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A multi sensor data fusion approach for creating variable depth tillage zones

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Abstract.

Efficiency of tillage depends largely on the nature of the field, soil type, spatial distribution of soil properties and the correct setting of the tillage implement. However, current tillage practice is often implemented without full understanding of machine design and capability leading to lowered efficiency and further potential damage to the soil structure. By modifying the physical properties of soil only where the tillage is needed for optimum crop growth, variable depth tillage (VDT) has been shown to reduce costs, labour, fuel consumption and energy requirements. To implement VDT it is necessary to determine and map soil physical properties, spatially and with depth through the soil profile.

In this research a multi-sensor and data fusion approach was developed that augmented data collected with an electromagnetic sensor with a standard penetrometer, and conventional methods for the measurement of bulk density (BD) and moisture content (MC). Packing density values were recorded for eight soil layers of 0-5, 5-10, 10-15, 15-20, 20-25, 25-30 30-35 and 35-40 cm. From the results only 62% of the site required the deepest tillage at 38 cm, 16% required tillage at 33 cm and 22% required no tillage at all. The resultant maps of packing density were shown to be a useful tool to guide VDT operations. The results provided in this study indicate that the new multi-sensor and data fusion approach introduced is a useful approach to map layered soil compaction to guide VDT operations.

Keywords. Variable depth tillage, data fusion, bulk density, packing density.

Introduction

Traditional tillage practices use a whole field approach in which the tillage effect is applied uniformly across the whole field. Management decisions on which tillage machinery to use and how deep to operate it at are usually decided on historical management or occasionally based on information derived from a soil profile inspection. This universal approach is attractive to growers because it requires little specialist knowledge of the soil, simply relying on tillage machinery design to achieve a satisfactory result. On the other hand there are several disadvantages to this approach. Firstly from an economic perspective, disturbing the soil unnecessarily in areas where the soil structure and condition is not required is wasteful of time and fuel (Keskin et al., 2011). Secondly, incorrect tillage depth can cause damage to the soil structure by smearing wet plastic soil (Gill and Vandenberg 1965) which can lead to the formation of an impervious layer, restricting the development of plants roots, negatively impacting on yield. Finally inappropriate tillage may cause the soil to be susceptible to erosion where nutrients are not retained in the soil but are lost to the environment through leaching and runoff.

The alternative approach to traditional tillage practices is variable depth tillage (VDT). VDT requires the state of the soil to be measured through the profile, in advance of tillage or on-the-go, to determine the optimum tillage depth spatially. Research on the suitability of various sensors has been carried out. In 2006, Domsch et al. evaluated the use of a four cone penetrometer array to determine optimum loosening depth. He concluded that soil penetration resistance can be used to determine the change in soil strength; however, the variation of cone index measured by a single penetrometer was very high. Krajco et al. (2007) investigated the use of apparent electrical conductivity (ECa) to determine the need for cultivation. By utilising two ECa surveys, the initial map would be created when the soil was in a desirable condition and then compared to subsequent ECa surveys revealing the areas of the field which require cultivation.

To overcome individual sensor limitations caused by relatively high soil heterogeneity and the complex relationship amongst variables, Mouazen et al. (2003a,b) proposed a data fusion method to predict dry bulk density (BD) as a function of the cutting depth (d) and measured horizontal force (D) of a mechanical soil resistance sensor, and soil moisture content. Initially Mouazen et al. (2003 a,b) used a statistical hybrid modelling scheme to establish an equation relating the variation of bulk density with soil MC, d and D of the soil mechanical resistance sensor. With the fusion of a soil mechanical sensor, depth measuring sensor, and moisture sensor a unique system was developed for evaluating soil compaction in the top 150 mm of the soil profile. (Mouazen and Roman, 2006, Hemmat and Adamchuk, 2008).

The objective of this research was to develop a new soil compaction measurement system utilising a multisensory data fusion approach which would extend beyond 150mm through the soil profile.

Materials and Methods

The research was conducted on a 2.43 ha site in Lincolnshire, UK. Located on the edge of the clay fens, the site is described as a relatively stone free loam material overlying sands and gravels between 30 and 80 cm (Soil survey of England and Wales). To facilitate simulation of a multi sensor platform a 90 x 270 m site was divided into nine 10 m transects for the apparent electro-conductivity (ECa) measurements and further sub divided into 243, 10 x 10 m squares for the sampling locations of the cone penetrometer.

ECa data was collected with a DUALEM 1S sensor (Dualem, Inc., Milton, ON, Canada). Data was recorded a 1 s intervals, providing a measurement every 2m along each transect. In total 2569 ECa measurements were recorded at each ECa depth, namely 0-40 cm and 0 – 120 cm. Soil resistances were recorded through the soil profile using an Amity mobile penetrometer (Amity Technology, ND, USA) every at 2 cm intervals down to 40 cm at 10m intervals along each transect. Further samples were taken spatially and with depth (4 x 10 cm) to provide lab-tested levels of bulk density (BD*)*, moisture content (MC) and clay content (CC). Sample locations were determined from ECa zones and were taken randomly from identifiable ECa ranges.

Data processing, mapping and tillage zone delineation

Geo-statistical analysis facilitated the initial data fusion. Data for each soil property (ECa, PR, ρ_b, MC, CC) were interpolated and transformed into a common 10 m raster using Manifold GIS (Manifold Software Ltd, Wanchai, HK). The resultant data set was a grid of common points, spatially joined at the mid-point of each raster square.

To delineate tillage zones the data from the raster analysis was clustered into three zones, by layer using a k-means algorithm. The clustering process transformed the data into normalised numerical values associated with each variable in the analysis. The differences in mean level of the individual soil properties defined the cluster characteristics for each soil layer which then in turn defined the spatial extent of each of the three zones.

Bulk density measurements are sensitive to changes in soil texture and moisture content making it unsuitable for VDT where soil texture is expected to change significantly in a short distance across the field and through the soil profile. Overcoming this limitation is therefore important and was achieved by adopting packing density instead of bulk density. Packing density takes account of the clay content of the soil thus transforming bulk density into a clay independent indicator of soil suitability for crop growth (Kaufmann 2008). The transformation was achieved using the equation developed by Renger (1970).

$$PD = BD + (0.009 \times CC)$$

where PD is packing density, BD is bulk density (g/cm3) and 0.009 CC is the correction term given as a product of clay content (CC) with the slope of the regression lines (Renger 1970).

Determination for the need and depth of tillage was based on the effect of packing density values on crop growth (Table 1). As can be observed tillage requirement starts from any packing density values in the upper optimum range (1.55-1.70 t/m3), but will be definitely needed for any packing density value larger than 1.70 t/m3. This was the guideline adopted in this work to calculate the need for variable depth tillage.

Table 1 - Packing density classifications for crop growth (Kaufmann 2008)

PD value (t/m^3)	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

Results and Discussion

Analysis of experimental site parameters.

Analysis of the site soil measurements revealed a predominately clay texture with a high organic matter (OM) range 10.9 % to 14.2% in the top 35 cm of the soil profile. At 40 cm and beyond the soil texture changes to clay loam with significantly less OM 3.6 % to 8.5 %. The general trend of the bulk density (BD) is that it increased with depth. In the shallow depths 5 – 15 cm, the topsoil remained in a range which would have little impact on crop growth in clay soils. However in the deeper soil, 20 – 40 cm, the BD increases within a much wider range indicating that VDT is suitable for this site. The soil moisture content varied very little with depth. In soil layers 5 to 25 cm the soil moisture was typically 38% ± 2%. At 30 cm and below the soil moisture reduced to 30%, in-line with the increasing bulk density.

The trend for penetration resistance was to increase with depth, which is in line with other research (Domsch et al. 2006; Chamen, 2011). Box plot analysis demonstrated the range of measurements increasing from 5 cm to 20 cm illustrating large penetration resistance variability within this region of the soil profile. Beyond 20 cm the range became much smaller, almost stable, at 25 and 35 cm suggesting tillage induced compacted where the repeated use of tillage equipment has formed a dense layer immediately below the plough pan e.g. > 35 cm. However, the trend of variation of bulk density with depth does not match that of bulk density confirming the penetration resistance measurement to be of less use to indicate soil compaction, since penetration resistance is simultaneously affected by moisture content, bulk density, organic matter content and soil texture (Kuang et al., 2013).

The ECa survey illustrated the spatial variation across the site with ECa values reducing from west to east, which indicates the increasing sand fraction and reducing clay fraction within the soil across that direction. This effect was not surprising because the influence of soil texture on the measured ECa values has been highlighted in previous research (Corwin and Lesch, 2005) where, soil with higher clay contents are expected to result in a higher measured value compared to soils with a higher content of sand fraction.

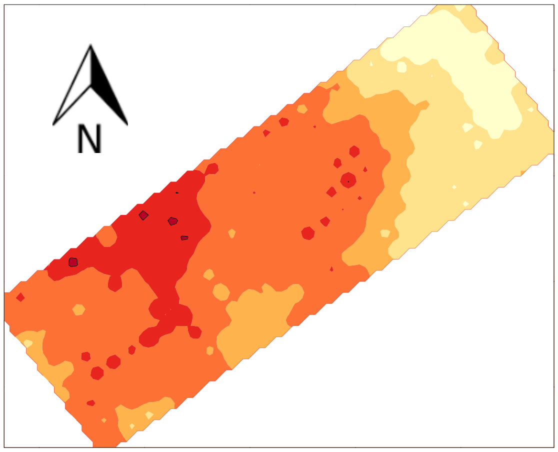

Figure 1 -Spatial variation of apparent electrical conductivity at 0 - 40 cm

Variable depth tillage management zones

Data processing

Multivariate k-means clustering was used for the creation of per layer management zones for the eight soil layers (Table 4-5). The selected variables were ECa at 40 cm (ECa 40) and 120 cm, (ECa 120), penetration resistance (PR), bulk density (BD) and moisture content (MC) with depth. Analysis parameters were set to maximise the initial Euclidean distance of the cluster separation whilst the cluster number was limited to three in order to minimise the amount of management zones created.

For analysis the normalised mean of each physical soil property was plotted at each depth (soil layer). A consistent feature of all the analysis is the high ECa value of cluster 2 and the low ECa value of cluster 3. The co-variables for these clusters also follow convention where a low penetrometer measurement is a function of a high moisture value and vice versa irrespective of the bulk density value. This is in line with findings of others where low soil resistance to penetration or soil cutting associated with high moisture content and vice versa (e.g. Mouazen et al., 2002). Cluster 1, on the other hand, has no consistency of ECa values being both high and low whilst the respective co-variables have no discernible pattern. The 20 cm depth is unique within the analysis as penetration resistance, bulk density and moisture content values of all three clusters converge irrespective of ECa value. This is indicative of a compacted layer and concurs with the soil physical property analysis discussed earlier.

Regarding soil compaction indicated as bulk density, cluster 1 had the highest bulk density in the soil layers down to 30 cm depth. Cluster 3 had the highest bulk density, which became of the largest bulk density in soil layers 30 and 35 cm, whereas cluster 3 has the highest bulk density for the soil layer of 35-40 cm.

Management Zone (MZ) maps by cluster analysis

The newly delineated clusters were plotted for the 8 individual soil layers using a Nearest Neighbour interpolation (Figure 2, a-h). The clustering process affords an a priori selection of cluster number which was set to three for this experiment. Using only three clusters, the pattern of variation is very distinct. Underlying trends of soil type are evident. Cluster 1 on the eastern side of the site, has an increased sand fraction when compared to the higher clay content soil on the western side which visually compares very well with the ECa results (Figure 1). Further evidence that these clusters process were closely related to soil texture can be drawn from box plot analysis that confirmed high bulk density values resulted in high penetrometer values thus indicating a natural clustering parameter and in line with what was expected. Cluster 3 demonstrated the most spatial variation across all depths. In the 0-5 cm and 5-10 cm there was a distinct change in cluster location from the small triangular area at the eastern extent 0-5 cm manifesting itself in a more general way at 5-10 cm. This was caused by the reducing bulk density values between a shallow layer of surface compaction and the looser soil just below. Cluster 3 has the most significant change in spatial extent occurring at 20 cm which was a result of the close alignment of normalised means of penetration resistance, bulk density and moisture content variables. Initially the map looked like a layer of compaction but this was discounted by the low bulk density means. A possible reason behind the spatial extent is the wide range of bulk density and penetration resistance values indicating a transient layer between the regularly cultivated surface and the less frequently cultivated subsoil. Below the 20 cm layer the clusters are spatially more stable, adding further evidence that 20 cm is a transient layer.

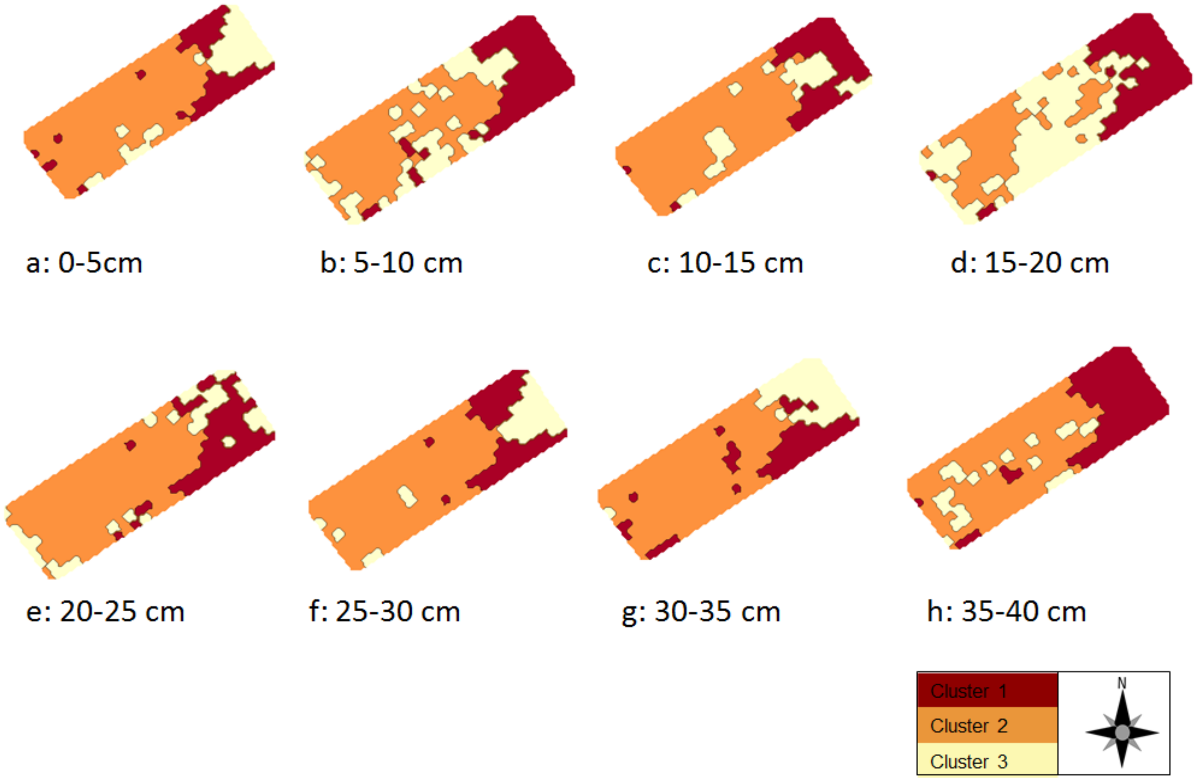

Figure 2 - Visualisation of the spatial extent of each cultivation management zone cluster, created using a nearest neighbour interpolation.

Derivation of packing density

Kaufmann (2008) highlighted that packing density is a better parameter to indicate soil compaction than bulk density because it transforms the bulk density value into a clay independent indicator by adding a correction term given as the product of clay content with the slope of the regression lines Using the equation developed by Renger (1970), the packing density values for the site were calculated.

For this research and according to the packing density classes in Table (1), values of packing density ≥ 1.7 t/m^3 were deemed to be yield and root growth limiting and tillage should be carried out. Results show the overall packing density range across the soil profile extends from 1.20 to 2.02 (Table 2). However, this range can be further sub-divided between the top 25 cm mean packing density of 1.45 - 1.53 t/m^3 and the lower 30 cm mean packing density range of 1.49 – 1.69 t/m^3. The reason for this stepped increase in packing density between the these two observed layers can be attributed to historical tillage practices where ploughing for root crops would often extend down to 25 cm, regularly disturbing the upper soil and potentially compacting the deeper sub soil with large vertical and shear forces.

Typically if a grower had identified a compacted layer like this he would look to remediate it with homogeneous deep tillage, which is an expensive and time consuming operation (Mouazen and Neményi, 1999). However with this approach of packing density cluster analysis it is possible to identify areas below 30 cm that do not require deep tillage offering the potential to reduce tillage depth saving money and resources. Examining the maximum packing density calculated per cluster in Table (2) reveals that values exceeding 1.6 t/m^3 already appear on the top layer of 5-10 cm deep, indicating the presence of surface compaction, and suggesting a gentle surface tillage to be considered down to 10 cm in the entire field. After this layer another layer but with critical values on crop growth can be observed at 15-20 cm layer in cluster 1 & 3, suggesting tillage of these two clusters only, whereas no tillage is needed for cluster 2. Going further down in the profile, it is observed that the presence of hard pan at cluster 1 and 2 at 30 cm layer which expands into cluster 2 at 35 cm layer, which has the highest packing density of 2.02 t/m^3. This may suggest the need for subsoiling down to 35 cm in cluster 2 in particular. At depth of 40 cm another compacted layer can be observed in the entire field with the three clusters.

Table 2 - Descriptive statistics of the packing density by cluster by depth.

Depth	Cluster	PD Mean	PD Min	PD Max	PD Std D
5 cm	1	1.43	1.35	1.53	0.05
	2	1.39	1.24	1.49	0.05
	3	1.31	1.20	1.39	0.04
10 cm	1	1.47	1.37	1.63	0.05
	2	1.46	1.46	1.60	0.03
	3	1.45	1.36	1.66	0.05
15 cm	1	1.44	1.39	1.60	0.05
	2	1.43	1.32	1.52	0.03
	3	1.40	1.34	1.47	0.03
20 cm	1	1.42	1.23	1.71	0.07
	2	1.43	1.30	1.63	0.06
	3	1.36	1.25	1.81	0.08
25 cm	1	1.53	1.44	1.66	0.05
	2	1.50	1.29	1.62	0.06
	3	1.45	1.31	1.54	0.05
30 cm	1	1.69	1.56	1.79	0.06
	2	1.61	1.43	1.81	0.07
	3	1.49	1.35	1.58	0.05
35 cm	1	1.49	1.42	1.64	0.03
	2	1.64	1.41	2.02	0.11
	3	1.42	1.25	1.65	0.10
40 cm	1	1.57	1.47	1.73	0.07
	2	1.58	1.32	1.89	0.08
	3	1.61	1.43	1.97	0.11

Where - green values indicates packing density values ≥ 1.6 (tillage may be required) and red values indicate packing density ≥ 1.7, where tillage should be carried out. Values highlighted in yellow indicate the final depths of tillage used for the VDT plan.

Variable depth tillage (VDT) plan

A VDT plan scaled in cm depth was developed using the area and depth of the yield limiting properties derived from the data found in Table 2. Cultivation depth was calculated as the depth of the largest maximum packing density value per cluster of each grid node + 3 cm. (The additional 3 cm was to ensure that the cultivator tine was sufficiently deep as to fully remove the compacted layer). The 40 cm depth layer was excluded from the tillage plan because of the distinctly different nature of the soil at that depth. Using the new the new depth attributes the data was interpolated using a nearest neighbour method to create a VDT plan (Figure 3).

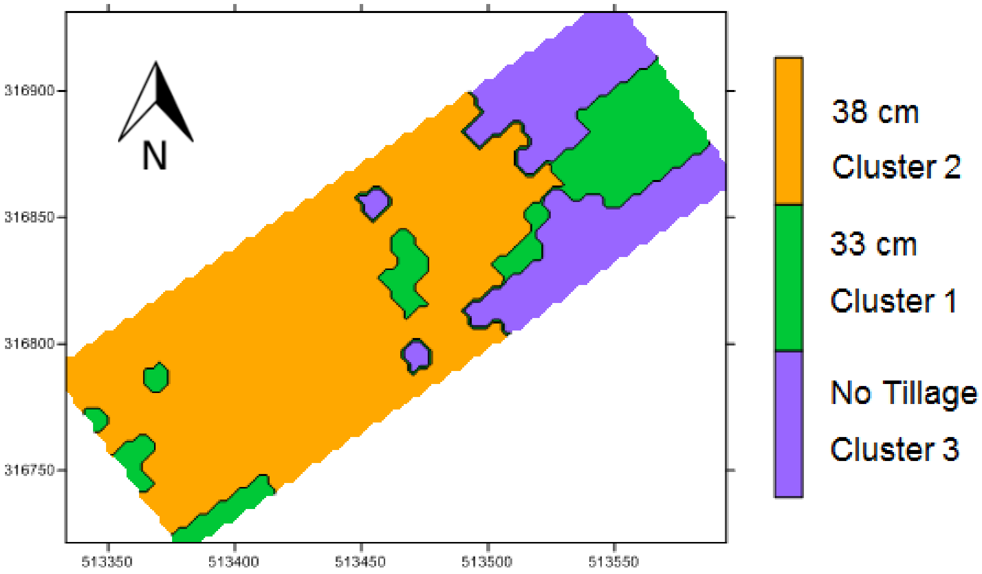

Figure 3 - Variable depth tillage plan illustrating the spatial variation of cultivation depth. Calculations based on the mean packing density values

From visual assessment, cluster 1 requires deep tillage down to 33 cm, cluster 2 requires deep tillage to 38 cm and cluster 3 requires no deep tillage, because at 23 cm the soil would be cultivated when the field is ploughed as part of the farms normal cultivation practice. On further analysis the depth zones within the VDT plan have a very close resemblance to the EMI scan results in Figure. (1). The deepest cultivation is required in the areas with the highest ECa values and vice versa. This is contrary to other studies where a negative correlation between recommended tillage depth and the soil ECa was found (Keskin et al 2011). In that study the soil was classified as Dothan sandy loam where the maximum ECa value was recorded at 7 mS/m2 in comparison to the 46 mS/m2 of the clay loam measured for this work. A possible reason for this contradiction could be that the current work takes into account all affecting factors to estimate the packing density, being the real parameter representing the soil compaction. This may also indicate the correct concept used in the current work and that the multi-sensor and data fusion approach is the way forward for optimising VDT.

Conclusions

In this research the assessment of soil compaction, indicated as packing density was successfully carried out for eight separate soil layers based on a multi-sensor data fusion approach. Measured values of soil penetration resistance (PR), apparent electrical conductivity (ECa), clay content (CC), bulk density (BD) and soil moisture content (MC) were fused by means of k-means clustering to delineate per layer management zone maps. The decision to cultivate or not to a certain depth was derived by calculating the packing density of each delineated zone. From the results of this research the following conclusions can be made:

1. The multi-sensor data-fusion approach can be used successfully to provide key information sufficient to derive a soils state of compactness as an indicator of whether to cultivate or not to a certain depth.

2. K-means multivariate clustering enabled the affecting soil physical soil parameters on soil compaction to be fused together to delineate management zones suitable for variable depth tillage. The user can also control the size and number of management zones thus reconciling the practical field management implications.

3. Because packing density is dependent on soil texture (e.g. per cent clay), it is a more suitable indicator of soil compaction than bulk density for variable depth tillage.

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