Soil & Tillage Research 134 (2013) 97–110

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

A prototype sensor for the assessment of soil bulk density

Mohammed Z. Quraishi, Abdul M. Mouazen *

Environmental Science and Technology Department, Cranfield University, Bedfordshire MK43 0AL, United Kingdom

ARTICLE INFO

Article history:
Received 29 March 2013
Received in revised form 24 July 2013
Accepted 25 July 2013

Keywords:
Bulk density
Vis-NIR spectroscopy
In situ measurement
Penetrometer
Artificial neural network

ABSTRACT

A prototype bulk density sensor (PBDS) to assess soil bulk density (BD) has been developed and tested for top soil (0–15 cm). It is a multi-sensor kit, consisting of a penetrometer equipped with a visible and near-infrared (vis-NIR) spectrophotometer. Artificial neural network (ANN) was used to develop a BD prediction model, as a function of penetration resistance (PR), soil moisture content (MC), organic matter content (OMC) and clay content (CLC), using 471 samples collected from various fields across four European countries, namely, Czech Republic, Denmark, the Netherlands and the UK. While penetration resistance (PR) was measured with a standard penetrometer (30 degree cone of 1.26 cm^2 cone-base area), MC, OMC and CLC were predicted with a vis-NIR (1650–2500 nm) spectrophotometer (Avantes, Eerbeek, The Netherlands). ANN was also used to model the vis-NIR spectra to predict MC, OMC and CLC. The PBDS was validated by predicting topsoil (0–0.15 m) BD of three selected validation fields in Silsoe experimental farm, the UK.

The ANN BD model performed very well in training (coefficient of determination (R^2) = 0.92 and root mean square error (RMSE) = 0.05 Mg m^{-3}), validation (R^2 = 0.84 and RMSE = 0.08 Mg m^{-3}) and testing (R^2 = 0.94 and RMSE = 0.04 Mg m^{-3}). The validation of PBDS for BD assessment in the three validation fields provided high prediction accuracy, with the highest accuracy obtained in Downing field (R^2 = 0.95 and RMSE = 0.02 Mg m^{-3}). It can be concluded that the new prototype sensor to predict BD based on, a standard penetrometer equipped with a vis-NIR spectrophotometer and ANN model can be used for in situ assessment of BD. The PBDS can also be recommended to provide information about soil MC, OMC and CLC, as the ANN vis-NIR calibration models of these properties were of excellent performance.

1. Introduction

Soil strength is a dynamic property that changes with time and space under the influences of climate, soil management practices and plant growth (Koolen and Kuipers, 1983). Soil deformation following a single or multiple passes of heavy agriculture machinery results in soil compaction and structure deterioration, which leads to increase in soil strength, reduction in hydraulic conductivity and infiltration rate, and poor root penetration and plant growth (Franzen et al., 1994; Quraishi and Mouazen, 2013a). Random traffic of heavy machinery during harvest also causes long lasting damage to the soil structure because of deep penetration of downward forces causing deep compaction (Ekwue and Stone, 1995). Deep compaction is difficult to ameliorate, since natural and biological activities are limited at deep soil horizons. Subsoiling is also of limited impact particularly if carried out under heavy and wet soil conditions. Due to the dynamic nature of the soil, soil strength is affected by soil moisture content (MC), organic matter content (OMC), degree of compaction and texture to name a few.

One of the properties to characterise soil compaction is BD (Mouazen and Ramon, 2002), which does not necessarily reflect soil function. Core sampling of a known volume of soil is utilised for the measurement of soil BD (British Standards, 2011), based on drying of the soil cylinder at 105 °C for 24 h. The disadvantageous of this method are that it is very difficult, labour intensive, time costly procedure and prone to measurement error, particularly under dry soil conditions (Mouazen and Ramon, 2006; Quraishi and Mouazen, 2013a). An innovative approach to assess BD based on a complex interrelationship between BD, MC, OMC, clay content (CLC) and penetration resistance (PR) was recently introduced by Quraishi and Mouazen (2013b). They used artificial neural network (ANN) to develop a model to assess BD as a function of PR, MC, OMC and CLC. This model enabled the assessment of BD based on traditional laboratory methods of soil analyses in addition to field measured PR (coefficient of determination (R^2) of 0.81 and root mean square error (RMSE) of 0.11 Mg m^{-3}). However, since soil samples had to be collected in the field where PR is measured, and transferred to the laboratory for the traditional analyses of OMC, MC and CLC, it was concluded that this method did not overcome

* Corresponding author. Tel.: +44 1234 750111; fax: +44 1234 752971.
E-mail addresses: a.mouazen@cranfield.ac.uk, mouazen2002@yahoo.com (A.M. Mouazen).

0167-1987/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.still.2013.07.011

the disadvantages of the core sampling method of being expensive, slow and labour intensive. Therefore, Quraishi and Mouazen (2013c) has replaced the traditionally measurement methods of MC, OMC and CLC with visible and near infrared (vis-NIR) spectroscopy. By substituting vis-NIR predicted values of MC, OMC and CLC into ANN BD prediction model, authors reported successful prediction of topsoil BD (R^2 of 0.80 and RMSE of 0.08 Mg m^{-3}). They confirmed that the proposed methodology is capable of overcoming the disadvantages of the traditional core sampling method of BD measurement, as vis-NIR spectroscopy enables cost effective and fast prediction of soil properties (Mouazen et al., 2005, 2007, 2009). At this stage, this new methodology requires the development of an instrumentation to enable in situ acquisition of multiple georeferenced data, including PR and vis-NIR spectra, to be fed as input data into models to predict BD, as a function of measured PR and vis-NIR predicted MC, OMC and CLC.

The aim of this paper was to design and validate a prototype BD sensor (PBDS), as a new tool for rapid, cost effective and in situ assessment of BD, as a function of measured PR, and vis-NIR predicted MC, OMC and CLC.

2. Materials and methods

2.1. Field measurement and soil sampling

Field measurement of topsoil (0–15 cm depth) PR and BD was carried out in summer of 2010, 2011 and 2012, in 19 fields across different Europe countries as shown in Table 1 (Quraishi and Mouazen, 2013a, 2013b, 2013c). Avenue, Orchard, Ivy ground, Beechwood, Clover hill, Upbury, Chipping and Downing fields are situated at Silsoe experimental farm, Cranfield University, the UK. Two fields were part of a Research Station for arable farming and field production of vegetables in Lelystad, The Netherlands. Two other fields were located at Wageningen University, Wageningen, The Netherlands. One field in Czech Republic and two fields in Denmark were measured in 2010 as part of FutureFarm FP7 project (http://www.futurefarm.eu/). Measurement at Odstone field in Leicestershire, the UK was carried out in a grassland field. Three fields were measured at Duckend Farm near Bedford in Bedfordshire, the UK. Fig. 1 and Table 1 show the texture classes of all fields used in this study.

Soil BD was measured using Kopecki ring core sampling kit, whereas PR measurement was carried out with Eijkelkamp penetrologger with a 30 degree cone of 1.26 cm^2 cone-base area (Eijkelkamp, 2009) in 2010 and 2011. In 2012, PR was measured using a new prototype penetrometer designed in this study, which is explained below. The number of samples collected from each field varied, depending on the size of the field, but ranged from 4 to 48 (Table 1). At each sampling point, three PR measurements, one bulk soil sample and one BD core sample were collected. The PR measurement was carried out within half a metre distance from the BD core sample location, ensuring that both measurements were taken either in or outside a wheel rut. The PR readings were averaged in one reading (Quraishi and Mouazen, 2013b). A total of 408 bulk soil samples and BD core samples were collected in 2010 and 2011. These samples were used to develop a general calibration model to predict BD. Three additional field measurements were carried out in 2012 to validate the measurement accuracy of PBDS using the general calibration model. These fields were Ivy Ground, Chipping and Downing (Table 1), all in Silsoe experimental farm. In total, 87 samples were collected from these three fields using the PBDS. Out of the 87 locations, BD was measured at 63 sampling points only using a Kopecki ring kit.

2.2. Prototype bulk density sensor (PBDS)

The PBDS was designed and developed to predict multiple soil properties in addition to BD. It consists of a rod and cone assembly connected to a load cell, which has a maximum load of 1000 N. A 50 channel global positioning system (GPS) was used to record the sampling location. The 30 degree, 1.26 cm^2 base-area cone connected to the rod were assembled with a fibre type standalone vis-NIR spectrophotometer (1650–2500 nm) (Avantes, Eerbeek,

Table 1
Information about test fields, where measurement took place in 2010, 2011 and 2012 (Modified from Quraishi and Mouazen, 2013b).

Field	Number of soil samples	Crop	Area (ha)	Clay (%)	OMC (%)	MC (%)	Soil texture (USDA)
2010							
Avenue, UK	25	Wheat	3.0	17	4	16	Sandy loam
Orchard, UK	25	Wheat	1.5	33	5	22	Clay loam
The Netherlands 1	4	Wheat	0.3	17	3	20	Sandy loam
The Netherlands 2	12	Onion	0.5	20	3	19	Loam
The Netherlands 3	25	Maize	2.0	2	3	13	Sand
The Netherlands 4	25	Maize	0.4	28	4	20	Silty clay loam
Czech Republic	25	Sugar beet	2.5	25	4	20	Silt loam
Denmark 1	25	Organic wheat	2.5	4	2	14	Loamy sand
Denmark 2	15	Organic barley	2.0	9	3	16	Sandy loam
Odstone, UK	20	Grassland	0.9	26	8	22	Silt loam
2011							
Duckend F1, UK	48	Wheat	16.0	27	3	18	Loam
Duckend F2, UK	30	Oilseed rape	5.0	32	4	19	Clay loam
Duckend F3, UK	33	Wheat	9.0	27	4	16	Sandy clay loam
Ivy Ground, UK	24	Oilseed rape	2.0	57	8	33	Clay
Clover Hill, UK	24	Oilseed rape	2.0	55	8	35	Clay
Beechwood, UK	24	Wheat	2.0	42	8	27	Clay
Upbury, UK	24	Beans	2.0	65	8	42	Clay
2012							
Ivy Ground, UK	17	Wheat	0.3	57	8	33	Clay
Chipping, UK	22	Wheat	0.3	13	3	10	Sandy loam
Downing, UK	24	Wheat	0.3	10	3	13	Sandy loam

BD = bulk density.
MC = moisture content.
OMC = organic matter content.
USDA = United State Department of Agriculture.