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Application of an on-line soil bulk density sensor for site specific cultivation

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Abstract

Tillage is the most energy consuming operation in the primary production in agriculture. The majority of farmers worldwide adopt homogeneous tillage operations to optimise crop establishment, reduce weeds and compaction, where soil disturbance took place across the entire field including areas where no soil preparation is needed. This practice consumes high energy and leads to decrease soil resistance to water and air erosion. This paper investigates the potential of a previously developed on-line soil bulk density (BD) sensor for the delineation of management zones for site specific tillage. The on-line sensor consisting of a multi-sensor platform pulled by a tractor was used to measure soil BD in two experimental fields with potato in East Anglia, UK. It consisted of a load cell to measure subsoiler draught, a wheel gauge to measure depth and a visible and near infrared (vis-

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NIR) spectrophotometer for the measurement of moisture content (MC). Based on these three on-line measured parameters, BD was calculated using a previously developed model with a hybrid numerical and multivariate statistical analysis. The packing density (PD) was then calculated for all on-line measured points as a function of BD and clay content (CC). Maps of soil BD and PD were developed, and both fields were divided into management zones with different tillage recommendations.

Results showed that the on-line BD sensor can map not only the spatial distribution in BD but enable estimation of PD too. Classifying the PD into three compaction classes revealed that only 4.8% of the field needs aggressive tillage (primary and secondary tillage) and about 34.8% of the field requires harrowing or surface loosening with a cultivator (reduced tillage), while the remaining area of the field do not need any sort of tillage. Virtual calculations of fuel consumption and CO_2 emission in one field based on the three PD classes confirmed that site specific tillage would significantly reduce energy consumption and CO_2 emission, as compared to reduced and conventional tillage practices. By this it can be concluded that the on-line multi sensor platform for the assessment of PD holds a great potential for mapping and managing soil compaction site specifically. A future study is needed to relate soil compaction to actual plant growth and yield, and evaluate cost of production and practical limitations of this approach.

Keywords: Packing Density, Site specific tillage, Multi-sensor

1 Introduction

The increasing world population, changing diet and climate change are the main challenges facing modern agriculture to produce sufficient food, feed and fuel. As a result, there is a growing consensus within our global community that the protection of natural resources and implementation of environmentally and economically sound agriculture practices is of the utmost priority. Under the Thematic Strategy for Soil Protection, a soil framework directive prepared by the European Commission (EU Framework Directive 232, 2006) has considered soil compaction as one of soil threats. Together with erosion, organic matter decline, contamination, salinisation, soil biodiversity loss, sealing, landslides and flooding, compaction occurs in specific risk areas, which must be identified and treated according to the framework directive.

Soil compaction is a major problem in the current food production system (Hamza and Anderson, 2005), as it hinders plant growth and reduces yield, increase soil erosion and water pollution. It increases production cost due to reduction in land productivity, input loss and increase in energy consumption by tillage to eliminate compaction and prepare the soil to a proper seedbed. Bulk Density (BD) is the most common parameter used as an indicator for soil compaction for all soils (Hakansson and Lipiec, 2000 and Mouazen and Ramon, 2006; Quraishi and Mouazen, 2013a) and indeed several studies have shown relationship between BD and crop yield (Negi et al., 1981; Pabin et al., 1991; Czyz, 2004). Recently, Packing Density (PD) has gained attention as an advanced indicator for soil compaction (Jones et al., 2003; Tobias and Tietje, 2007), as it is defined as a composite index of BD and clay content (CC). It was originally developed by Renger (1970) to describe soil compaction for the German soil mapping manual. So far, PD was not explored as a parameter to indicate the need for tillage site specifically.

One of the major limitations that affect successful management of soil is the huge spatial variability of soil properties (including compaction) within a field. However, the current practice for conventional and reduced tillage is that famers and growers used to cultivate the whole field uniformly, as a way to manage the risk of soil compaction, reduce fuel consumption and improve soil quality. Variable cultivation approach will offer many economic and environmental benefits to farmers and growers though reductions in the volume of disturbed soil. Therefore, there is a need to map the spatial variation in soil compaction (Mouazen et al., 2003), at sufficient sampling resolution to allow tillage equipment to respond to this variation and treat compacted zones only. One of the promising technologies to overcome within field variability in soil compaction is on-line soil sensors (Hemmat and Adamchuk, 2008, Mouazen et al., 2005a), capable of collecting high number of samples (Kuang and Mouazen, 2013), which also allow for rapid and cost-effective analysis and enable simultaneous estimation of a variety of soil properties including BD and CC (Mouazen et al., 2009).

The majority of studies reported in the literature on mapping soil compaction with on-line sensors were based on measurement of draught (e.g., Godwin, 1975; Al-Janobi, 2000; Andrade-Sánchez et al., 2007) or penetration resistance (e.g., Tekin et al., 2008; Tobackci et al., 2010). More advanced studies realised the importance of soil moisture on penetration resistance so that a multi-sensor approach was introduced to account for the influence of moisture content (MC) (Sun et al., 2006). Mouazen and Ramon (2002) proposed a methodology to map the spatial variation in soil compaction referred to as BD with high sampling resolution, based on on-line multi-sensor platform. This was based on a hybrid modelling approach of finite element analysis and multiple linear regression analyses to establish a model to predict BD as a function of draught of a soil cutting tool (subsoiler), depth and soil moisture content, which was later expanded to the majority of soil textures (Quraishi and Mouazen, 2013b). A recent study by Naderi-Boldaji et al.

(2016) developed empirical models to predict soil relative density from measurements of horizontal penetrometer resistance and MC in a wide range of soil textures. Authors did not account for particle size distribution in their estimation, and their hypothesis was that the model coefficient would be texture dependent when soil compaction is expressed as BD. So far, no on-line measurement of PD was reported in the literature, to provide data to develop recommendations for variable tillage.

The aim of this study is to map with high sampling resolution the spatial variability in soil PD in two fields in the UK using the on-line multi-sensor platform of Mouazen and Ramon (2006). The scope was to divide these two fields into management zones with different crop limiting indexes for variable cultivation approach based on the degree of compaction within a field.

2 Materials and methods

2.1 On-Line multi-sensor platform

The on-line multi-sensor platform designed and developed by Mouazen (2006) was used (Fig. 1) in this study (Quraishi and Mouazen, 2013b). 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. An optical probe was attached to the backside of the subsoiler chisel to acquire soil spectra in diffuse reflectance mode from the smooth bottom of the trench (Mouazen et al., 2005b). The retrofitted subsoiler was attached to a frame, which was mounted onto the three point linkage of a tractor. An AgroSpec mobile, fibre type, vis–NIR spectrophotometer (tec5 Technology for Spectroscopy, Oberursel, Germany) with a measurement range of 305–2200 nm was used to measure soil spectra in diffuse reflectance mode. A single-ended shear beam load cell with a maximum capacity of 90 kN (Griffith Elder & Company Ltd., Suffolk, UK) for the measurement of draught and a draw wire linear sensor (Penny & Giles Controls Ltd., Dorset, UK) connected to a wheel gauge for the measurement of subsoiler depth were used in combination with the vis–NIR moisture sensor for the measurement of soil BD. More detailed information about data acquisition can be found in Quraishi and Mouazen (2013b).

2.2 Experimental sites and on-line measurement

Two test sites with potato crop production were measured in this work, namely, Thetford field (3.5 ha) with a clay loam soil texture (43.1% sand, 29.5% silt and 27.4% clay) and Wypemere field (peatland of 4 ha) with a silty clay soil texture (5.1% sand, 45.3% silt and 49.6% clay) in Cambridgeshire, UK. On-line measurement with the multi-sensor platform (Fig. 1) was performed in parallel transects to the tramlines. The length of transects depended on the dimension of the field. However, a constant gap of about 10 m was kept between neighbouring transects. Measurement was carried out at an average speed of 2 km h^{-1}.

In Wypemere field it was decided to carry out the on-line soil measurement after soil preparation with ordinary tillage, which included mouldboard ploughing followed by seed bed preparation. In Thetford field, the on-line measurement took place in compacted soil directly after crop harvest and before any tillage operation, where soils are supposed to have higher BD (compacted), compared to Wypemere field (cultivated). This *a prior* planned measurement was to show differences in soil compaction and comparing tillage needs in compacted and recently disturbed (non-compacted) soil conditions.

Before on-line measurement took place, 70 soil samples from both sites (35 samples per field) were collected from randomly selected points for the development of calibration models of vis–NIR spectrophotometer. This sample set was designated as the calibration set. Another 40 soil samples (19 samples from Thetford field and 21 samples from Wypemere field) were collected from both 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 1). These samples were used as a 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 200g of soil was collected from each sample and kept in a refrigerator at 4^{o}C until laboratory analysis.

2.3 Laboratory chemical and physical analyses

Gravimetric soil MC was determined by oven drying of the soil samples at 105 ºC for 24 h (BS EN 13040:2007), which was also used to calculate BD (BS EN 13041:2011). The soil texture was determined by measuring the particle size distribution (PSD) by sieving and sedimentation method (BS 7755 Section 5.4:1998). Texture class was determined according to the United State Department of Agriculture (USDA) classification system. Soil OC was measured by a TrusSpecCNS spectrometer (LECO Corporation, St. Joseph, MI, USA) using the Dumas combustion method (BS EN 7755:1995). Sample statistics of the measured soil properties are shown in Table 1.

2.4 Laboratory optical measurement

Each soil sample was dumped into a glass container and mixed well. Big stones and plant residue were excluded (Mouazen et al., 2005b). Then each soil sample was placed into three petri dishes, which were 2 cm deep and 2 cm in diameter. The soil in the petri dish was shaken and pressed gently before levelling with a spatula. A smooth soil surface ensures maximum diffuse light reflection and high signal-to-noise ratio (Mouazen et al., 2005b). The soil samples were scanned with the same AgroSpec portable spectrophotometer used during the on-line field measurement. A 100% white reference was used before scanning. A total of 10 scans were collected from each cup, and these were averaged in one spectrum.

2.5 Calibration models of on-line visible and near infrared sensor

Spectra pre-treatment preceded the development of vis–NIR calibration models of MC and CC. The vis–NIR spectra were first reduced to 371–2150 nm to eliminate the noise at both edges of spectrum. Spectra were further reduced by averaging three successive points in the visible range, and 15 points in the near infrared range (Kuang and Mouazen, 2013). Savitzky–Golay smoothing, maximum normalisation and first derivation (Martens and Naes, 1989) were successively carried out using Unscrambler 7.8 software (Camo Inc., Oslo, Norway). The pre-treated spectra and the laboratory chemical measurement values were used to develop calibration models for MC and CC. The 70 samples (35 sample each) collected from the two test fields before the on-line measurement (Table 2) were gathered with other samples collected previously from two other fields with vegetable crop production in the UK (Aldhumayri, 2012) to develop calibration models for MC and CC . Partial least squares (PLS) regression analysis with leave-one-out cross-validation was used to develop all models using Unscrambler 7.8 software (Camo Inc., Oslo, Norway). The resulting calibration models of MC and CC were further validated using the remaining 40 samples of the prediction set collected during the on-line measurement (Table 2) based on on-line collected spectra. However, this paper will not deal with validation of the vis-NIR measurement of soil properties, as validation was reported in previous work (Mouazen et al., 2014).

2.6 Derivation of on-line measured bulk density

Mouazen and Ramon (2009) developed a calibration function (Eq. (1)) for on-line assessment of BD in Mg m^{-3}, as a function of MC in kg/kg, subsoiler draught (D) in kN and depth (d) in m, which was valid for light soils, e.g., loamy sand, loam, silt loam, and silt soils.

$$BD = \left(\sqrt[3]{\frac{D + 21.36MC - 73.9313d^2}{1.6734}}\right) \times (1.255 - 0.772\,MC) \qquad (1)$$

Eq. (1) has been generalised to cover majority of soil textures, by developing a correction factor (CF) for each soil texture class (Quraishi and Mouazen, 2013b). Equation (1) was used in this study to calculate BD for Wypemere and Theltford fields, considering CF values of 0.27 and 0.079 for silty clay and clay loam soils, respectively.

2.7 Calculation of packing density

Kaufmann et al. (2010) correlated optimum (BD_{opt}) and limiting (BD_{lim}) values of bulk density with clay content (Eqs. 2 and 3), to refer to optimum condition for root growth and conditions, where root growth is limited (stopped or reduced growth).

$$BD_{opt} = 1.493 - 0.00564\ CC \qquad (2)$$

$$BD_{lim} = 1.778 - 0.00673\ CC \qquad (3)$$

Where BD_{opt} is optimum bulk density for root growth (g cm^{-3}), BD_{lim} limiting bulk density for root growth (g cm^{-3}) and CC is clay content (%).

They also convert BD_{opt} and BD_{lim} values into respective values of optimum packing density (PD_{opt}) and limiting packing density (PD_{lim}), confirming that the PD is a more suitable indicator for compaction and crop growth. Finally, they establish critical ranges for PD values in regard to crop growth (Table 3).

The following formula developed by Renger (1970) was used to calculate PD, indicating soil compaction for soils with known CC:

$$PD = BD + 0.009\ CC \qquad (4)$$

where PD is packing density (-), BD is bulk density (g cm^{-3}) measured by on-line sensor (Equation 1) and CC is clay content (weight-%) measured by online sensor.

Soil BD was calculated according to Eq. (1), where MC was obtained with the on-line vis-NIR spectroscopy measurement. Soil CC was also predicted using the on-line vis-NIR measured soil spectra that is transferred into CC content using PLS calibration models. By substituting on-line predicted BD and CC into Eq. (4), PD was calculated for both fields.

2.8 Geostatistical analysis and mapping

Semi-variogram analysis was carried out using Vesper 1.63 software developed by the Australian Centre for Precision Agriculture (Minasny et al., 2005). Exponential models were adopted for all properties to calculate semi-variance, since it resulted in the lowest root mean square error of prediction. Using the semi-variogram data, maps of MC, CC, BD, and PD, based on all on-line measured points in the two fields were developed with ordinary kriging using ArcGIS ArcMap (ESRI ArcGISTM version 10, CA, USA). The PD maps were classified into five categories to reflect conditions for crop growth based on the value of PD as suggested by Kaufmann et al (2010) (Table 3).

3 Results and discussion

3.1 Variation in on-line measurement soil properties

The BD measurement was carried out in the two study fields by using the on-line multi-sensor platform consisting of draught (measured with a load cell), depth (measured with a wheel gauge) and MC sensor based on vis-NIR spectroscopy. Equation 1 was used to calculate the BD, based on on-line measured D, d and MC. Since texture affects the values of BD derived with Eq. (1), CF developed by Quraishi and Mouazen (2013a) was used to correct for BD for the soil texture classes of the two fields (Table 4). In Wypemere field, with a silty clay soil type, low BD (average BD = 0.884 Mg m^{-3}) was measured, which is attributed to the recent tillage carried out before the on-line measurement took place. Tillage prior to planting temporarily decreases bulk density on the surface (USDA, 2015). However, large variation in BD can be observed in this field with a standard deviation (SD) of 0.145 Mg m^{-3}, which is larger than that of Thetford field (SD = 0.118 Mg m^{-3}). This spatial variation in BD is mainly attributed to texture variation, since the soil in this field was loose when the on-line measurement took place. It is worth noting that BD decreases with increasing CC and vice versa (Abramson et al., 2002). In Thetford field of a clay loam soil, higher BD (average BD = 1.340 Mg m^{-3}) is measured, as compared to that in Wypemere field, as Thetford field had not received any tillage before the on-line measurement took place (Fig. 2). However, MC in Thetford field was smaller than that in Wypemere field (Fig. 3). Also Thetford field shows higher within field spatial variability in bulk density (ranging from 1.69 to 0.876 M gm^{-3}). The north western part of the field (top right) shows higher BD compared to the south eastern part.

There was no clear visual spatial similarity between BD maps (Fig. 2) and MC (Fig. 3) maps in both fields. Distinguished spatial similarity between MC and CC can be observed, particularly in Wypemere field at the northern half of the field. This can be attributed to the strong correlation exists between CC and MC, since the higher the CC the higher is the water holding capacity of the soil (Nelson and Miller, 1992; Mouazen et al., 2014). In fact, Wypemere field is almost divided into two distinguished parts, with the northern (top) half having almost double the CC as compared to the Southern (bottom) half. This is the reason why this field still shows large range of BD variation, although the soil was prepared to a fine tithe before the on-line measurement took place. Since the northern half of the Wypemere field (Fig. 4) has a high CC reaching up to 50%, BD in this half is also small and is much smaller than that of the Southern half (Fig. 2), which explains that in fields with recently prepared soils, the on-line soil sensor can be used to map variation in soil texture. Further research is needed to confirm this statement. In contrast, the southern half of the field has low CC, and this is correctly reflected in higher BD measured with the on-line soil sensor (Fig. 2). However, the spatial similarity between BD and CC maps in Thetford field is minimal, which can be attributed to the variation of BD density that is attributed to variation in soil compaction rather than texture. For example, although the north western corner of the Thetford field has the highest CC (Fig. 4), the highest BD was measured at this corner of the field (Fig. 2) indicating high soil compaction as a result of access use of agricultural machinery during the cropping season. Therefore, PD that takes into consideration soil texture (clay content) when assessing BD is important to consider and evaluate as a replacement of BD.

3.2 Packing density classes and virtual tillage requirement

The PD values were calculated for all data points collected with the on-line sensor in the two sites based on on-line measured BD and CC (Eq. 4). The maps of PD for both fields are shown in Fig. 5. The PD map developed for the Wypemere field (Fig. 5) shows almost perfect homogeneous but loose soil across the entire area of the field. This is the beauty of the PD compared to BD for the assessment and mapping of soil compaction, where variability in CC is taken into consideration. In fact, the inclusion of CC in the PD calculation by Eq. 4 leads to exclude the influence of CC on the spatial distribution of soil compaction when BD is measured after soil tillage (Fig. 2). The low PD measured with the on-line compaction sensor in the Wypemere field after tillage indicates tillage effect in loosening the soil and create non-compacted medium for optimum condition for crop growth. The almost perfect uniform spatial distribution of PD is a good indicator to prove the on-line multi-sensor platform used in this study to be a reliable and accurate tool to quantify and map the spatial variability in soil compaction indicated as PD.

In Thetford field, the spatial distribution of PD shows a completely different picture, demonstrating much larger variability, as compared to that in Wypemere field. In this field PD values reached up to 1.82, indicating a sever soil compaction. Remarkably, the PD of 95% of Thetford field area is smaller than 1.7, which indicates optimum soil condition for the root to grow according to the classes assigned by Kaufmann et al. (2010) in Table 4.

Only less than 5% of the field area is of a PD range more than 1.7. Kaufmann et al. (2010) reported that the optimum PD for plant growth is around 1.55 and the compaction will gradually increase (crop growth reduce) with the increase in PD > 1.7, where the plant growth can be severely affected. Also other studies associated PD values > 1.75 with heavy compaction and values < 1.40 with no compaction. Tobias and Tietje (2007) found PD values between 1.6 and 1.8 to indicate a critical state of compaction. Based on Kaufmann et al. (2010) and Tobias and Tietje (2007) classification of PD in regards to crop growth, we assume the following three classes of soil compaction in respect to the need for tillage:

1- PD ≥ 1.7: here soils are considered as extremely compacted and needs aggressive tillage operations (e.g., conventional tillage consisting of primary and secondary tillage).
2- PD is in the range of 1.55 – 1.7: only reduced tillage is sufficient (e.g., surface loosening with a cultivator or surface harrowing). Areas in the field with PD values below 1.6 indicate no need for tillage.
3- PD ≤ 1.55: Here no tillage is needed as compaction is below the limit of crop growth.

Adopting this classification system of tillage needs in Thelford field, where no tillage were implemented before the on-line measurement, indicates that only 4.8% of the field would need aggressive conventional tillage (primary and secondary tillage) and about 34.8% (PD = 1.55 – 1.7) of the field would require harrowing or surface loosening (reduced tillage). However, with the current uniform tillage practice, farmers would cultivate the entire area of the Thetford field with conventional tillage. If the farmer is to adopt site specific tillage, as suggested above 95 % of the field would receive no or minimum soil disturbance by tillage (using current no-till or min-till practice), which would reduce the amount of fuel consumption by at least 50% for the large proportion

(95%) of the field, as well as reducing soil disturbance. Therefore, the cost of production will be reduced by saving fuel and operational time for tillage in addition to reducing soil susceptibility to erosion by adopting no-tillage or reduced tillage practice in 95% of the field area.

Furthermore, this approach if validated with a larger number of fields could also be recommended for variable depth cultivations. For example, we may assume the following tillage depth ranges for different PD classes; deep cultivation (30 cm) for a PD ≥ 1.8, medium deep cultivation (20 cm) for PD values between 1.7-1.82, shallow cultivation (7 cm) for a PD range of 1.55 – 1.7 and no till for a PD ≤ 1.55. Uniform depth cultivation is the only available option where spatial variations in soil compaction within the field are not possible to map. The on-line sensor used in the current work for mapping PD opens new research and practical opportunities for managing soil compaction by providing the best recommendation of tillage system (conventional, reduce, no-till), and configurations of tillage depth based on the degree of soil compaction of different parts within a field.

3.3. Potential benefits of site specific tillage

Having calculated the area per PD class (Table 5) for both fields, the next step is to calculate the potential economic and environmental benefit of site specific tillage as compared to conventional and reduce tillage practices. Stajnko et al (2009) compared the diesel consumption for field operations in conventional tillage and reduced tillage system. Authors show that reduced tillage consumes about 50% less fuel (35-39 L ha^{-1}) and produces less carbon emissions (96-107 kg ha^{-1}) than conventional tillage (68-82 L ha^{-1} and 188-225 kg/ha^{-1}, respectively). In order to evaluate the benefits of the site specific tillage proposed in the current work, we compare three different tillage scenarios for

Thetford field only: 1) The entire area of the field is cultivated using uniform conventional tillage 2) The entire area of the field is cultivated using reduced uniform tillage and 3). Site specific tillage is adopted based on the above three classes for tillage proposed in the current work (Table 6). We assumed the average fuel consumption and carbon emission of 37 L ha^{-1} and 101.5 kg CO_2 ha^{-1}, respectively for reduced tillage and 75 L ha^{-1} and 206.5 kg CO_2 ha^{-1}, respectively, for conventional tillage. For site specific tillage, PD classes of 1.55-1.7 and larger than 1.7 will be treated as reduce tillage and conventional tillage classes, respectively. Classes of PD smaller than 1.55 are considered as no tillage treatments. Examining Table 6 reveals that site specific tillage would potentially consumes the smallest amount of diesel, while producing the smallest CO_2 emission. The total fuel consumption per field were 57,89, 129,5 and 262.5 L calculated for site specific tillage, reduce tillage and conventional tillage, respectively (Table 6). The site specific tillage would consume 44% and 22% diesel, and produce the same percentage of CO_2 emission of that of reduce tillage and conventional tillage, respectively. For CO_2 emission, however, there is a need for further field trails to validate this assumptions and provide robust evidence on cost benefits of variable intensity and depth cultivations in term of fuel saving, operational time, disturbed soil volume and practicality for farmers and growers.

4 Conclusions

An on-line multi-sensor and data fusion approach is adopted to determine the spatial variation in soil bulk density (BD), moisture content (MC) and clay content (CC) to map the variation in packing density (PD) as indicator for the soil compaction. Maps of PD with five classes are developed in two fields, one measured before tillage and the other one measured after tillage. Results allowed the following conclusions to be drawn:

Examining the on-line visible and near infrared (vis–NIR) spectroscopy measurement output revealed that strong correlations exist between MC and CC, which is in line with previous reports available in the literature. Clear spatial similarity between CC and BD maps was observed only in one field whose soil was cultivated before the on-line measurement took place. Variability in BD is this field was mainly attributed to variability in texture, as compaction was eliminated by tillage.

Classifying PD into three classes reported in the literature revealed that significant part of the compacted field may well be suitable for the crop to grow without the need for tillage. However, we proposed a refined PD classification system, consisted of three classes to be used as guidelines for tillage selection. We have assumed that by applying this into the compacted study field indicated that only 4.8% of the field needs aggressive tillage (primary and secondary tillage) and about 34.8% of the field requires harrowing or surface loosening with a cultivator (reduced tillage), while the remaining area of the field do not need any sort of tillage. Virtual calculations of fuel consumption and CO_2 emission based on the three PD classes confirmed that site specific tillage would significantly reduce energy consumption and CO_2 emission, as compared to the reduce and conventional tillage practices.

This findings support the final conclusion of this work that multi-sensor and data fusion approach is a useful approach for the implementation of site specific tillage based on the actual degree of the compaction measured in the soil with the on-line multi-sensor platform used in the current work. This approach potentially will reduce fuel consumption and also reduce greenhouse emissions. However, detailed field trails and a larger number of fields are necessary to provide robust evidence to quantify the economic and environmental benefit of site specific tillage, as alternative to the uniform cultivation. The future study needs to validate the current findings by field studies relating soil compaction to actual plant growth, cost of production and practical limitations of this approach.

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Figure Captions

Figure 1. Multi-sensor platform for the on-line measurement of soil properties (Mouazen et al., 2014).

Figure 2. Full-point bulk density (BD) maps based on exponential variograms shown for Wypemere field (top) and Thetford field (bottom)

Figure 3. Full-point moisture content (MC) maps based on exponential variograms shown for Wypemere field (top) and Thetford field (bottom)

Figure 4. Full-point clay content (CC) maps based on exponential variograms shown for Wypemere field (top) and Thetford field (bottom)

Figure 5. On-line measured packing density (PD) map in two studied fields; Wypemere after cultivation (top) and Thetford before cultivation (bottom)

Figures

Figure 1. The multi-sensor platform for the on-line measurement of soil properties (Mouazen et al., 2014).

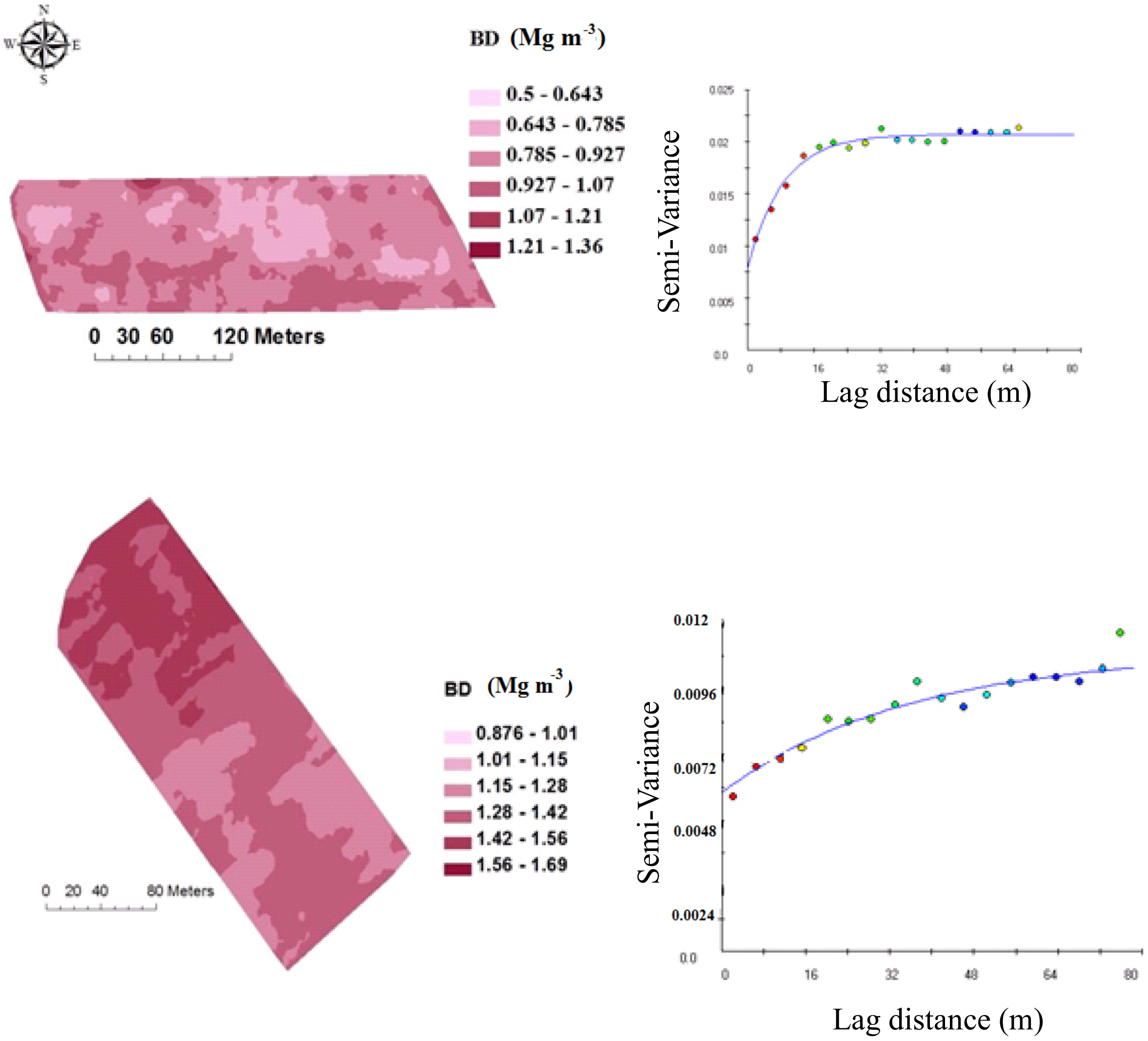

Figure 2. Full-point bulk density (BD) maps based on exponential variograms shown for Wypemere field (top) and Thetford field (bottom)

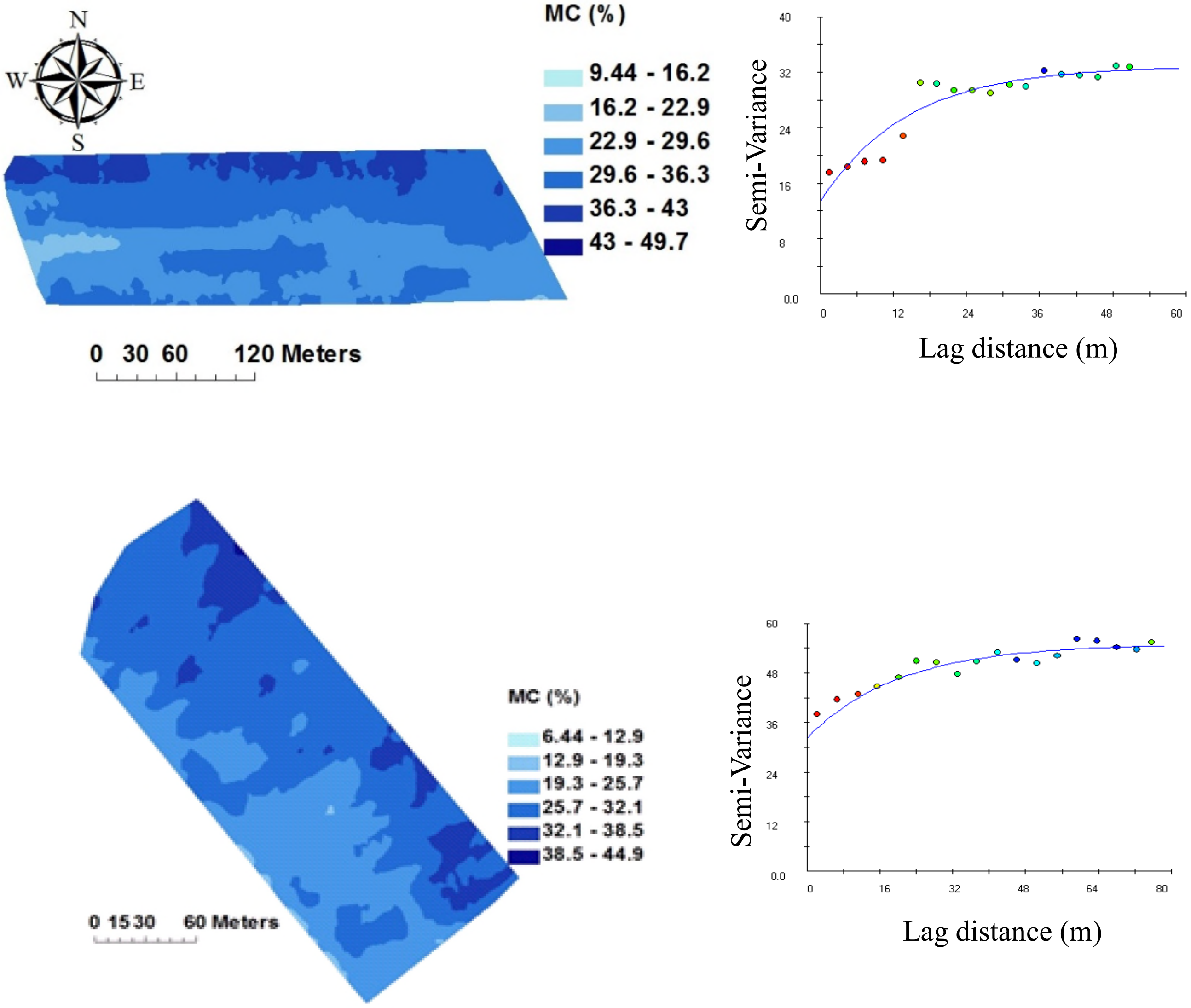

Figure 3. Full-point moisture content (MC) maps based on exponential variograms shown for Wypemere field (top) and Thetford field (bottom)

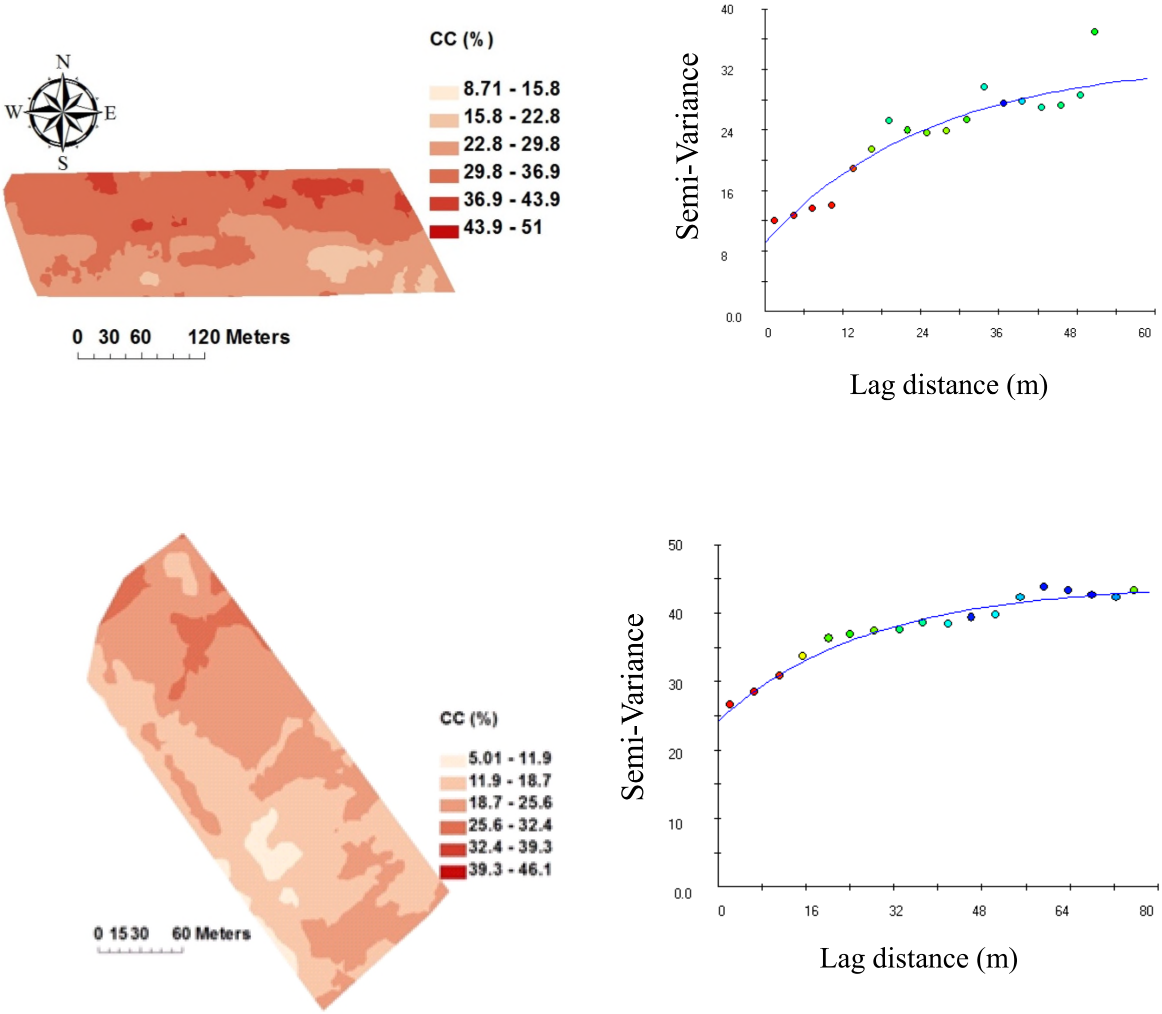

Figure 4. Full-point clay content (CC) maps based on exponential variograms shown for Wypemere field (top) and Thetford field (bottom)

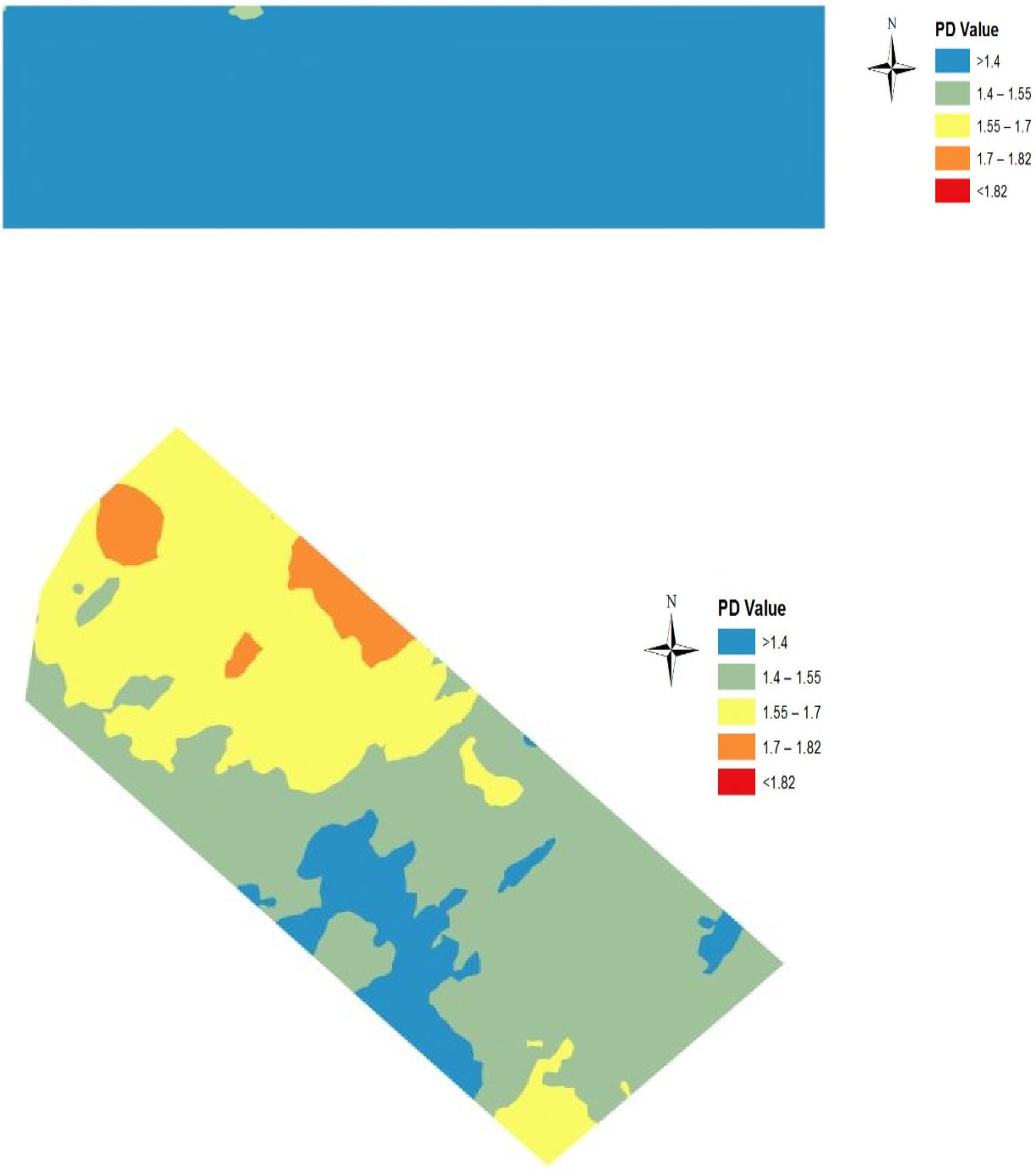

Figure 5. On-line measured packing density (PD) map in two studied fields;

Wypemere after cultivation (top) and Thetford before cultivation (bottom)

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

		OC, %	MC, %
	NR	35	35
Wypemere	Min	1.5	26.87
	Max	17.85	52.81
	Mean	9.472	40.24
	SD	3.416	6.54
Thetford	NR	35	35
	Min	1.068	14.53
	Max	7.107	26.23
	Mean	2.213	19.57
	SD	1.265	3.09

Table 2 Sample statistics of moisture content (MC) and clay content (CC) in the calibration and validation sets for two study sites.

Sites		Calibration set		Validation set	
		MC	CC	MC	CC
Wypemere	NR	167	262	19	19
	Min, %	30.1	22.82	32.57	37.9
	Max, %	45.8	48.08	50.93	57.7
	Mean, %	38.9	35.95	43.16	48.3
	SD %	5.19	6.54	5.59	6.04
Thetford	NR	167	262	21	21
	Min, %	18.4	14.69	17.44	20.2
	Max, %	25.7	35.84	26.23	37.4
	Mean, %	21.9	23.79	21.27	27.2
	SD %	2.27	5.87	2.58	5.75

SD is standard deviation.

Table 3: The packing density (PD) classes as related to soil suitability for crop growth (Kaufmann et al., 2010)

PD value	Crop growth condition
< 1.40	Below optimum range
1.40-1.55	Lower optimum range
1.55-1.70	Upper optimum range
1.70-1.82	Lower limiting range
> 1.82	Upper limiting range

Table 4 On-line measured bulk density (BD) in the two study sites

Site	CF	BD (M gm^{-3})			
		Min	Max	Mean	SD
Wypemere	0.270	0.500	1.355	0.884	0.145
Thetford	0.079	0.876	1.691	1.340	0.118

CF is correction factor

Table 5 Percentage of area for each packing density (PD) class in both Wypemere and Thetford fields, according to classes proposed by Kaufmann et al. (2010)

PD zones	Crop growth condition	Wypemere Area (%)	Thetford Area (%)
< 1.40	Below optimum range	99.9	10.0
1.40-1.55	Lower optimum range	0.1	50.4
1.55-1.70	Upper optimum range	0	34.8
1.70-1.82	Lower limiting range	0	4.8
> 1.82	Upper limiting range	0	0

Table 6 Potential fuel consumption (FC) and carbon dioxide emission (CE) per packing density (PD) class calculated for site specific tillage, reduced tillage and conventional tillage. Calculations were made according to three classes proposed in the current work.

		Site specific tillage		Reduce tillage		Conventional tillage	
PD class	Area (ha)	FC (L ha^{-1})	CE (kg CO_2 ha^{-1})	FC (L ha^{-1})	CE (kg CO_2 ha^{-1})	FC (L ha^{-1})	CE (kg CO_2 ha^{-1})
< 1.55	2.11	0	0	78.07	214.17	158.25	435.72
1.55-1.7	1.22	45.14	123.83	45.14	123.83	91.5	251.93
> 1.7	0.17	12.75	35.105	6.29	17.255	12.75	35.105
Sum	3.5	57.89	158.935	129.5	355.25	262.5	722.75