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Combining frequency domain reflectometry and visible and near infrared spectroscopy for assessment of soil bulk density

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ABSTRACT

This paper introduces a new approach for the assessment of soil bulk density (BD), which relies on an existed model to predict BD as a function of a visible and near infrared spectroscopy (vis-NIRS) measured gravimetric moisture content (ω) and a frequency domain reflectometry (FDR) measured volumetric moisture content (θv). A total of 1013 soil samples collected from England and Wales, from 32 arable and grassland fields with different soil types were measured with a vis-NIR spectrophotometer (LabSpec®Pro Near Infrared Analyzer, Analytical Spectral Devices, Inc., USA) after in situ measurement with a ThetaProbe FDR (Delta-T Device Ltd.). Two calibration methods of the vis-NIRS were tested, namely, partial least squares regression (PLSR) and artificial neural network (ANN). ThetaProbe calibration was performed with traditional methods and ANN. ANN analyses were based on a single-variable input or multiple-variable input (data fusion). During ANN – data fusion analysis, vis-NIRS spectra and ThetaProbe output voltage (V) were fused in one matrix with or without laboratory measured texture fractions and organic matter content (OM). For the vis-NIRS and ThetaProbe traditional calibration, samples were divided into calibration (75%) and prediction (25%) sets, whereas for the ANN analyses these were divided into calibration (65%), test (10%) and independent validation (25%) sets. Results proved that high measurement accuracy can be obtained for ω and θv with PLSR and the best performing traditional calibration method of the ThetaProbe with R^2 values of 0.91 and 0.97, and root mean square error of prediction (RMSEp) values of 0.027 g g^{-1} and 0.019 cm^3 cm^{-3}, respectively. However, the ANN – data fusion resulted in improved accuracy (R^2 = 0.98 and RMSEp = 0.014 g g^{-1} and 0.015 cm^3 cm^{-3}, respectively). This data fusion approach led to the best accuracy for BD assessment when vis-NIRS spectra and ThetaProbe V only were used as input data (R^2 = 0.81 and RMSEp = 0.095 g cm^{-3}). It can be concluded that BD can be measured by combining the vis-NIRS and FDR techniques based on ANN-data fusion approach.

1. Introduction

Forest, arable and grasslands are important natural resources, which have been subjected to artificial and natural compression stresses through the ages. Heavy agriculture machinery, intensive use of the arable lands and livestock impact on grasslands during the wet soil conditions, are among the major factors causing compression stresses, which lead to soil compaction [1]. Soil compaction is normally associated with damage of the soil structure, deterioration of physical and hydraulic properties and creation of unfavourable conditions for plant root system. Compacted soils demand large amount of fertilisers, in order to substitute the small volume available for plant roots, which might cause contamination hazardous of the ground water by the deep percolation or the run off to the surface water [2]. Highly compacted soils can be considerably of low productivity and require more mechanical power for soil preparation. Among other parameters used to assess soil compaction, bulk density (BD) that is the closer packing of solid particles or the reduction in porosity is a widely used parameter [3–6]. However, BD might be considered as a sing of soil compaction, as it does not necessarily reflect soil functioning (e.g. air and water movement) [7]. Other parameters e.g. saturated hydraulic conductivity and infiltration rate are more closely related to soil compaction [8], as compared to BD. However, in comparison with the former parameters, assessment of BD with a portable system is possible [7] and enables faster, easier and more cost effective data acquisition, which is particularly useful for precision agriculture applications.

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Table 1
Detailed information of experimental fields, where soil samples were collected from the top layer of 10–20 cm during 2011 and 2012.

Fields	Samples No.	Soil texture	Clay %	Silt %	Sand %	OM %	Land use
Avenue, Silsoe	45	Sandy loam	16	20	63	3.60	Arable land
Avenue, Silsoe	40	Sandy loam	29	19	51	2.98	Grassland
Beechwood, Silsoe	40	Clay	66	11	23	5.80	Arable land
Chilpolea, Silsoe	20	Loam	21	30	49	2.50	Arable land
Clover Hill, Silsoe	20	Clay loam	35	24	41	4.80	Arable land
Copse, Silsoe	40	Clay loam	38	26	36	4.83	Arable land
Dowings, Silsoe	20	Sandy clay loam	28	19	53	4.10	Arable land
Far Warden, Silsoe	20	Clay	59	27	14	5.10	Arable land
Ive, Silsoe	40	Clay	53	19	28	2.96	Arable land
Middle field, Silsoe	20	Clay	55	25	15	4.65	Arable land
Mound, Silsoe	38	Sandy loam	16	21	63	3.50	Arable land
Near Warden, Silsoe	20	Clay	54	25	16	5.53	Arable land
Onley, Silsoe	20	Clay	60	30	10	5.40	Grassland
Orchard, Silsoe	20	Clay loam	33	26	41	4.15	Arable land
Showground, Silsoe	40	Sandy clay loam	24	17	59	3.34	Arable land
Upbury, Silsoe	20	Clay	54	24	22	4.50	Arable land
Field 1, Wilstead	32	Clay loam	32	27	40	3.45	Arable land
Field 2, Wilstead	20	Clay	47	38	15	3.80	Arable land
Field 3, Wilstead	20	Clay	48	31	15	5.30	Arable land
10 Acres, Wilstead	20	Clay	50	28	22	3.50	Arable land
Howne sand, Wilstead	53	Sandy loam	14	18	68	3.30	Arable land
Runway, Wilstead	60	Clay loam	35	25	40	4.20	Grassland
Barn right, Wilstead	60	Clay loam	30	30	40	3.60	Arable land
Barn left, Wilstead	25	Loam	18	35	47	3.50	Arable land
Gayhurset	25	Clay	44	35	21	5.40	Grassland
Haversham	34	Clay loam	37	27	36	4.60	Grassland
Flawborough	20	Clay	51	33	15	7.20	Grassland
Flawborough	20	Clay	51	35	14	5.40	Arable land
Morpeth	47	Clay	52	22	26	7.08	Arable land
Morpeth	45	Clay	55	23	22	8.04	Grassland
Nafferton	28	Sandy loam	13	22	65	7.50	Grassland
Brecon, Wales	40	Silt loam	21	65	14	5.94	Grassland
Total	1013						

Texture is classified according to the United State Department of Agriculture (USDA) classes.
OM: Organic matter content in the soil.

The most common traditional method for BD measurement is the core sampling method (e.g. Kopecki ring), which is laborious, time consuming, expensive and difficult to conduct under dry soil conditions [9]. This is the reason why penetrometers to measure soil penetration resistance, known as cone index is widely used to map the variation in soil compaction with depth [10]. However, Mouazen and Ramon [11] explained that penetration resistance is simultaneously affected by moisture content, texture, BD and organic matter content (OM). Therefore, a new method to measure BD is required that should be fast, easy, cost effective and do not need an expert operator.

For years, visible and near infrared spectroscopy (vis-NIRS) has provided a proven and versatile analytical method for soil analyses [12–16]. It is fast measurement technique, non-destructive and cost effective [17]. It was successfully used to measure gravimetric moisture content (ω) under laboratory non-mobile measurement conditions [18–21] and on-line mobile conditions [17]. These successful applications were attributed to the strong influence of O-H bond on vis-NIR spectra of soils [16,22].

The measurement of dielectric constant (K) based on frequency domain reflectometry (FDR) is a popular technique for the measurement of soil volumetric moisture content (θv) [23–25]. This is due to the fact that K of the water (~80) is significantly greater than that of the dry soil matrix materials (~4) and of the air (~1). ThetaProbe [26] was reported to be capable to measure soil θv with ±0.01 $m^3\ m^{-3}$ accuracy after a single two-point gravimetric calibration, although, ±0.05 $m^3\ m^{-3}$ accuracy can be achieved when generalised calibration by the manufacturer is applied [27–30].

Multiple sensor and data fusion is being introduced as a new concept in proximal soil sensing [22]. Data fusion is an important tool that may improve the performance of a detecting system while various integrated sensors are available [31]. Despite the fact that this is a new concept, several studies were reported for non-mobile [9,32] and mobile [11,17,33–37] measurement conditions. Quraishi and Mouazen [9] reported a data fusion approach of BD assessment, based on the fusion of data on ω, OM and clay content (C), measured with a vis-NIR spectrophotometer and penetration resistance measured with a penetrometer. However, a large

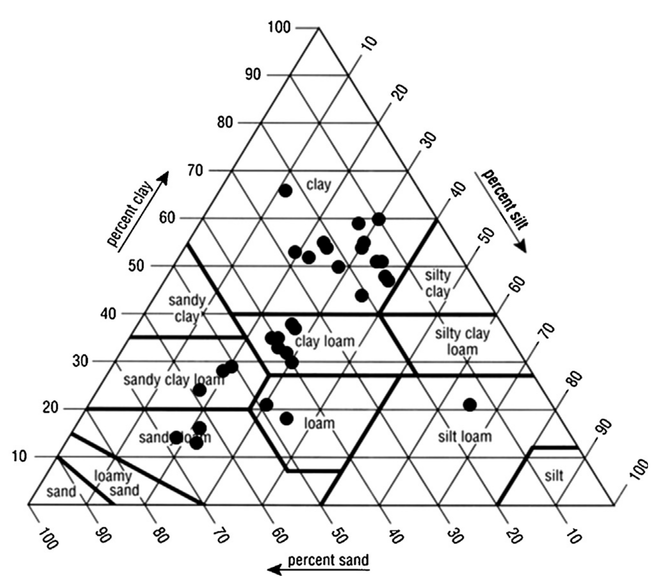

Fig. 1. Texture of study fields classified according to the United State Department of Agriculture (USDA) classification system.