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The effect of soil moisture deficit on the susceptibility of soil to compaction as a result of vehicle traffic

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Abstract.

Soil compaction negatively affects soil productivity, fertilizer use efficiency and water infiltration. The extent of compaction is dependant on soil strength, which is influenced by the soil moisture content. The purpose of this study was to determine the extent of soil compaction (measured by changes in soil bulk density and shear strength) and soil deformation incurred due to a single pass of a tractor and a fully loaded slurry tanker over grassland soils at a range of soil moisture deficits (SMD). The study should identify threshold values of SMD at which adverse soil compaction becomes significant for the soil-crop system. These values may be incorporated into the forecasting and decision making process for slurry spreading. SMD was used as a proxy for volumetric water content. Treatments of a single pass by a Landini Vision 105 tractor and a loaded 7.2 m^3 single axle slurry tanker (total weight of c. 18 tonnes) were conducted on well, moderate and poorly drained grassland soils at forecasted SMD of 0, 5, 10 and 20 mm. The moderately drained soil was classified as a loam, while the well and poorly drained sites were classified as sandy loams. Changes in soil bulk density and torsional shear strength were used as indicators of compaction, with rut profile measurements taken to measure the extent of surface deformation, which is often the most visible indicator of compaction on the soil surface. Grass yields were measured at 30 and 60 days subsequent to trafficking. Results showed that SMD at the time of traffic had an effect on the changes in bulk density, shear strength and the extent of soil rutting following wheel traffic. Preliminary results indicate that higher SMD at the time of trafficking resulted in smaller changes to soil characteristics and more rapid recovery from surface deformation than when trafficking occurred at lower SMD. Trafficking at an SMD of 20 mm led to mean increases in soil bulk density of 8% and formation of ruts with cross sectional areas in the range of 29.4 cm² to 98.3 cm². Trafficking at 0 SMD (field capacity) led to mean increases in bulk density of 15% and the formation of rut profiles in the range of 91.6 cm² to 197.9 cm². These preliminary results indicate that forecasted SMD provides a valuable tool to determine the suitability of the soil for supporting farm vehicle operations such as slurry spreading. This study is still ongoing, with more detailed results and analysis to be forthcoming.

Keywords. Compaction, traffic, soil moisture deficit, bulk density, shear strength, rut profile

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Introduction

Soil compaction is widely recognized as a threat to soil health and productivity (E.P.A., 2010; SOWAP, 2006), and is regarded as one of the eight threats to soil quality (E.P.A., 2010). Compaction is the increase in bulk density and reduction in pore space of a soil (Hillel, 1980) and it may occur both as a result of natural degradation processes within the soil, and as a result of human interaction (E.P.A., 2010). The Soil and Water Project (SOWAP) indicated that soil compaction is, along with erosion, the most significant threat to EU grasslands. Van Ouwerkerk and Soane (1994) suggested that approximately 33 million ha in Europe are affected by soil compaction, accounting for c. 24% of EU agricultural land at that time.

It is well documented that soil compaction impairs soil productivity and reduces crop yield (Ahmad, 2006; Cook et al., 1996; Dawkins et al., 1984; Drewry et al., 2001; Frame and Merrilees, 1990; Frost, 1988; Mamman et al., 2007; Masle and Passioura, 1992; Negi et al., 1981). It results in increased soil penetration resistance which restricts root growth (Taylor et al., 1981), reduced nutrient uptake by crop roots (McCoy, 1987), and impaired drainage which can lead to prolonged saturation of the soil (Brady and Weil, 1999). Furthermore, increased soil bulk density leads to a greater draft requirement when tilling the soil, hence greater fuel consumption and reduced efficiency (Rafiee and Jafari, 2010; Voorhees and Walker, 1977).

Soil strength is the ability of a soil to withstand forces exerted upon it without undergoing deformation (Brady and Weil, 1999), and it is strongly influenced by the soil moisture content (Earl, 1996). As soil moisture content increases, soil strength decreases, due to reduced frictional forces between soil particles (Collins et al., 1986/2004). Although moisture content is known to determine the susceptibility of a soil to compaction (Atterberg, 1911; Hanson, 1996; Meek et al., 1992; Sridharan and Nagaraj, 2005), it is a poor diagnostic tool for in-situ decision making, due to the vast array of data required to accurately predict a soil’s volumetric water content (Earl, 1996; Herbin et al., 2011). Therefore, it is preferable to use an easily predictable proxy for actual moisture content such as the hybrid soil moisture deficit (SMD) model developed by Schulte et al. (2005). SMD refers to the quantity of water required to bring the soil to field capacity, hence, SMD equates to 0 when the soil is at field capacity. SMD does not strictly equate to volumetric moisture contents, but rather it is a theoretical state of soil wetness relative to field capacity. The main advantages of the hybrid SMD model are; it has relatively low data input requirements when compared to other models (Schulte et al., 2005), it allows SMD to be forecasted, thus enabling better planning of grazing and farm operations (Fitzgerald et al., 2008; Herbin et al., 2011; Piwowarczyk et al., 2011; Premrov et al., 2010), and it is calibrated for three drainage classes, which are easily identifiable by land managers, using visual assessment.

The hybrid model is based upon the following equation:

$$SMD_t = SMD_{t-1} - Rain + ET_a + Drain$$

Where:

- SMD = soil moisture deficit on day t,
- SMD_{t-1} = soil moisture deficits on day $t-1$,
- $Rain$ = precipitation in millimetres,
- ET_a = daily actual evapotranspiration in millimetres,
- $Drain$ = quantity of water in millimetres per day removed by overland flow or percolation through the soil.

The three drainage classes used by this model are identified according to their ability to return to field capacity following precipitation. The hybrid model integrates characteristics of the model designed by Brereton et al. (1996), which predicts SMD for well drained soils, and the Met Eireann model (Keane, 2001), which was developed for poorly drained soils. The objective of this study was to determine the relationship between soil moisture deficit and the extent of compaction exhibited by a range of soils with different drainage classes as a result of vehicle traffic for a range of soil drainage classes. The data produced by this study will contribute to a slurry spreading decision support system based on the hybrid SMD model.

Materials and methods

Site description

The study was conducted at Johnstown Castle Environmental Research Centre, Teagasc, Co. Wexford, Ireland, located at 52.292°N, 6.5°W. The tests were performed at three different sites comprising well, moderate and poorly drained soils. According to the British soil textural triangle the moderately drained soil is classified as a loam, while the well and poorly drained soils are sandy loams (Brady and Weil, 1999). The climate is classified as cool maritime, with a mean annual rainfall of 1002 mm and a mean temperature of 9.6ºC. The sites have been under perennial ryegrass pasture for three years. The experiment commenced in September 2011 and is ongoing.

Experimental design

The experiment utilized a complete randomized block design with eight treatments per site, replicated four times. As a result of the experimental design there were 32 plots per site, which were divided into four blocks. The dimensions of the plots were 4 m by 5 m. The treatments were forecst (on the day); SMD = 0, 5, 10 and 20 mm (field capacity to drier) each as part of a wetting and drying phase. Repeated measurement analysis of variance was conducted using the statistical package GenStat (14th edition). As the experiment is ongoing, the wetting phase has been excluded from the analysis presented in this paper.

SMD forecasts were calculated using the Schulte et al. (2005) model, and meteorological data supplied by Met Eireann. The target SMD values selected were 0, 5, 10 and 20 mm. Wetting and drying phases were defined as when the SMD had followed a trend of either wetting or drying for at least three out of five previous days. On a day when a target SMD was forecast a single pass was made over the plots using a Landini Vision 105 tractor and a fully loaded 9092 litre single-axle Hi-Spec slurry tanker. The combined weight of the equipment was c. 18 tonnes. The combined weight of the equipment amounted to c. 18 tonnes. The tractor was equipped with radial tyres at an inflation pressure of 2 bars for the front tyres and 1.4 bars for the rear tyres. The slurry tanker was equipped with radial tyres (23.1R26), at an inflation pressure of 2.4 bars. The actual SMD was calculated on the subsequent day using meteorological observations, and recorded.

Measurements

Soil bulk density (SBD) and shear strength were selected as measures of soil compaction. SBD is commonly used as a measure of compaction (Hakansson and Lipiec, 2000). Rut profiles were also measured to quantify the extent of soil surface deformation, which is often one of the most significant indicators of soil compaction (Adam and Erbach, 1995; Botta et al., 2009; Soane, 1980). Grass yield was calculated as kg [DM] ha^{-1} to determine the yield penalty incurred as a result of vehicle traffic.

Prior to trafficking, the grass was cut to 40 mm with a lawnmower. Ten shear vane and four SBD measurements were taken across each plots. Subsequent to trafficking, ten shear vane measurements were taken both within, and outside of the wheel rut and four bulk densities were taken within and outside of the wheel-rut. Two rut profile measurements were taken from each wheel rut. Soil bulk density was determined for the upper 40 mm of the soil using a 40 mm diameter bulk density ring. Soil bulk density tests were conducted in accordance with USDA (1999).

Shear strength was measured using a Geonor shear vane. This test was conducted in accordance with ASTM D2573 (2008). Measurements were taken using the 20 mm by 40 mm bladed vane, to a depth of 0-50 mm, as shown in Figure 1.

Figure 1: Geonor shear vane used for shear strength measurements

Rut profiles were measured using a rut-profile meter. This device consists of 37 pins (spaced 12 mm apart) in an H-frame which was placed across the wheel track at a right angle, allowing the pins to drop to the rut surface. To allow fast and accurate field measurements, the profile meter was subsequently placed on a laminated sheet of graph paper and photographed. The area of deformation could subsequently be calculated by measuring the length of the pins and applying the offset method equation. This system allowed for reliable measurements to be made, even in adverse weather conditions. Furthermore, this method allows the operator to calculate the rut area using the images at a later date, thus reducing the time spent in the field.

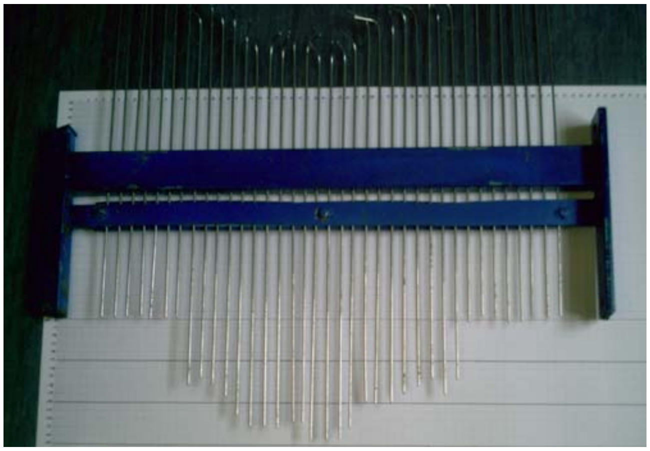


Figure 2: Rut profile meter and measurement chart

All measurements were repeated at 30 and 60 days subsequent to trafficking, which allowed the response of the soil and its natural alleviation of compaction over time to be quantified. At these intervals, grass yield measurements were also taken within and outside of the wheel rut. This was performed in accordance with the guidelines described in the Teagasc Grazing Notebook (2009). After each yield sample was taken, the plots were cut again to a uniform height of 40 mm to encourage uniform grass re-growth across the whole area of the plot.

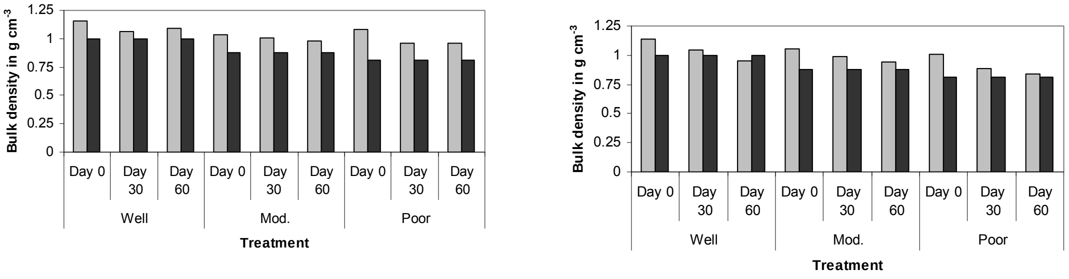
Proctor test (B.S.I., 1990) measurements were performed to identify the maximum level of compaction achievable on each soil following the specification outlined in BS 1377-4 (1990).

Results and discussion

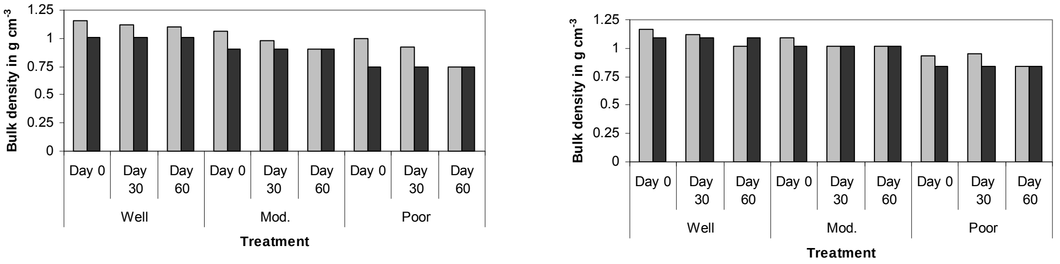
Soil bulk density (SBD)

For each of the soil types, SBD was found to increase significantly with vehicle trafficking (P<0.001) and this was inversely related to the soil moisture deficit. This was due to the greater volumetric soil moisture content at a lower SMD.

The SBD recorded for each treatment, at days 0, 30 and 60 subsequent to trafficking (Figure 3) showed that SBD decreased over time subsequent to trafficking. The decrease in bulk density was found to be significantly linked to the SMD at the time of trafficking, i.e.; when the soil was trafficked at a lower SMD, the level of alleviation of bulk density was lesser than when trafficking occurred at a higher SMD. This suggests that soil compaction occurring as a result of trafficking at low SMD is more persistent than that occurring at a greater SMD. The changes in bulk density in the non-wheel tracked area were not significant, and so have been excluded from the graphs.


(a) SMD 0

(b) SMD 10


(c) SMD 5

(d) SMD 20

Figures 3: Changes in soil bulk density recorded at 0, 30 and 60 days post-trafficking for the well, moderately and poorly drained soils at a 0 (a), 5 (b), 10 (c) and 20 (d) SMD in a drying phase. Grey = Wheel Rut SBD, Black = Pre-traffic SBD.

(LSD = 0.048, n = 16, P < 0.001)

The values of SBD observed in this study, although low, were in line with those reported by Kiely et al. (2009), who demonstrated that Irish grassland soils typically display bulk densities ranging between 0.80 g/cm³ and 1.00 g/cm³ in the top 0-100 mm of soil, Lalor (2004) and Herbin et al. (2011).

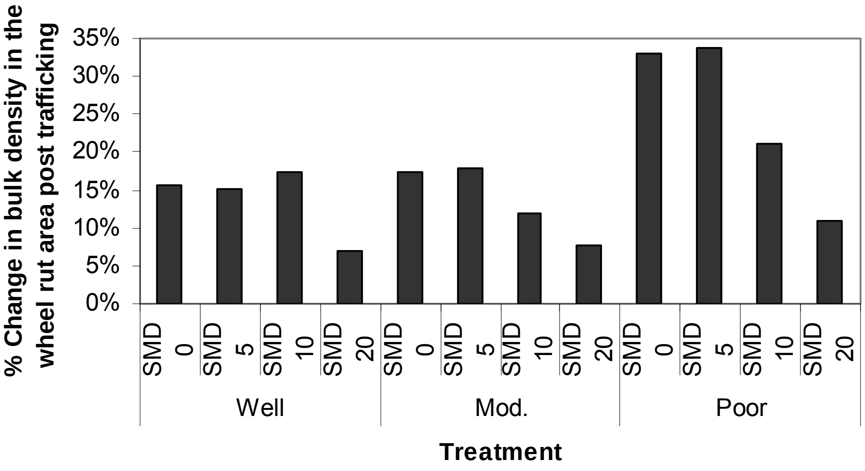


Figure 4: Changes in bulk density in the wheel rut post trafficking, as a percentage of the initial bulk density

Fig. 4 shows the percentage change in SBD exhibited in the wheel rut immediately subsequent to trafficking compared to the pre-traffic values. It is clear from this graph that the compaction undergone by the poorly drained soil at a given SMD was far greater than that on the well or moderately drained soils, at the same SMD. This was due to the greater volumetric moisture content of the poorly drained soil. Consequently, it seems likely that a different threshold SMD for safe slurry spreading must be determined for each of the drainage classes.

The results of this experiment are consistent with many papers demonstrating the relationship between soil water content and vulnerability to compaction. Studies by Proctor (1933), Défossez et al (2003), Berli et al (2003), Adam and Erbach (1995) and McNabb et al. (2001) are amongst many others describing this relationship.

Shear strength

Shear strength was found to increase significantly with trafficking, (P<0.001) (Fig. 5). However, there were some difficulties in using shear strength as a measure of soil compaction. As the volumetric moisture content changed between day 0 and day 30, the value of shear strength recorded also varied as a result. Furthermore, the SMD model is strictly a theoretical model, meaning that each SMD value does not equate with a particular soil moisture content. For example, depending on the rainfall pattern it is possible that an SMD equivalent to 20 mm may have greater volumetric moisture content that SMD value of 10. This creates some difficulties in interpreting the shear vane results. Further results and analysis of these measurements shall be forthcoming in a later paper.

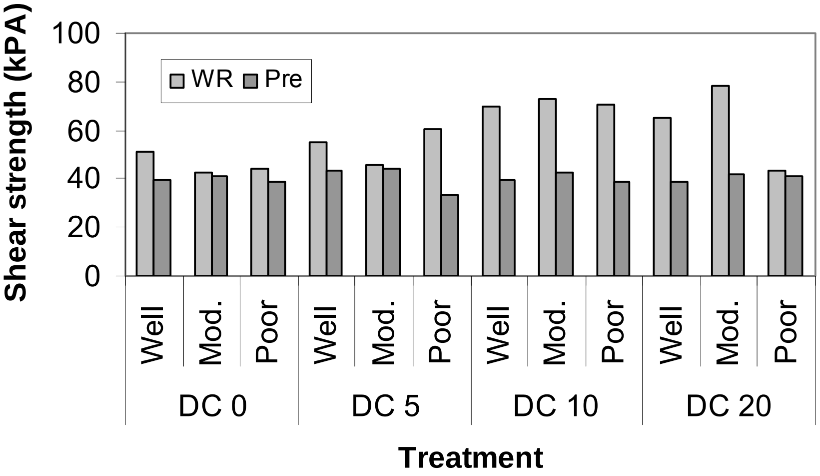


Figure 5: Changes in shear strength in the wheel rut (WR) subsequent to trafficking compared with shear strength measured immediately pre-trafficking (Pre); LSD = 3.953, n = 64, P<0.001

Rut profiles

It was found that the area displaced by the wheel rut increased significantly with decreasing SMD at the time of trafficking ($P<0.001$) (Figure 6). When trafficking occurred at low SMD (0 mm and 5 mm), the rate of recovery of the soil was lesser than when trafficking occurred at higher SMD. Bakker and Davis (1995) observed that even in incidences where the increases in bulk density were minimal, significant displacement of the soil could occur in the form of rutting due to wheel traffic. The results are consistent with those of Godwin et al. (1991), which showed that depth of wheel rutting was closely related to herbage yield loss.

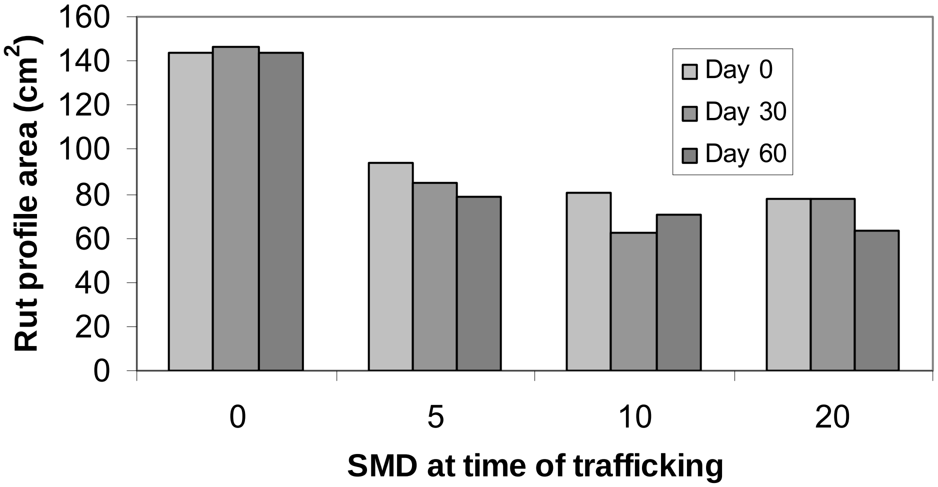


Figure 6: Rut profiles over time, averaged across all soils; LSD = 29.18, n = 16, P<0.001

Dry matter yield (DMY)

This study found that a significant loss in yield occurred within the wheel rut as a result of a single trafficking event ($P<0.001$) (Figure 7). DMY at 30 days subsequent to trafficking was found to decrease by between 30% and 59% when compared to the non-wheel tracked area. These values are in line with those observed by Cook et al (1996), Frost (1988) and Frame and Merrilees (1990). These losses represent significant costs to the farmer in terms of an impaired potential for grazing on land suffering from compaction.

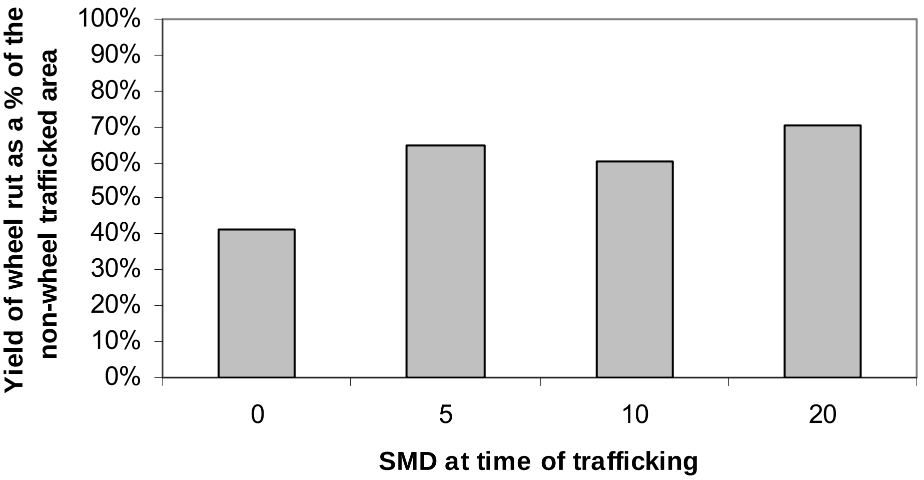


Figure 7: Herbage dry matter in the wheel rut as a % of the yield of the non-wheel tracked area, averaged across all soils; LSD = 172.02, n= 8, P<0.001

Conclusion

Soil moisture deficit, as a proxy for volumetric water content, was shown to have a significant effect on the response of a soil to vehicle traffic. In order to incorporate the SMD prediction model into a farm scale decision support system, threshold values need to be determined for safe slurry spreading. While a value of 10 SMD was proposed by in earlier work (Earl, 1996) as a trafficable limit, this study found a significant natural alleviation of soil compaction within 60 days when trafficked at this point, but with some impact on herbage availability for grazing following spreading. Until the experiment has been completed it will not be possible to draw firm conclusions about the most appropriate limit for each drainage class. Due to variability in the volumetric moisture content between the drainage classes at a given SMD, different threshold values are likely to be determined for each class. It is suggested that the soil moisture deficit model (Schulte et al., 2005) used in this study is a suitable basis for a slurry spreading decision support system, in which vulnerability to soil compaction would be an important parameter.

The results depicted here are for SMD values in a drying phase. Data collection is still ongoing for values on a wetting phase. It is expected that the response of the soil to vehicle traffic may differ between the wetting and drying phases, even when trafficking takes place at the same SMD. Overall results and conclusions will be published at a later date, upon completion of the experiment.

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