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Multiple on-line soil sensors and data fusion approach for delineation of water holding capacity zones for site specific irrigation

Abdul M. Mouazen *, Saad A. Alhwaimel, Boyan Kuang, Toby Waine

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

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ABSTRACT

Soil water holding capacity (WHC) and available water (AW) are key parameters for water management and irrigation scheduling. Measurement of within field variation in WHC should account for affecting soil properties, namely organic matter (OM) or organic carbon (OC), clay content (CC), bulk density (BD) and plasticity index (PI). The aim of this paper is to implement on-line multi-sensor and data fusion approach for the delineation of management zones of WHC for site specific irrigation. A multi-sensor platform was used, which consisted of a load cell to measure subsoiler draught, a wheel gauge to measure depth and a visible and near infrared (vis–NIR) spectrophotometer for simultaneous measurement of moisture content (MC), OC, PI, CC and BD. An electromagnetic induction (EMI) sensor was implemented separately apart from the multi-sensor platform to measure apparent electrical conductivity (ECa) in three experimental fields with vegetable crop production in East Anglia, UK. Partial least squares (PLS) regression analysis with full-cross validation was adopted to establish vis–NIR calibration models of MC, OC, PI and CC, which were validated with prediction sets. Artificial neural network (ANN) and multiple linear regression (MLR) analyses were carried out on the six named soil properties to derive maps of WHC. The validation of the on-line measurement accuracy for OC and MC were good to excellent with root mean square error of prediction (RMSEP) values of 0.06–0.72% and 0.97–2.49% and residual prediction deviation (RPD) values of 2–2.57 and 1.94–2.1, respectively. For CC and PI, the measurement was of fair to moderate accuracy with RMSEP values of 1.4–3.94% and 2.43–2.77% and RPD values of 1.41–1.77 and 1.25–1.48, respectively. Accordingly each field was divided into four classes, with normalised ranges of WHC of 0–0.25, 0.26–0.50, 0.51–0.75 and 0.76–1. These were designated, respectively, as low, medium, high and very high WHC, with the low category being the most susceptible to water changes and entitled to accommodate the largest number of moisture sensors and receive the largest amount of water. A comparison between calculated WHC and measured AWC maps showed distinguished spatial similarity, to recommend the multi-sensors and data fusion as a new approach to optimise irrigation scheduling.

1. Introduction

According to readily available records, the demand for water for both industrial and domestic needs is constantly increasing due to the increasing levels of industrial activity and urban development (Parsons and Bandaranayake, 2009). As a result, the amount of water available for agricultural purposes such as irrigation is in a constant decline. Furthermore, with the current climate change and extreme weather conditions, the high shortage of water resource becomes a serious environmental problem. In this regard, it becomes an urgent requirement for managing water used for irrigation in agriculture efficiently. One way to achieve this is by site specific irrigation, which can conserve the water resources and potentially improve the crop growth and yield at the same time, since the correct amount of water is applied in the correct time and place in the field. But, site specific irrigation requires the use of moisture sensors to be placed permanently at known positions in the field, to provide input data for the control of water use in irrigation. However, until today, optimising the number and position of moisture sensors in the field has been a major problem for growers adopting precision

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

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farming technologies (Aldhumayri, 2012; Alhwaimel, 2013). Furthermore, these water sensors provide only limited data at coarse spatial sampling resolution, e.g. based on one or limited number of moisture sensors used per field of multi hectare area.

Soil water is a key property for plant growth and development. Only part of this water, known as available water can be used by plants. Available water content (AWC) is directly related to water holding capacity (WHC) of a soil (Hall et al., 1977), and is expressed as the difference between water content at field capacity from that at permanent wilting point (Hunt and Gilkes, 1992). It is essential to maintain crop growth all year round, because AWC in a field has been reported to have a profound influence on yield (Forbes and Watson, 1992). However, quantifying WHC or AWC at fine spatial sampling resolution is a main requirement for site specific irrigation. But, this is a difficult task to accomplish, as WHC depends simultaneously on soil organic matter (OM) or organic carbon (OC), clay content (CC), bulk density (BD) and soil plastic index (PI) (Kvaernø et al., 2007; Waiser et al., 2007). Measurement or assessment of WHC at high sampling resolution will only be possible, if OM or OC, CC, BD and PI are all measured simultaneously at high sampling resolution. Data are then modelled with a data fusion technique to derive WHC at high sampling resolution.

In recent years, proximal soil sensing technologies such as electromagnetic induction (EMI) and visible and near infrared (vis–NIR) spectroscopy have been reported as being very useful for various applications in precision agriculture. However, a recent review by Kuang et al. (2012) concluded that EMI and other on-line geophysical sensing methods are limited technologies for quantifying soil properties. The vis–NIR spectroscopy has proven to be the most capable proximal soil sensing technology for on-line measurement of within field variation of various soil physical and chemical properties (Shibusawa et al., 2001; Mouazen et al., 2007; Bricklemyer and Brown, 2010; Kuang and Mouazen, 2013a; Kodaira and Shibusawa, 2013; Marin-González et al., 2013). In addition to robustness, vis–NIR spectroscopy has been described as a cheap, rapid and semi-invasive method for on-line gathering of information about soil properties, which assisted implementing variable-rate fertilisation and mapping of crop potential management zones (Vrindts et al., 2005; Maleki et al., 2008). Compared to the most successful on-line measurement recorded for OC and moisture content (MC) (e.g. Mouazen et al., 2005, 2007; Muñoz and Kravchenko, 2011; Kuang and Mouazen, 2013b), less success has been reported for CC (Bricklemyer and Brown, 2010; Alhwaimel, 2013). However, no reports about on-line measurement of soil PI can be found in the literature. Fusing of data from non-mobile EMI and vis–NIR sensors has shown a good partnership in delineating zones for variable-rate irrigation in a vegetable crop production system (Hedley et al., 2010). EM38 survey data was fused with a rainfall time series and a wetness index extracted from a digital elevation model based on regression analyses to spatially predict water table depth and moisture content at 50 cm for irrigation scheduling (Hedley et al., 2013). To our best knowledge, no reports about fusion of on-line data of apparent electrical conductivity (ECa) collected with an EMI sensor with on-line data on OC, MC, CC, BD and PI collected with a multi-sensor platform for deriving WHC map for site specific irrigation can be found in the literature.

The aim of the study was to implement a multi-sensor platform and data fusion approach for the delineation of management zones for site specific irrigation. This was based on on-line measurement of MC, OC, PI, CC, BD and ECa to derive water holding capacity zones. The output is expected to be a valuable system to identify the number and positions of stationary soil moisture sensors for improved site-specific irrigation. This will also inform the optimal amount of water for site-specific irrigation.

2. Materials and methods

2.1. Experimental sites

Three test sites with vegetable crop production were used in this work, namely, Thetford (3.5 ha area with a sand silt loam texture), Vicarage (8 ha area with a silt clay texture) fields in Lincolnshire and Wypemere (4 ha area with a clay loam texture) field in Cambridgeshire, UK. Before on-line measurement 35, 35 and 32 soil samples from Thetford, Wypemere and Viscarage fields, respectively, were collected from randomly selected points for the development of calibration models of vis–NIR spectrophotometer (Table 1). Another 60 soil samples were collected from the three fields from randomly selected points during the on-line measurement from the bottom of trenches opened by the on-line sensor at about 15 cm depth (Table 2). These samples were used as prediction set for the validation of the on-line measurement. The sample positions were carefully recorded using a digital global positioning system (DGPS) (EZ-Guide 250, Trimble, USA). Around 200 g of soil was collected from each sample and was kept in a refrigerator at 4 °C until analysis.

2.2. On-line measurement

The on-line multi-sensor platform designed and developed by Mouazen (2006) was used (Fig. 1) in this study. It consists of a subsoiler that penetrates the soil to the required depth, making a trench, whose bottom is smoothed due to the downwards forces acting on the subsoiler. The optical unit was attached to the backside of the subsoiler chisel to acquire soil spectra from the smooth bottom of the trench (Mouazen et al., 2005). The retrofitted subsoiler was attached to a frame, which was mounted onto the three point linkage

Table 1
Laboratory measured soil organic carbon (OC), soil moisture content (MC) and plasticity index (PI) using soil samples collected for the three study sites before the on-line measurement.

Site	Property	Min (%)	Max (%)	Mean (%)	SD (%)	No. samples
Vicarage	OC	1.227	4.527	1.571	0.754	32
	MC	15.51	23.20	18.69	2.19	32
	PI	2.190	12.60	5.774	2.198	32
Wypemere	OC	1.500	17.85	9.472	3.416	35
	MC	26.87	52.81	40.24	6.54	35
	PI	14.58	31.04	20.11	4.065	35
Thetford	OC	1.068	7.107	2.213	1.265	35
	MC	14.53	26.23	19.57	3.09	35
	PI	9.20	22.83	15.92	3.848	35