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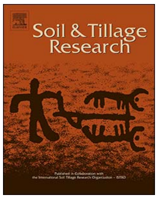

Research paper

Influence of soil moisture content on assessment of bulk density with combined frequency domain reflectometry and visible and near infrared spectroscopy under semi field conditions

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ABSTRACT

The potential of combining frequency domain reflectometry (FDR) and visible and near infrared spectroscopy (vis-NIRS) was shown to successfully assess soil bulk density (BD). However, the accuracy of both sensing tools was reported to be influenced by the soil moisture content (MC). The aim of the paper is to evaluate the influence of soil MC level on accuracy of BD assessment under semi field conditions by the combination of FDR and vis-NIRS data. Measurements of volumetric moisture content (θv) in the field and gravimetric moisture content (ω) in the laboratory using a FDR and a vis-NIRS (350–2500 nm) techniques were conducted in five arable fields of different soil texture classes in Silsoe, Bedfordshire, UK. In order to account for different MC levels, three measurement campaigns were carried out during the period from July 2011 to October 2012, where a total of 300 soil samples were used, representing three natural MC levels of low (L1), medium (L2) and high (L3). L1, L2 and L3 datasets were subjected to artificial neural network (ANN) analysis to predict ω and θv based on fusion of vis-NIRS spectra and FDR output voltage, and subsequently the predicted values were substituted into a model to assess BD.

Results showed that MC has large influence on both the vis-NIRS and FDR sensors for measuring ω and θv, respectively. The accuracy of BD assessment improved with soil MC increase, with root mean square error of prediction (RMSEp) values of 0.079, 0.072 and 0.061 g cm^{-3}, for average ω of 0.106 (L1), 0.197 (L2) and 0.28 (L3) g g^{-1}, respectively. The accuracy of θv measurement with the FDR depended on ensuring good contact with the soil, which is not the case for dry soil conditions, at which accuracy of θv measurement and BD assessment was deteriorated. It is recommended to set an optimal MC range (depending of soil texture), over which precise soil BD estimation can be certain.

1. Introduction

Soil compaction is a critical problem in agricultural soils that has negative agronomic and environmental influences (Hamza and Anderson, 2005). The former problem is associated with poor crop growth and yield, whereas the latter is linked to poor hydraulic properties of soils, and high risk to flooding, soil erosion and degradation. Understanding therefore how and to what extent soil compaction may be eliminated seems of vital importance to the future wellbeing of agricultural systems. Land management is the key factor for this target, where a quantitative and realistic measuring system of soil compaction is one of the successful tools that can be used to generate maps of compacted areas, to enable the identification of management actions that could be deployed to solve the problem. Due to the complex nature of agricultural soils, it has been difficult to characterise soil compaction rapidly, easily and cost effectively (Aragón et al., 2000; Horn et al., 2000; Mouazen and Ramon, 2006), which has hindered the study of soil compaction and its consequent remediation.

Apart from penetration resistance, one of the main parameters to quantify soil compaction is bulk density (BD), which is widely used (Grossman, 1981; Bardy, 1984; Singh et al., 1992). Although penetration resistance is easy to use, it is not the best parameter to adopt for compaction estimation, since it is affected simultaneously by BD, moisture content, organic matter (OM) and texture. The most common, traditional method for BD measurement is the core sampling method (e.g. Kopecki ring), which is laborious, time consuming, expensive difficult to conduct and prone to error particularly under dry soil conditions (Quraishi and Mouazen, 2013a). However, although BD

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Table 1
Detailed information about the five experimental fields in Silsoe experimental farm, where soil samples were collected at low (L1), medium (L2) and high (L3) moisture content, during 2011 and 2012.

Fields	Soil texture	Clay, %	Silt,%	Sand,%	OM,%	L1		L2		L3	
						Crop	SN	Crop	SN	Crop	SN
Avenue	Sandy loam	16	20	63	3.6	Wheat	20	Barely	20	AH	20
Beechwood	Clay	66	11	23	5.8	Beans	20	Wheat	20	AH	20
Clover hill	Clay loam	35	24	41	4.8	Wheat	20	Beans	20	AH	20
Orchard	Clay loam	33	26	41	4.15	Barley	20	Wheat	20	Bean	20
Showground	Sandy clay loam	24	17	59	3.34	Wheat	20	Barley	20	AH	20

SN is sample number; OM is soil organic matter content; AH is after harvest of previous crop.

might be considered as an indicator of soil compaction, it does not necessarily indicate changes in soil function, for example, air and water movement (Quraishi and Mouazen, 2013b). Other parameters such as saturated hydraulic conductivity and infiltration rate are more closely related to soil compaction (Fleige and Horn, 2000). In comparison with the latter parameters, assessment of BD with a portable measurement system is possible (Quraishi and Mouazen, 2013c; Al-Asadi and Mouazen, 2014) and enables faster, easier, and more cost effective data acquisition, which is particularly useful for precision management of soil compaction.

Apart from the Kopecki ring method to measure BD, gamma ray attenuation, thermo-TDR and combined sensor approaches were introduced. An early study by Wells and Luo (1992) reported a successful measurement of BD by gamma ray attenuation under field conditions. More recently, Lahham et al. (2017) used gamma ray spectroscopy with a NaI(T1) scintillation detector to measure soil BD in the field, reporting a very good measurement accuracy with an error range of 0.5 and 6%, which was attributed to soil surface roughness. However, in addition to the negative influence of the radioactive energy source on human health, the volume covered by this method is large. Liu et al. (2008) implemented a thermo-time domain reflectometry (thermo-TDR) for measurement of BD, reporting 5% and 10% relative error under laboratory and field measurement conditions, respectively. However, the triple probe used needed to be horizontally inserted in the soil profile to acquire data at particular depth, which requires additional preparation of the soil profile before measurement. Recent approaches based on multi-sensor and data fusion were introduced for off-line (Quraishi and Mouazen, 2013c; Al-Asadi and Mouazen, 2014) and on-line (Mouazen and Ramon, 2006; Naderi-Boldaji et al., 2013; Quraishi and Mouazen, 2013b) measurements. Naderi-Boldaji et al. (2016) have reported a new concept for on-line measurement of soil relative density. Shamal et al. (2016) achieved successful on-line measurement of soil packing density (PD) based on an on-line multi-sensor platform (Mouazen, 2006), where the effect of soil texture was accounted for in a model ($PD = f$ (BD, clay content) to calculate PD.

A new multi-sensor kit based on portable penetrometers equipped with a load cell to measure soil penetration resistance, near infrared spectroscopy (NIRS) to measure key soil properties including gravimetric moisture content (ω) and frequency domain reflectometry (FDR) to measure volumetric moisture content (θv) was introduced (Al-Asadi, 2015). Al-Asadi and Mouazen (2014) reported successful measurement of soil BD by combination of visible and near infrared spectroscopy (vis-NIRS) and FDR to measure ω and θv, respectively. However, previous work confirmed that both vis-NIRS (Chang et al., 2005; Stenberg, 2010; Tekin et al., 2012) and FDR (Fernández-Gálvez, 2008) are influenced by soil moisture content (MC), which in turn can affect the accuracy of BD assessment by means of combined FDR and vis-NIRS data. Therefore, it is essential to quantify the effect of MC on the measurement of both ω and θv with NIRS and FDR, respectively, and to propose an optimal moisture conditions for field measurement of BD, which was not investigated earlier by Al-Asadi and Mouazen (2014).

The aim of this paper is to evaluate the influence of the soil MC level on the prediction accuracy of vis-NIRS to measure ω and a FDR sensor to measure θv and consequently BD assessment obtained from the combination of both sensors' data. The final target is to determine the optimal moisture conditions, at which the highest accuracy of BD estimation is foreseen.

2. Materials and methods

The effect of soil MC on the prediction accuracy of θv and ω with FDR and vis-NIRS techniques, respectively, and on BD assessment was studied under semi field measurement conditions. While θv measurement was carried out in the field in the natural position of the soil, measurement of ω was carried out in the laboratory. Results were validated by laboratory measurement of θv, ω and BD using the standard oven drying method.

2.1. Study sites

Field measurements were carried out in five fields with arable crop production (Table 1), during different seasons (representing naturally varied MC levels). These five fields were located in Silsoe, Bedofordshire, UK and were also used together with other 27 fields by Al-Asadi and Mouazen (2014). Three field measurement campaigns were carried out within the period from July 2011 to October 2012. Samples in the second and third visits were collected from nearby locations of samples collected in the first visit, assisted by a global positioning system (GPS). A total of 300 soil samples were collected from the three experimental visits at 10–20 cm depth using kopecki rings, with 100 samples from each visit (e.g., 20 samples per field per visit). The following three average levels (L) of soil MC were obtained during the three field measurement campaigns, after oven drying of samples (Table 2):

- Low (L1) with averages of 0.106 g g^{-1} and 0.147 cm^3 cm^{-3} ω and

Table 2
Sample statistics of the laboratory analysis of three moisture content levels of low (L1), medium (L2) and high (L3), used for the artificial neural network (ANN) analyses.

	Item	Level	Minimum	Maximum	Average	SD	Range
θv		L 1	0.080	0.222	0.147	0.044	0.142
	θv	L 2	0.130	0.410	0.231	0.079	0.28
		L 3	0.136	0.512	0.320	0.137	0.376
		Collective	0.080	0.512	0.236	0.121	0.432
ω		L 1	0.062	0.145	0.106	0.026	0.083
	ω	L 2	0.114	0.394	0.197	0.086	0.28
		L 3	0.120	0.440	0.28	0.135	0.32
		Collective	0.062	0.440	0.188	0.113	0.378
BD		L1	1.092	1.671	1.364	0.122	0.579
	BD	L2	0.913	1.423	1.215	0.130	0.51
		L3	0.879	1.529	1.195	0.159	0.65
		Collective	0.879	1.671	1.304	0.130	0.796

SD is standard deviation; θv is volumetric moisture content (cm^3 cm^{-3}); ω is gravimetric moisture content (g g^{-1}); BD is soil bulk density (g cm^{-3}).