African Journal of Agricultural Research Vol. 6(11), pp. 2506-2515, 4 June, 2011
Available online at http://www.academicjournals.org/AJAR
DOI: 10.5897/AJAR11.071
ISSN 1991-637X ©2011 Academic Journals

Full Length Research Paper

Characterization of paddy soil compaction based on soil apparent electrical conductivity zones

Mastura M.[1]*, Amin M. S. M.[1,2] and Aimrun W.[1]

[1]Smart Farming Technology Laboratory, Institute of Advanced Technology, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.
[2]Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

Accepted 22 March, 2011

Soil apparent electrical conductivity (EC_a) is one of the most common and frequently used measurements to determine field soil variability, especially for precision farming. Soil cone index (CI) is a measure of soil compaction that poses a big challenge for water management in poorly drained soils. The soil compaction affects the root penetration and development of the rice plant. The purpose of this study was to characterize the CI within the EC_a zones for a Malaysian paddy soil. The study of soil compaction and EC_a was conducted on silty clay paddy soil at Sawah Sempadan, Tanjung Karang, Selangor (latitude 3°35" N and longitude 101°05" E). Measurement of EC_a and CI were done using Veris 3100 and hand-operated soil cone penetrometer, respectively. The deep EC_a (EC_ad) was compared to the minimum, mean and maximum CI and also within EC_ad zone. The maximum CI was found at 0.147 MPa with average maximum at 0.081 MPa. The results indicate that the hardest layer exists at a depth of 10 to 20 cm. EC_ad in Zone 2 (50 to 100 mS m^{-1}) showed that the CI values have the highest significant negative correlation with EC_ad. The significant correlation of EC_ad and soil cone index was found at mid range of the soil EC_ad.

Keywords: Zone delineation, paddy field, cone index, regression.

INTRODUCTION

Soil variability always exists within a field and can be mapped using some precision farming tools and software. Corwin and Lesch (2003) found that the soil electrical conductivity has become one of the most frequently used measurements to characterize field variability for application of precision farming. Soil sensor such as the Veris EC sensor is a useful tool in mapping soil apparent electrical conductivity (EC_a) in order to identify areas of contrasting soil properties (Amin et al., 2004; Aimrun et al., 2007). The bulk soil electrical conductivity measurement called soil apparent electrical conductivity (EC_a) measures conductance through soil solution and solid soil particles and also via exchangeable cations which exist at the solid-liquid interface of clay mineral (Corwin and Lesch, 2003).

Paddy soil is basically compacted which is caused by vehicle traffic such as tractors and combine harvesters. When soil is compacted, there are changes in physical properties of soil such as, soil structure, pore space, and density, which play an important role in the growth and development of plants (Sudduth et al., 2008). Soil compaction has been used to assess root growth and penetration. The soil compaction is measured by the value of cone index. The higher the cone index, the greater is the amount of energy that must be expended by the roots to widen the soil pores (Chen et al., 2005).

The cone index (CI) is a measure of a soil's resistance to penetration and is regarded as an indicator of soil strength. Two distinct peaks in the CI profile are labeled hardpan and fragipan depth where it can be determined, based on value of CI. The CI must have at least three consecutive data points that exceed 1 MPa (145 psi) to be classified as hardpan layer as mentioned by

---

*Corresponding author. E-mail: cekmas2ra@yahoo.com. Tel: + 603-89468469, +603-86566061.

Abbreviations: **EC_a,** Apparent electrical conductivity; **CI,** cone index; **EC_ad,** deep EC_a; **EC_as,** shallow EC_a; **TAKRIS,** Tanjung Karang rice irrigation scheme; **r,** coeficient of correlation.

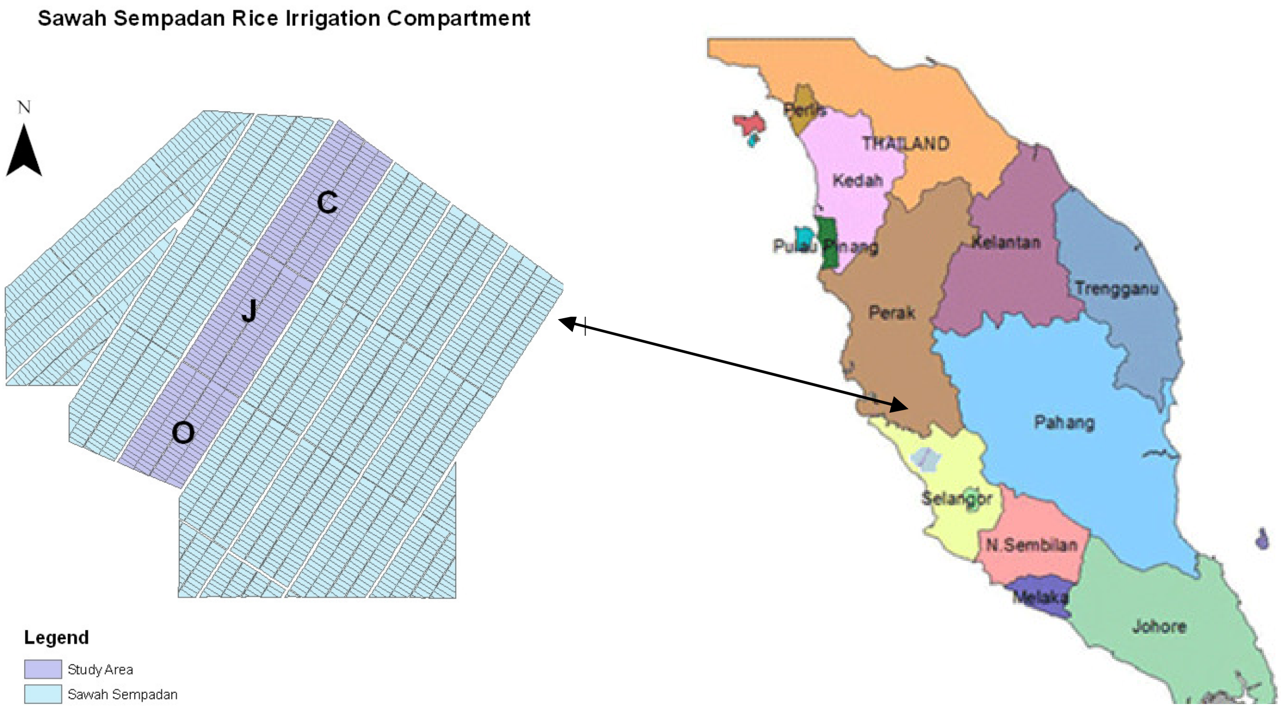

Figure 1. Study area at blocks C, J, and O at TAKRIS, Tanjung Karang, Selangor, Malaysia.

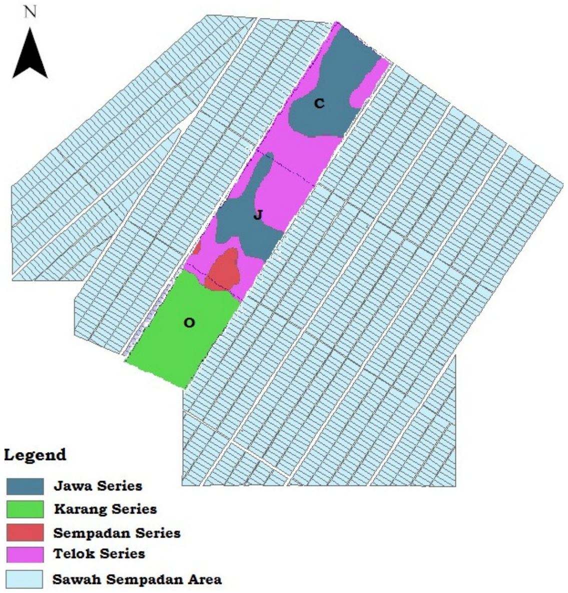

Figure 2. Soil series in blocks C, J and O, covering area of 380 ha in Sawah Sempadan showing Jawa, Karang, Sempadan and Telok series.

Isaac et al. (2002) for maize plant. The readings of cone penetrometer require a “stop-and-go”, making it difficult to collect enough data to accurately map compaction variations within a field (Sudduth et al., 2008).

Assessment and interpretation of spatial variability of soil compaction and apparent electrical conductivity are very important for precision farming. Farmers need quick, reliable, and inexpensive technique and sensing technology to measure soil variability such as soil compaction and other properties that can characterize soil variability in their fields. The objective of this study was to characterize the relationship between EC_a and the soil profile based on CI for identifying soil variability in a paddy field in a humid tropical region practicing double cropping of rice per year.

MATERIALS AND METHODS

Study site

This study was conducted at Sawah Sempadan irrigation compartment, of the Tanjung Karang rice irrigation scheme (TAKRIS), (Figure 1) in the district of Kuala Selangor, Malaysia. The total area of Sawah Sempadan is 2,300 ha and divided into 24 blocks namely Blocks A to X. However, only blocks C, J and O were selected. Each block consists of about 100 lots and the size of each lot is 1.2 ha (200 × 60 m). These three blocks are located on the same tertiary irrigation canals and block C is located in the upstream, close to the main canal, and then followed by blocks J and O. The total area was 380 ha with 312 paddy lots. The soil series for the whole area are *Jawa (Sulfic Tropaquept), Teluk (Sulfic Tropaquept), Sempadan (Sulfic Tropaquept)* and *Karang (Thypic Sulfaquept),* (Aimrun et al., 2002) and can be referred on Figure 2. The soil series were grouped as acid sulfat soil from this order; mineral soil-alluvium soil- marine alluvium (parent material)-acid sulfat soil. The characteristics are having poor drainage and fine texture. The field study was carried out in December 2007 after harvest of the second season.

Figure 3. The veris 3100 sensor showing GPS receiver and six coulters to determine electrical resistance across the soil profile.

Soil apparent electrical conductivity

Data acquisition of EC_a was obtained by using a sensor known as Veris 3100 sensor (Figure 3). The sensor was pulled across each field behind a tractor in a series of parallel transects spaced about 15 m apart. The sensor was calibrated using an Ohmmeter to ensure that its resistance is lesser than 2 Ohm. This sensor was used in conjunction with a differential global positioning system (DGPS) receiver and Veris data logger. The EC_a data were geo-referenced to create spatial variability map.

The sensor has three pairs of coulter-electrodes to determine soil EC_a. The coulters penetrate the soil into a depth of 6 cm. One pair of the coulter emit an electrical current and the other two pairs detect the resistance (Lund et al., 1999; Amin et al., 2004; Aimrun, 2006). The six coulters can be named and arranged as 1, 2, 3, 4, 5 and 6 from left to right. The center pair (plates 2 and 5) passes the electric current (reference) into the soil. The coulters 3 and 4 integrate resistance between depths of 0 and 30 cm (shallow), while the outside pair (coulter plates 1 and 6) integrates the electrical resistance between 0 and 90 cm (deep). The veris data logger recorded the latitude, longitude, elevation, shallow EC_a (EC_as) and deep EC_a (EC_ad) data (mS m^{-1}) in an ASCII text format. The reading of EC_a in the data logger is conversion of resistance to conductivity (1/resistance=conductivity). The EC data logger was available to receive reading only when DGPS signal was available. The data were then transfered from the data logger to a computer. The data quality screening was done by removing all negative values and it is generally not more than 10% of the total data count, otherwise it should be collected again.

Zone delineation based on EC_ad

The EC_a data in ASCII format was transferred from the veris data logger to a diskette and then to a computer. ArcGIS software was used to view, analyze the EC_a data and to create a map. Spatial analysis was done to interpolate the data using kriging method, and then to produce the soil EC_a variability map. The EC_ad zones were delineated to three classes or zones. Zone 1 was defined as low for the EC_ad value lesser than 50 mS m^{-1}, zone 2 was defined as moderate (51 to 100 mS m^{-1}), and zone 3 was defined as high for EC_a value of higher than 100 mS m^{-1}. The sampling point were decided based on these zones. The EC_ad was chosen as a map base for zone delineation, because it was found that the zone pattern is always similar for many seasons (Aimrun, 2006). Chinthia et al. (2001) stated that field classification zones using EC_a can provide an effective map for soil sampling.

Figure 4a shows soil variability map for Block C which is located in the upstream and close to the main canal. The map of EC_ad showed the variability clearly, especially for low and high EC_a levels. Earlier study by Aimrun (2006) and Aimrun et al. (2009) also found the pattern of a former river clearly as continuous lines in the northern and central regions of the study area. The former river was about 45 m wide. The kriging map of Block J (Figure 4b) shows the variability of EC_ad only for moderate and high level. The level EC_ad for Block O (Figure 5 c) was high with EC_ad value of more than 100 mS m^{-1} and no variability were found in this block. Block O is located closer to the sea (approximate 7 km) indicating higher salt content, hence, higher EC_ad compared to the other blocks (approximate 11 km).

Sampling points

The soil samples were taken from 30 points within the study area. Figure 4 shows the soil variability map used for determing the sampling points. For zones 1, 2 and 3, the number of soil sampling points were 12, 10 and 8 points, respectively. Block C had high variability (three zones were found), so more points were collected from this area (15 points). Block J had lower variability than Block C, and Block O had no obvious variability. The total numbers of sampling points were 8 and 7 points for Block J and O, respectively.

The cone index measurement

The soil compaction was determined by using CI value, based on soil resistance to penetration. The hand-operated soil cone penetrometer was used in this study following the American Society of Agricultural Engineering (ASAE) standards (S313.2) (ASAE, 1999). The equipment has cone base size of 32.3 cm² and 2.027 cm diameter, with 1.6 cm diameter shaft for soft soil. Graduation on the driving shaft is 2.54 cm apart and used to identify the depth of hand- operated device (Figure 5). The equipment was pressed up to 50 cm from the soil surface and the readings were recorded

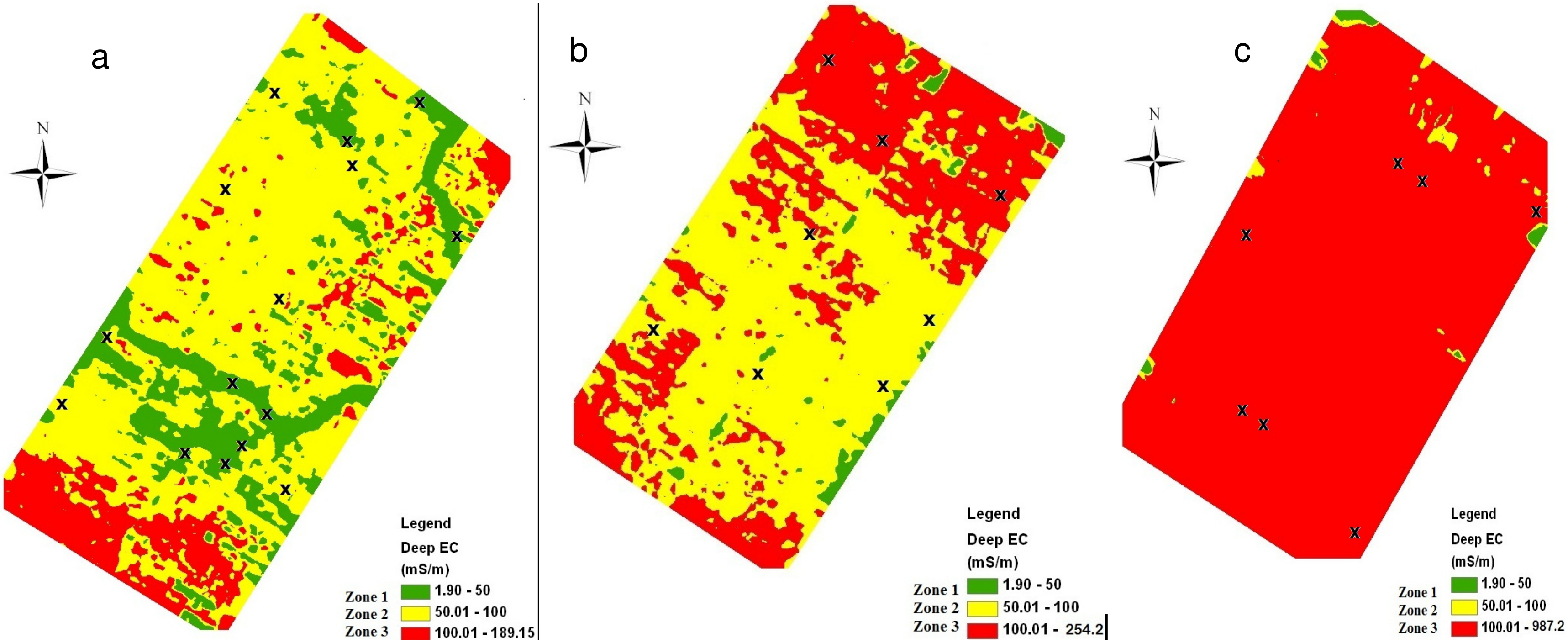

Figure 4. Kriging map of $EC_a d$ for determining soil sampling points; (a) Block C; (b) Block J; and (c) Block O. Sampling point are marked by (x).

at every 2.5 cm (1 inch). The cone Index (CI) is defined as the force per unit area required to push the penetrometer through a specified small increment of soil. CI can be calculated by using the formula:

Cone index (MPa) = (division × 0.05 kg × 9.81×10^{-6}) ÷ A (m^2)

Where: 1 division in pressure gauge = 0.05 kg and A is cone basearea (3.23×10^{-4} m^2)

Statistical analysis

It is known that we can never be completely (100%) certain that a relationship exists between the two variables. There are too many sources of error to be controlled, for example, sampling error, researcher bias, problems with reliability and validity and simple mistakes. Correlation is a type of analysis to find the relation between two variables and show how the variables are related. The purpose is to get the significant relation and explainable by considering the value of r. The bivariate correlation procedure was chosen to determine the correlation. Pearson correlation was selected because the relation between variables is a linear association.

Regression analyses were run to see the prediction model from independent variable with dependent variable. Before this analysis was run, the correlation was done to make sure the variables have significant correlation to each other. There are two types of regression, that is, linear and non-linear. Linear regression was chosen to find the prediction of one variable with another variable. The analysis shows the prediction model from multiple dependent variables. The R^2 was used as an indicator to determine how well the model fits the given data. The highest R^2 was chosen as the best model. Ronnie et al. (2003) used stepwise method in regression analysis and found that EC_a was often a key loading factor that changes in soil texture.

RESULTS AND DISCUSSION

Soil apparent electrical conductivity

The EC_a measurements were integrated over a soil depth of 0 to 30 cm for $EC_a s$ and 0 to 90 cm for $EC_a d$. Total number of EC_a data was 115 908

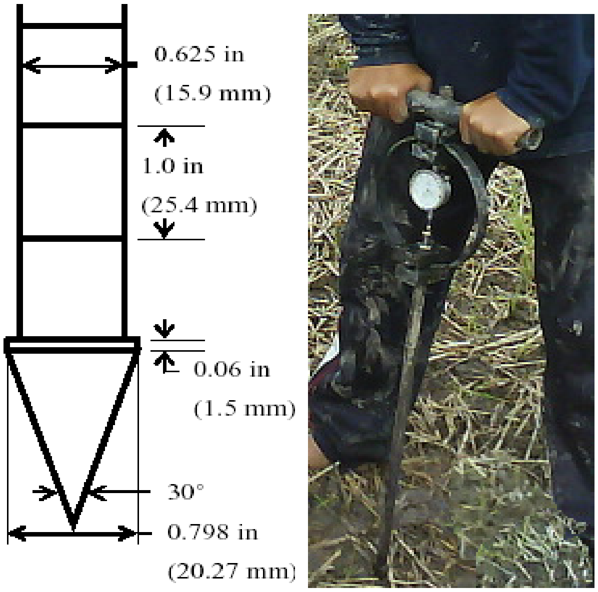

Figure 5. The ASAE standard cone and hand-operated cone penetrometer pushed into the paddy soil profile.

Table 1. Descriptive statistics for EC_a.

Block	EC_a	n	Min	Max	Mean	Std.D	CV
Block C	EC_as	48070	1.00	369.6	43.63	19.3	41.5
	EC_ad	48070	1.00	413.70	73.0	33.5	45.9
Block J	EC_as	37937	1.00	346.1	42.21	15.7	37.3
	EC_ad	37937	1.00	933.6	96.86	32.8	33.9
Block O	EC_as	29901	1.00	307.60	116.61	46.3	39.7
	EC_ad	29901	1.00	992.5	254.29	80.1	31.5
At sampling points	EC_as	30	7.89	163.57	55.22	38.2	69.2
	EC_ad	30	11.0	370	108.3	90.3	83.4

*n = No. of sampling point samples.

points for an area of 380 ha. The average number of EC_a data for each lot was 366 points and slightly lesser as compared to 500 points used by Aimrun et al. (2007) for their research at Seberang Perai paddy field, Pulau Pinang. The number of data depended on the speed of the tractor and the condition of the soil surface. With the logging interval of one second, a slow drive can collect more data points (Amin, 2004).

The descriptive statistics of soil EC_a within the 3 blocks are shown in Table 1. The values of EC_as at sampling points were found to be 7.89, 163.57 and 55.2 mS m^{-1} for minimum, maximum and mean, respectively. For EC_ad, the values of minimum, maximum and mean were 11.00, 370.00 and 108.3 mS m^{-1}, respectively. The CV$_s$ For EC_as and EC_ad, were 69.2 and 83.41%, respectively. This higher CV of the sampling points were due to the zones of the soil variability map. The mean EC_as values at Block C, J and O were 43.63, 42.21 and 116.6 mS m^{-1}, respectively. The mean EC_ad values at Block C, J and O were 73.0, 96.86 and 254.29 mS m^{-1}, respectively.

The results showed the values of EC_a increased from Block C to O (upstream to downstream). This happened because the soils in Block O and Block C are too different in their characteristics. As can be observed, soils in Block O have very shallow topsoil layer and greyey soil was found at very shallow depth. While Block C has lower average EC_a because of many areas are occupied by peat soil and acid sulfate for *Jawa* and *Telok* series. The

Table 2. The classes of CI values.

Depth	Depth 1	Depth 2	Depth 3	Depth 4
cm (Inches)	0 to 13 (0 to 5)	13 to 26 (5 to 10)	26 to 39 (10 to 15)	39 to 52 (15 to 20)

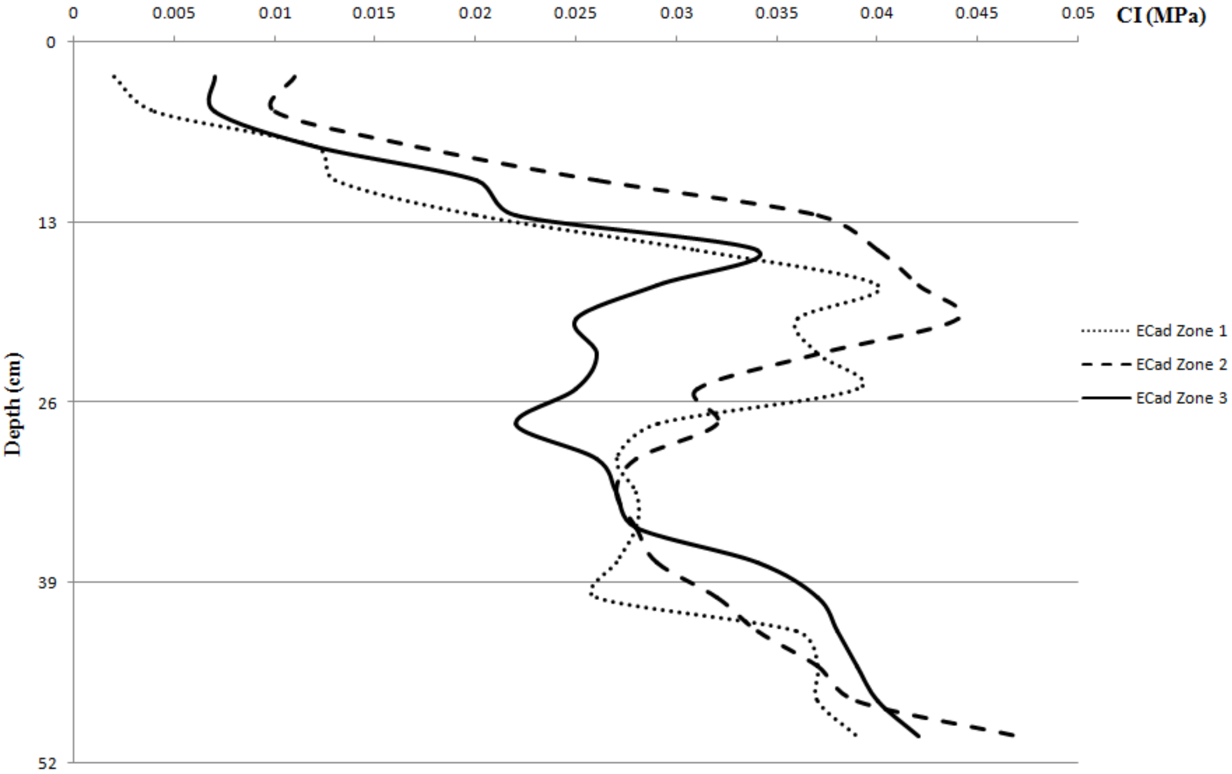

Figure 6. Graph of minimum CI values with paddy soil depth for various EC_ad zones.

mean values of the EC_ad were higher than those at the shallow depths. The effect of soil parent materials at the subsoil layer probably caused the higher EC_a values (Aimrun, 2006).

Previous studies in paddy fields at Malaysian Agricultural Research and Development Institute (MARDI) Seberang Perai Station, Penang, by Aimrun et al. (2007) found the values for EC_as ranged from 0.9 to 64 mS m^{-1} with the average and standard deviation of 5.67 and 3.04 mS m^{-1}, respectively for an area of 9 ha. The EC_ad values from 5202 data points ranged from 1.3 to 48.9 mS m^{-1} with the average and the standard deviation of 9.1 and 6.8 mS m^{-1}, respectively. Comparing these two sites, the data of EC_a at Sawah Sempadan were higher than those at Seberang Prai, Pulau Pinang. The percentages of clay were found to have positive correlation with EC_a with values for Sawah Sempadan and Seberang Perai of 46.77 and 21.68 %, respectively. The low EC_a at Seberang Perai was probably due to less clay particles to transmit the electric current.

Cone index

The values of CI were randomly divided into four depths according to depth of penetration of the soil profile (Table 2). The groups were depths 1 to 4. These small groups eased evaluation of the data. The studies by Bockari-Gevao et al. (2005) at Sungai Burong Compartment (latitude 3° 35" N and longitude 101° 05" E) of the TAKRIS, found the values of cone index ranged from 0.11 to 0.28 MPa. Whereas, the results of this study were lower (0.02 to 0.147 MPa). These were possibly due to the different soil series in that area. The soil series in Sungai Burong study site is *Selangor Series and* has medium soil texture compared to fine texture for soil series (*Telok and Jawa*) in this study area (Sawah Sempadan). The study at Kerian paddy field, Perak, Malaysia, by Ngoo and Burkhanuddin (2008) found peak CI at 0.15 MPa. These similar CI was probably due to same parent material (marine alluvium).

Figures 6, 7 and 8 show the graph of CI for minimum,

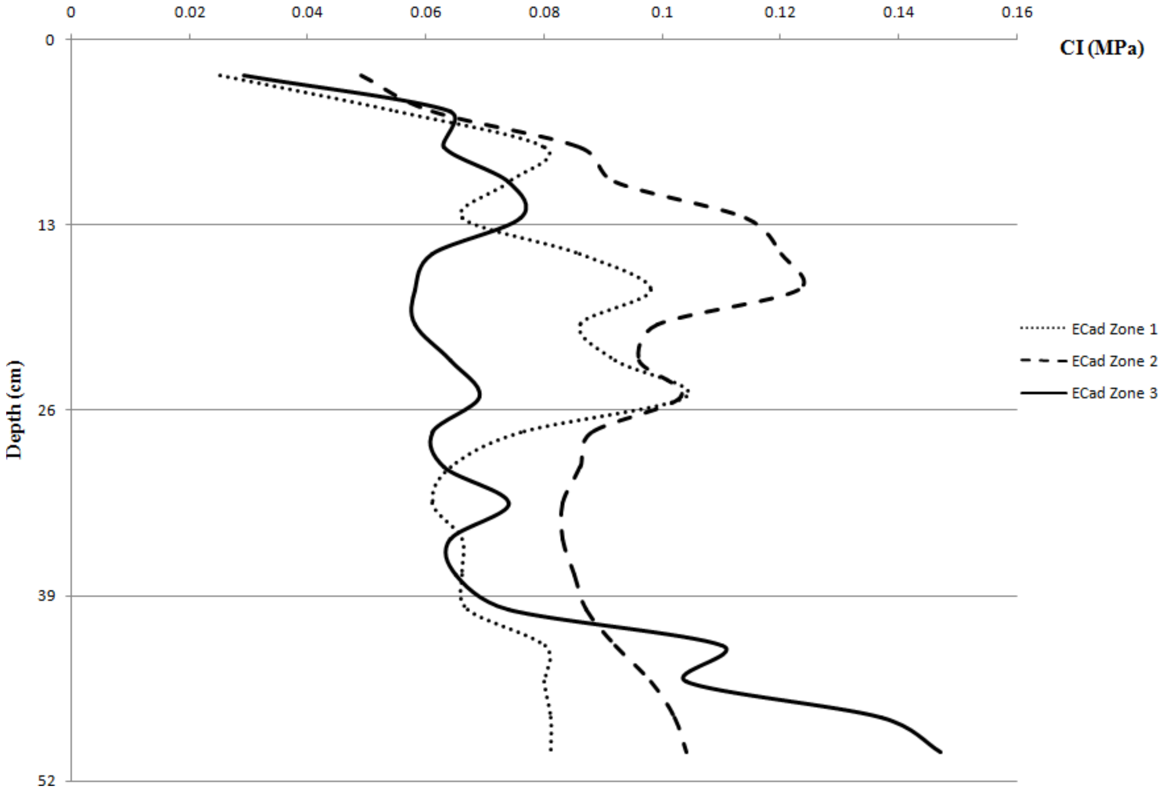

Figure 7. Graph of maximum CI values with paddy soil depth for various EC_ad zones.

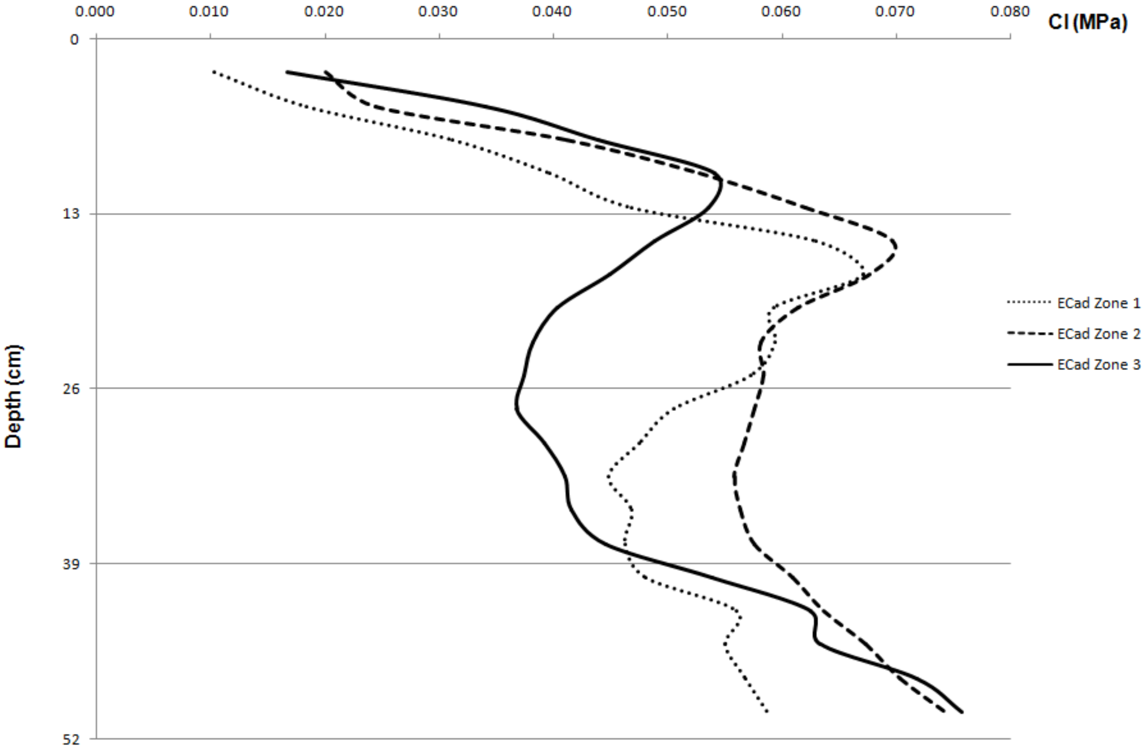

Figure 8. Graph of mean CI values with paddy soil depth for various EC_ad zones.

Table 3. The significant correlation of CI and soil EC_a with soil depth, n= 30.

CI	EC_a	Depth 1 (< 13 cm)	Depth 2 (13 to 26 cm)	Depth 3 (26 to 39 cm)	Depth 4 (> 39 cm)
Min.	EC_as	ns	-0.442*	ns	ns
	EC_ad	ns	-0.523**	-0.05*	ns
Mean	EC_as	ns	-0.445*	ns	ns
	EC_ad	ns	-0.541**	ns	ns
Max.	EC_as	ns	-0.383*	ns	ns
	EC_ad	ns	-0.475**	ns	ns

** Correlation is significant at the 0.01 level; * Correlation is significant at the 0.05 level.

maximum and mean values within each zone based on spatial variability map of EC_ad. The graphs increased continuously and reached a peak MPa at depth 2 (13 to 26 cm) and then decreased at depth 3 but increase again at depth 4. The maximum compaction was found as only 0.147 MPa. The hardpan is described as the layer harder to penetrate and no roots are usually found between 10 and 30 cm from the surface (Aimrun et al., 2010; Ngoo and Burkhanuddin, 2008)

Measurements of CI indicated that the hardest layer or the most compacted layer existed at approximately 16 cm depth. The graph shows the CI at EC_ad zone 2 is higher than in zone 1 and 3. This means that mid range EC_a at 51 to 100 mS m^{-1} has highest CI. The CI at zone 3 is lowest; therefore, it has the softest soil or the least bearing capacity indicating the weakest soil strength to withstand the weight of a combine harvester during harvest. Most of the areas of Block C were in zone 3. From the visual observation, combine harvester and tractors were always bogged down due to low bearing capacity on areas with low CI values.

Correlation analysis

The matrix correlation of EC_a and cone index was determined by Pearson's 2-tailed technique in SPSS statistical software. There were two relations founds, each group of CI with EC_a zones and CI within each EC_ad zone. The results of correlation analysis between soil EC_a and cone index were clustered based on the soil depth. Table 3 shows EC_ad has significant negative relation with mean CI at 15 to 25 cm (depth 2) with coeficient of correlation, (r) of -0.541** at 0.05 significance level. EC_as also has the same correlation with r = -0.445* at 0.01 significance level. For maximum values of CI, the condition is the same where it has significant negative correlation with deep and EC_as at 15 to 25 cm with r = -0.475** and 0.383*, respectively. Minimum values of CI also give the same results and correlation where r = -0.523** and 0.445*, respectively. The results show that EC_ad has better correlation compared to EC_as by considering the significance level.

Table 4 shows the significant correlation for CI and EC_a within EC_ad zone. The soil EC_a values were found to have significant negative correlation at zone 2 of EC_ad. Each depth of CI has significant negative correlation with minimum, mean and maximum CI except for depth 1. No significance (ns) was found in the other zones.

Regression analysis

The tests showed that EC_ad have significant correlation to CI within Zone 2. The regression analysis showed that CI could be estimated by using EC_ad. The CI in paddy soils was apparently not influenced by EC_as because no significant correlation was found. Prediction models were developed for each depth except for depth 1 since there was no significant correlation. Table 5 shows the equations to estimate CI based on the EC_ad values. Each model only used EC_ad as independent variable because there was no significant correlation found with EC_as. The constants of the models are different for each model but the coefficients remained the same at 0.001. The general equation is the form of: CI = a – (0.001 EC_ad) with R^2 ranging from 0.318 to 0.784.

The study showed that the spatial variability of the soil apparent electrical conductivity varied highly at Block C as compared to Blocks J and O. Soil EC_ad and EC_as have significantly negative correlation with cone index at depth 2 (13 to 26 cm) where the highest soil compaction occurs. The study shows that EC_ad can be used as an indicator to determine the hardest layer in the paddy field with mid range EC_ad (zone 2). The hardest layer is found typically between 13 to 26 cm (depth 2).

ACKNOWLEDGEMENTS

The authors would like to thank members of the Precision Farming Engineering Research and Development (PREFERD) group for their assistance in data collection and analysis. The financial support from MOSTI is

Table 4. Correlation of CI and soil EC_ad zones 1, 2 and 3.

Zone and EC_ad		EC_a	Depth 1	Depth 2	Depth 3	Depth 4
Zone 1 (1 – 50 mS m^{-1}) n = 12	Min	EC_as	ns	ns	ns	ns
		EC_ad	ns	ns	ns	ns
	Mean	EC_as	ns	ns	ns	ns
		EC_ad	ns	ns	ns	ns
	Max	EC_as	ns	ns	ns	ns
		EC_ad	ns	ns	ns	ns
Zone 2 (51 – 100 mS m^{-1}) n = 10	Min	EC_as	ns	ns	ns	ns
		EC_ad	ns	-0.765**	-0.849**	-0.897**
	Mean	EC_as	ns	ns	ns	ns
		EC_ad	ns	-0.731**	-0.858**	-0.877**
	Max	EC_as	ns	ns	ns	ns
		EC_ad	ns	-0.617*	-0.871**	-0.858**
Zone 3 (101 mS m^{-1} and upward) n = 8	Min	EC_as	ns	ns	ns	ns
		EC_ad	ns	ns	ns	ns
	Mean	EC_as	ns	ns	ns	ns
		EC_ad	ns	ns	ns	ns
	Max	EC_as	ns	ns	ns	ns
		EC_ad	ns	ns	ns	ns

Table 5. Model development for CI in zone 2.

	Depth	Model developed	R^2
Minimum	Depth 2	0.136 – (0.001 × EC_ad)	0.543***
	Depth 3	0.134 – (0.001 × EC_ad)	0.693***
	Depth 4	0.163 – (0.001 × EC_ad)	0.784***
Mean	Depth 2	0.148 – (0.001 × EC_ad)	0.487***
	Depth 3	0.141 – (0.001 × EC_ad)	0.709***
	Depth 4	0.171 – (0.001 × EC_ad)	0.746***
Maximum	Depth 2	0.162 – (0.001 × EC_ad)	0.318**
	Depth 3	0.150 – (0.001 × EC_ad)	0.743***
	Depth 4	0.179 – (0.001 × EC_ad)	0.711***

acknowledged. The invaluable assistance from members of the Smart Farming Technology Laboratory, Institute of Advanced Technology (SFTL, ITMA), Universiti Putra Malaysia (UPM) is highly appreciated.

REFERENCES

Aimrun W (2006). Paddy field zone delineation using apparent electrical conductivity and its relationship to the chemical and physical properties of soil. Unpublished phd's thesis, Universiti Putra Malaysia, Serdang, Malaysia.

Aimrun W, Amin MSM, Ahmad D, Hanafi MM, and Chan CS (2007). Spatial variability of bulk soil electrical conductivity in a Malaysia paddy field: Key to soil management. Paddy Water Environ., 5: 113-121.

Aimrun W, Amin MSM, and Ezrin MH (2009). Small scale spatial variability of apparent electrical conductivity within a paddy field. Applied and Environmental Soil Science. Volume 2009, Article ID 267378, 7 pages doi:10.1155/2009/267378

Aimrun W, Amin MSM, and Gholizadeh A (2010). Spatial Variability of Irrigation Water Percolation Rates and Its Relation to Rice Productivity. Amer. J. Appl. Sci., 7(1): 51-55.

Aimrun W, Amin MSM, Mokhtaruddin MM, Eltaib SM (2002). Determination of physical properties in lowland rice area of Tanjung Karang Irrigation Scheme, Malaysia. Proceedings of the 2nd World Engineering Congress, Sarawak, Malaysia, 22-25 July 2002.

Amin MSM, Aimrun W, Eltaib SM, Chan CS (2004). Spatial soil variability mapping using electrical conductivity sensor for precision farming of rice. Inter. J. Engine. Technol., 1(1): 47–57.

ASAE (1999). Soil cone penetrometer. S313.2, ASAE Standards, 46 editions.

Bockari-Gevao SM, Wan Ishak WI, Azmi Y, Teh CBS (2005). Soil tilth index for Malaysian paddy fields. Malaysian J. Sci., 9: 53-63.

Chen Y, Cavers C, Tessier S, Monero F, Lobb D (2005). Short-term tillage effects on soil cone index and plant development in a poorly drained, heavy clay soil. Soil and Tillage Res., 82: 161-171.

Chinthia KJ, Doran JW, Wienhold BJ, Shanahan JF (2001). Field-Scale Electrical Conductivity Mapping for Delineating Soil Condition. Soil Sci. Soc. Am. J., 65: 1829-1837.

Corwin DL, Lesch SM (2003). Soil electrical conductivity in precision agriculture. Agron. J., 95: 455-471.

Corwin DL, Lesch SM (2005). Apparent soil electrical conductivity measurements in agriculture. Comput. Electron. Agric., 46: 11-43.

Isaac N, Taylor R, Staggenborg S, Schrock M, Leikam D (2002). Using cone index data to explain yield variation within a field. Agricultural Engineering Inter. CIGR J. Sci. Res. Develop, Manuscript PM 02 004. Vol. IV.

Lund ED, Christy CD, Drummond PE (1999). Practical applications of soil electrical conductivity mapping. Proceedings of the 2nd European Conference on Precision Agriculture, Odense, Denmark, 11-15 July 1999.

Ngoo TY, Burkhanuddin A (2008). Investigating Soil Trafficability in Kerian Paddy Areas.Technical paper. http://www.nahrim.gov.my/my/the-news/kertas-teknikal.

Ronnie WH, Robert GM, David EC (2003). Using soil electrical conductivity to improve nutrient management. Agron. J., 95: 508-519.

Sudduth KA, Sun OC, Pedro AS, Shrinivasa KU (2008). Field comparison of two prototype soil strength profile sensors. Comput. Electron. Agric., 61: 20-31.