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Predicting the relative density from on-the-go horizontal penetrometer measurements at some arable top soils in Northern Switzerland

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ABSTRACT

This study sought to develop empirical models to predict soil relative density (ρ_{rel}) from measurements of horizontal penetrometer resistance (PR) and soil water content (θ_g) in a wide range of soil textures. This permits the comparison of the state of soil compactness in different soil textures. It was hypothesised that model coefficients would be texture-dependent when soil compactness was expressed as bulk density (ρ_d) and that a model with constant coefficients could be obtained when soil compactness was expressed in terms of ρ_{rel} (obtained as the ratio of ρ_d to reference bulk density (ρ_{ref})). Field measurements were conducted in 2014 using a horizontal penetrometer at 0.25 m depth in 10 fields in Switzerland with a wide range of soil textures covering sandy loam, silt loam, loam, clay loam and clay (clay concentration, (CC) = 153–585 g kg^{-1} and organic matter concentration, (OM) = 9–168 g kg^{-1}). At selected locations along the penetrometer measurement transects, cylindrical soil cores were sampled for determination of soil texture, OM, θ_g and ρ_d. Soil water potential and effective stress (σ') were also estimated for each location. Standard Proctor tests were performed on eight soils with variable textures. Proctor density was well described as a function of CC and OM (R^2_{adj} = 0.97, RMSE = 0.046 Mg m^{-3}) and was used as reference density to obtain ρ_{rel}. From this we developed a model for prediction of ρ_{rel} from PR and σ' that allows comparisons between soils without changes in model coefficients. However, σ' cannot be obtained from on-the-go measurements and the model is therefore of limited value for soil compaction mapping. A model for estimating ρ_{rel} from PR and θ_g yielded satisfactory predictions (R^2_{adj} = 0.66, RMSE = 3.3%), although θ_g is a texture-dependent measure of soil water that cannot be compared across soils. Moreover, ρ_d was well predicted from PR and θ_g (R^2_{adj} = 0.93, RMSE = 0.05 Mg m^{-3}), possibly because all our measurements were carried out at similar soil water potential, which implies that θ_g carries soil textural information. Future research should test the proposed equations for a wide range of soil water potential values. The findings presented can be of use in developing measurement systems for mapping soil compactness that combine the proposed prediction functions with horizontal penetrometer and water content sensor systems.

1. Introduction

Soil compaction (i.e. reduction of soil porosity) caused by agricultural field traffic is one of the main threats to sustaining soil quality in Europe (COM, 2006) and worldwide (Oldeman et al., 1991; Farrakh Nawaz et al., 2013). A range of important ecological functions is affected when soil is compacted (e.g. van Ouwerkerk and Soane, 1995; Alaoui et al., 2011). For example, compaction reduces saturated hydraulic conductivity and thus triggers surface runoff and soil erosion by water and also reduces soil aeration and increases mechanical impedance to plant roots and the energy required for mechanical tillage. Consequently, soil compaction is one of the causes of a number of environmental and agronomic problems (flooding, erosion, greenhouse gas emissions, leaching of chemicals to water bodies, crop yield losses) resulting in significant economic damage to society and agriculture (Taylor, 1992; Hamza and Anderson, 2005).

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Mapping the state of soil compaction across agricultural fields and landscapes would provide (i) better estimates of the extent of land degradation by compaction (severity of compaction and area affected), and (ii) information on soil traffic management and land use impacts on soil compaction, which in turn would help in the development and refinement of sustainable management guidelines. Moreover, the identification and delineation of areas with a similar degree of soil compactness within arable fields could help to explain within-field crop yield patterns (e.g. Keller et al., 2012) and allow farmers (i) to apply site-specific soil management (e.g. site-specific tillage) (Raper, 1999; Khalilian et al., 2002; Raper et al., 2005), and (ii) to achieve better timeliness in field operations.

A suitable sensor for on-the-go measurement of the state of soil compaction must permit measurements in a soil profile to enable site-specific delineation of the thickness and depth of compacted layers, e.g. for precision (variable-depth) tillage applications. This cannot be achieved (as yet) by non-intrusive sensors such as remote sensing or surface-contact sensors, e.g. seismic surface wave sensors (Donohue et al., 2013) or electrical conductivity sensors (see Naderi-Boldaji et al., 2014). Moreover, soil density cannot be measured directly with on-the-go methods. Most suitable on-the-go devices for such applications seem to be soil strength sensors (Hemmat and Adamchuk, 2008), typically in the form of horizontal penetrometers that can be pulled through the soil by a tractor. Horizontal penetrometers operate at a specific soil depth, but multi-probe tools have been designed that measure PR simultaneously at various depths (e.g. Chukwu and Bowers, 2005; Chung et al., 2006). Moreover, horizontal penetrometers could be integrated on farm implements (e.g. in front of a seed drill), so that no extra field operations are needed when mapping soil compaction.

PR is an attractive measurement because it is relatively simple, fast and cheap, can be carried out on-the-go, thus yielding spatial information, and is sensitive to soil bulk density, which makes it an excellent measure for assessing soil compaction. However, PR is strongly influenced by soil water content and soil texture, and therefore water content and texture have to be measured simultaneously with PR. This can be achieved by a 'sensor fusion system' as demonstrated by e.g. Naderi-Boldaji et al. (2013a).

Relationships between vertical penetrometer resistance (Q) (i.e. cone index) and soil characteristics have been the subject of numerous studies. A variety of empirical functions have been developed that express Q as a function of bulk density (ρ_d) and some measure of soil water, either in the form of water content, water potential or effective stress (for an overview, see Dexter et al. (2007) and Vaz et al. (2011)). It is worth mentioning that Q and PR are strongly correlated but are not identical, due to their different direction of motion (i.e. vertical compared with horizontal) and that the correlation between Q and PR is affected by cone size and working depth (see Hemmat and Adamchuk, 2008). However, both Q and PR are similarly affected by soil properties (texture, density, water content) and therefore similar models can be used to describe PR and Q as a function of water content and bulk density, although the model coefficients may differ. Some of these functions are purely empirical, while others may be classified as 'semi-physical' (equations derived based on physical considerations, but where the coefficients are empirically derived). The equations usually work very well for a particular soil. When a range of soils is considered, the typical approach is to develop empirical relationships between the model coefficients and soil basic properties (soil texture, organic matter concentration) (e.g. Silva and Kay, 1997). Prediction of penetrometer resistance from bulk density and soil water content is a useful tool in studies on root growth, draught requirement of tillage implements or trafficability (Dexter et al., 2007).

In the context of the present study, i.e. soil compaction mapping, the focus is on predicting soil density from penetrometer measurements (in contrast to the work cited above, which predicts penetrometer resistance from bulk density). Because penetrometer resistance is strongly influenced by soil water, such a model will have the general form:

$$\rho_d = f(Q, m) \quad (1)$$

where m is an expression of soil water content. An example of such a model for prediction of ρ_d was developed by Mouazen et al. (2003) and tested by Mouazen and Ramon (2006) on a 2.3 ha field using on-the-go measurements of draught force of a soil cutting tool (i.e. a chisel) and water content. Similarly to the models for prediction of Q, a model for estimation of ρ_d can be expected to perform well for any particular soil. For example, the field investigated by Mouazen and Ramon (2006) varied in texture within a relatively narrow range (clay concentration between 75 and 92 g kg^{-1}). However, such a model is expected to perform less well when different soils are compared. As with the prediction models for Q, a possible approach is to combine Eq. (1) with a number of empirical regression equations for estimation of model coefficients from easily-available soil properties. Mouazen and Ramon (2009) and Quraishi and Mouazen (2013) added empirical correction factors that could be predicted from soil texture to the model developed by Mouazen and Ramon (2006). In this study, we assumed that the density in Eq. (1) could be expressed in terms of relative density. The use of relative density is intended to normalise bulk density in such a way that a certain relative density describes the same state of compactness in any soil, i.e. independently of soil texture. Hence, relative density can be used for comparisons across soil types. In contrast, values of absolute bulk density may indicate a dense state in one soil, but a loose state in another soil. Consequently, optimum and critical limits of bulk

Table 1
Textural composition of the soils studied (at 0.25 m depth). Sand: sand concentration (0.05–0.2 mm); Silt: silt concentration (0.002–0.05 mm); Clay: clay concentration (<0.002 mm); OM: organic matter concentration.

Field no.	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	OM (g kg^{-1})	Particle density (Mg m^{-3})	USDA soil class	Proctor test
F1	242.6	537.1	220.3	15	2.56	Silt loam	*
F2	330.3	475.0	194.7	19	2.55	Loam	*
F3	161.1	358.2	480.8	168	2.34	Clay	*
F4	430.3	284.8	284.8	31	2.59	Clay loam	*
F5	238.0	571.7	190.2	17	2.64	Silt loam	*
F6	39.0	366.0	595.0	52	2.60	Clay	*
F7-LC	537.4	295.8	166.8	23	2.61	Sandy loam	*
F7-HC	399.2	340.1	260.7	18	2.66	Loam	*
F8	320.4	413.3	266.3	19	–	Loam	–
F9	569.1	239.8	191.1	17	–	Sandy loam	–
F10	434.4	305.2	260.4	40	–	Loam	–

*Indicates the soils tested for Proctor reference density.