen supply for roots and microorganisms were sufficient at $\varepsilon_a < 10\%$. They concluded that for their study conditions, limiting and non-limiting physical conditions for root growth were fuzzy. Another study noted that at a matric potential of −100 hPa soils can be expected to have an $\varepsilon_a <$ 10% when degree of compactness is >87% (Håkansson and Lipiec

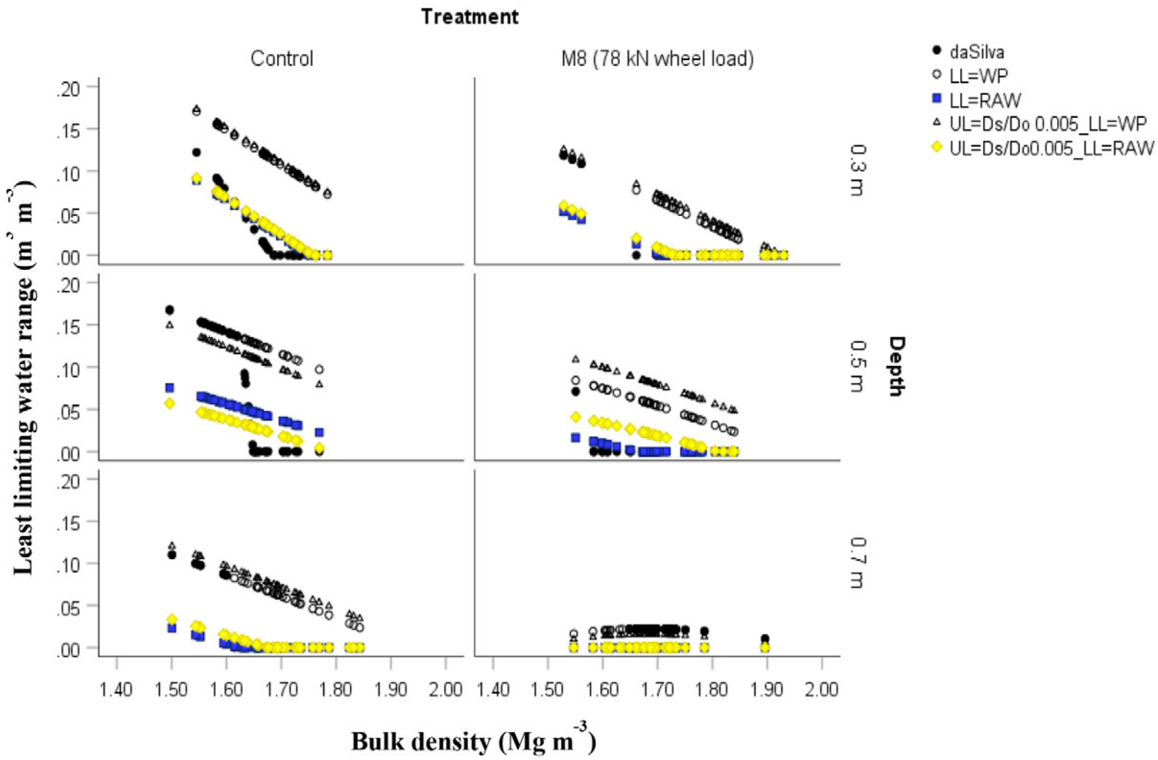

Fig. 5. Least limiting water range (LLWR) as a function of bulk density for the Control and M8 (78 kN wheel load) at the Aarslev site at 0.3, 0.5 and 0.7 m depth. Each line in the graph represents different LLWR boundary approaches: (i) daSilva, upper limit (UL) was either field capacity at −100 hPa or air-filled porosity of 10%, and the lower limit (LL) either penetration resistance (PR) at 2.0 MPa or wilting point (WP) at 15000 hPa; (ii) LL = WP, from the daSilva approach, the LL was only defined by WP; (iii) LL = RAW, from the daSilva approach, the LL was only defined by critical moisture based on the definition of readily available water (RAW); (iv) UL = Ds/Do0.005_LL = WP, the UL was only defined by air-filled porosity at which gas diffusivity reached 0.005 (Ds/Do0.005) and the LL by WP; (v) UL = Ds/Do0.005_LL = RAW, the UL was only defined by Ds/Do0.005 and the LL by RAW.

2000). This is in correspondence with results from M8 and M6 at Aarslev and Taastrup site. In the case of Aarslev site at 0.3 and 0.5 m depth, degree of compactness was reported to range from 95 to 101% (Pulido-Moncada et al., 2019).

Lipiec and Håkansson (2000) showed that a gradual change occurs 'from a completely non-restrictive to a completely restrictive situation as soon as one of the critical limits is exceeded', which is a key aspect to consider when modeling the importance of factors influencing the soil conditions for root growth. The estimation of the upper limit on the LLWR concept based on the use of a fixed critical value of ε_a fails to consider the pore organization, continuity and pore connectivity, which are factors considered to be probably more important than pore volume for fluid flow (Ball et al., 1988). To take account of pore characteristics, we propose the use of ε_a at D_s/D_o = 0.005 as the critical threshold (Grable and Siemer, 1968). This approach was previously considered but not applied by Kadžienė et al. (2011). In our study, when using the value of ε_a at which 0.005 of D_s/D_o is reached, the ε_a values varied between treatments and among depths. The $\theta_{\varepsilon a,0.005}$ was very close to ε_a 10% for Aarslev but lower for Taastrup (both for the Control and with Traffic), which may be attributed to a soil type effect. This is in accordance with the studies summarized by Håkansson and Lipiec (2000) reporting that the critical limit for ε_a at which diffusion coefficient approached zero varies with soil type. To our knowledge, the critical limit of 0.005 for D_s/D_o is being used across soil types, plant species and soil depths. We recommend further evaluation of critical oxygen diffusivity values for different conditions to be able to optimize the refined LLWR estimation.

Refined Lower Limit Approach

As mentioned above, difficulties arose in this study when using PR as a limiting factor for LLWR and especially for heavily compacted treatments. When 2 MPa was set as the critical value for the PR model, there was, in general, an acceptable degree of statistical confidence for the Control treatment, but there was poor or no statistical relationship between the variables, thus fitting was not achieved for the Traffic treatments (data not shown). The narrow range of water contents used in our study does not allow a confident estimation of the mathematical relationships between water content, PR, and water potential.

The lack of clear relationships between soil water content and PR appears to limit the integration of PR in the LLWR when working with limited data for compacted subsoil layers (Fig. 4). A relatively strong, linear, negative relationship between water content and PR has been found to be dependable on soil structural conditions because of the multiple changes that soil structure undergoes during cropping and farm traffic activities (Lapen et al., 2004). Our dataset shows that the PR slightly changed with drying within the range of water contents tested in the studied soils (Fig. 1). Scatter between soil water content and PR for the Aarslev site, could also be related to a pronounced

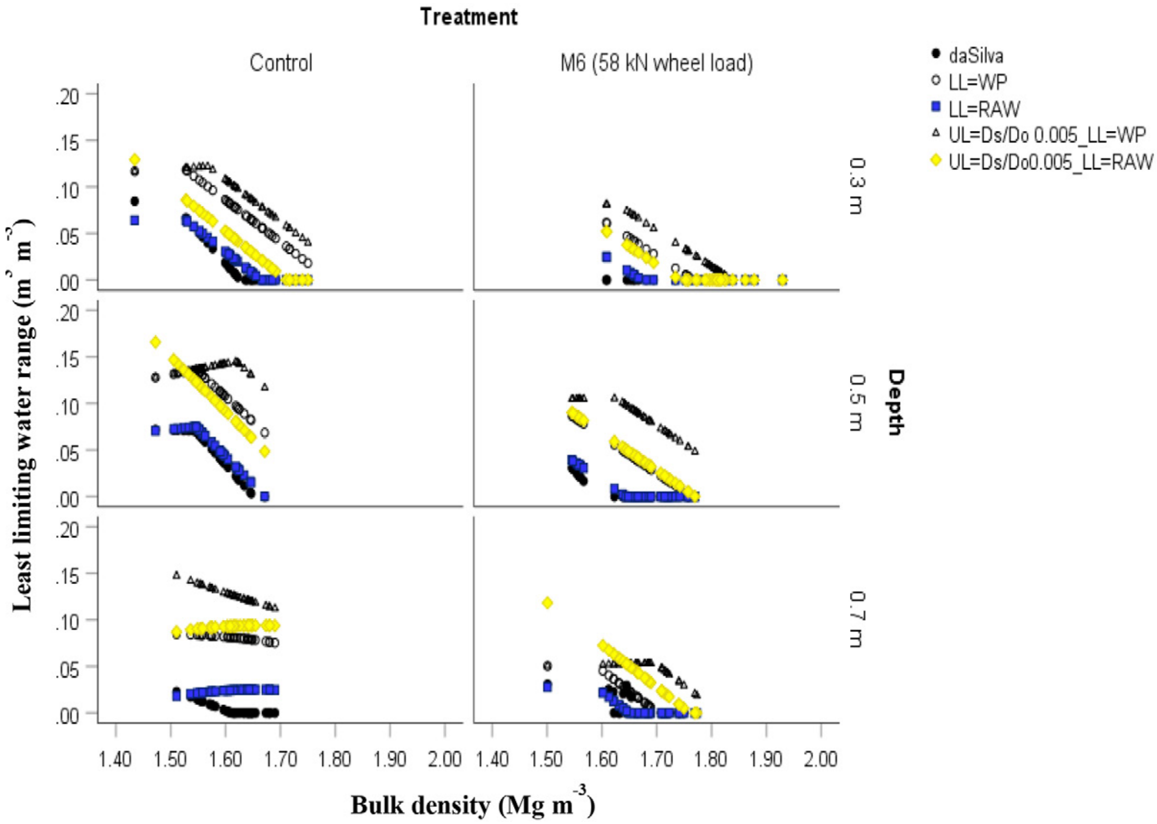

Fig. 6. Least limiting water range (LLWR) as a function of bulk density for the Control and M6 (58 kN wheel load) at the Taastrup site at 0.3, 0.5 and 0.7 m depth. Each line in the graph represents different LLWR boundary approaches: (i) daSilva, upper limit (UL) was either field capacity at −100 hPa or air-filled porosity of 10%, and the lower limit (LL) either penetration resistance (PR) at 2.0 MPa or wilting point (WP) at 15000 hPa; (ii) LL = WP, from the daSilva approach, the LL was only defined by WP; (iii) LL = RAW, from the daSilva approach, the LL was only defined by critical moisture based on the definition of readily available water (RAW); (iv) UL = Ds/Do0.005_LL = WP, the UL was only defined by air-filled porosity at which gas diffusivity reached 0.005 (Ds/Do0.005) and the LL by WP; (v) UL = Ds/Do0.005_LL = RAW, the UL was only defined by Ds/Do0.005 and the LL by RAW.

textural variation across the experimental field especially at deep layers (Pulido-Moncada et al., 2019).

It is also noticeable that, especially at 0.3 m depth, PR was high (2–3 MPa) for both the Control and traffic stress treatments (M8 and M6) in wet conditions (−50 hPa matric potential). The Control treatment, which represents the best condition in the field, was already in a compacted state, with PR values at 0.3 m depth exceeding 2 MPa (at −100 hPa). The maximum PR values reached more than 3 MPa for the Control treatment at all depths at −100 hPa suggest that 3 MPa could be used as the critical value instead. This corresponds with other studies where compacted layers below 0.3 m depth showed PR values between 2 and 3 MPa (Arvidsson, 2001). When 3 MPa was set as the critical PR value, the θ_v line in the LLWR coincided with the θ_{WP} for the Control treatment in Fig. 3 and 4 (data not shown). Values of 3 MPa at −100 hPa were on average surpassed at ρ_b of 1.70 Mg m^{-3} for M8 and M6. Our results then agree with Håkansson and Lipiec (2000), who mentioned that the higher the degree of compactness, the lower is the tension at which penetration resistance becomes critical. Large PR values for subsoil were also reported in a study conducted in a loess soil, where root growth of oats ceased at PR values from 4.6 to 5.1 MPa at 0.25–0.60 m depth, whereas a lower critical PR limit (3.6 MPa) was found in the topsoil (Ehlers et al., 1983).

Importantly, it can be speculated that critical PR values will vary depending on the time of year that LLWR is estimated (Gregory et al., 2007). Additionally, variation in PR with soil depth and time and its effect on root length might be negligible when biopores, cracks or vertical macropores are present because these are pathways with non-restricting strength (Ehlers et al., 1983; McKenzie and McBratney, 2001).

The use of WP as one of the lower limits for LLWR also appears to be theoretically inaccurate, because this water content represents the ultimate dry limit (van Lier and Gubiani, 2015). The RAW approach proposed by Silva et al. (2015) instead is more appropriate because it represents a critical limit where significant drought stress is expected to occur. The increase in θ_{RAW} after the impact of heavy farm machinery evidences a reduction in water availability in compacted subsoil layers (Fig. 2 and 3). In a study conducted on a clayey soil, the use of RAW on the LLWR showed an increase in water retention with increasing ρ_b but a decrease in plant available water (Silva et al., 2015). In our sandy loam soils, the opposite trend with increasing ρ_b was observed for the Aarslev site, but for the Taastrup site, no trend was established. When using θ_{RAW} as the lower limit, θ_{PR} must be $>\theta_{RAW}$ to be considered as the lower limit factor.

Further Considerations for Estimation of Limiting Water Range

Validation of the proposed LLWR approach for compacted subsoils by combining soil physical and plant growth measurement is needed. McKenzie and McBratney (2001) suggested that the ability of roots to exploit the soil volume through vertical pores or other pathways should be taken into account in the LLWR estimation. Previous studies have demonstrated that (vertical) biopores are less affected by compaction caused by heavy traffic (Schäffer et al., 2007; Schäffer et al., 2008), and therefore are important for air flow in compacted subsoil layers (Schjønning et al., 2019). The results from Schjønning et al. (2019) and Pulido-Moncada et al. (2019) for Aarslev site showed the importance of vertical pores for air flow in compacted subsoils from the data relationship between gas diffusion, air permeability and water retention.

Other studies have attempted to include the use of physiological parameters in the calculation of the LLWR boundaries (Mohammadi et al., 2010; van Lier and Gubiani, 2015). The integration of physiological parameters into the limiting factors is desirable, but the required physiological data is not readily available for many studies. Instead, the variation in water stress during a growing season appears to be a factor to be taken into account to extrapolate effects on crop growth. Benjamin et al. (2003) proposed the term 'water stress day', calculated from LLWR and in-season water dynamics, to account for the amount of water stress that the plant undergoes during the growing season. Crop growth and/or water stress indicators have a better correlation with yield than the original LLWR concept (Benjamin et al., 2003; Cecagno et al., 2016). Finally, further efforts are needed to explore PR limits for subsoils within water ranges where roots can develop and preserve their functionality.

CONCLUSION

Our results confirmed the hypothesis that heavy traffic induced soil compaction narrows the LLWR in the subsoil. Compaction narrowed the refined LLWR at both sites down to 0.7 m depth.

When using the ε_a at which 0.005 of D_s/D_o is reached as the upper limit for the Taastrup soil, a wider LLWR span was estimated in compacted subsoils as compared to the traditional approach using ε_a = 10% (v/v) as the critical limit. Thus, the compacted subsoil layers with a low ε_a maintained well-connected pores that contributed to air diffusivity. When using readily available water content as lower limit, compaction reduced water availability. The readily available water content marks a limit at which significant drought stress occurs as opposed to using the wilting point where ultimate drought stress occurs, as the lower limit. Further studies involving different type of soils and root growth parameters are needed to validate the use of the refined LLWR evaluated in this study.

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