PREDICTING PADDY SOIL PRODUCTIVITY

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ABSTRACT

Paddy soils are naturally heterogeneous in terms of their physico-chemical properties which affect rice productivity. Currently, uniform application of agricultural inputs on the entire field is not efficient and could result in either insufficient or excess nutrient supply. Good agricultural practices can be achieved if soil and nutrient variations within a farm are considered, and a soil-yield interrelationship is established. Thus, simple and rapid methods to characterize soil properties differences are needed. This study was conducted on two different plots in MARDI research station, Malaysia. The soils were sampled at two depths and analyzed for the physico-chemical properties. Crop cutting test yields were taken at the same soil sampling locations. Geo-referenced ECa measurements were obtained by using Veris 3100 cart equipped with a differential global positioning system. The results of correlation analysis showed that the coefficients between yield and soil measurements were generally low and inconsistent for both 9-ha and subsurface drainage plots. On the contrary, when the two plots data were pooled and correlated, the coefficients between yield and soil measurements were high, consistent, and significant. A boundary line using a log-normal function was fitted to the upper edge of data in the scatter plots. Significant relationships between potential grain yield (Ypo) and ECa were detected with $r^2 > 0.8$ in four out of six cropping seasons. Comparison of Ypo and observed yield (Yob) delineated farm areas into different management zone and allows for discriminate fertilizer application, thus avoiding under or over-fertilisation.

Keywords: *Soil Electrical Conductivity, Paddy Soil Productivity, Veris Machine, Physical Chemical Properties of Paddy Soil*

INTRODUCTION

Paddy soils are naturally heterogeneous. Complex inter-relationships existing between physical, chemical and biological soil properties have long been recognised. Their responses along with management-induced soil changes like tillage, liming and fertiliser amendments result in soil variation within cropped fields [1,14,17]. Apart from spatial variation, there is also temporal variation, such as nutrient status. The variation of soil properties in space and time implies that soils have varying capacity to retain and supply nutrients to rice crop. This makes it difficult to correctly manage field input applications.

Currently, agricultural inputs such as seeds, irrigation, fertilisers, and pesticides have been applied as evenly as possible over a given field, but the yield at the end of the growing season often varies across the field. Changes in soil texture, organic matter, salinity, subsoil characteristics, and water holding capacity are all factors that can cause changes in yield. Perhaps, it may be more economical to apply different amounts of agricultural inputs to sections of the field that have different soil properties. To do this, good field maps showing how soil changes across the fields are needed.

Traditional soil surveys for each sampling unit coupled with climatic information often provide estimates of crop productivity and suitability of crop type [30]. Detailed soil productivity indices have been developed using soil properties to characterise the variability between soil types at field-level [4,7,8,16,22] and regional [12,31] scales. However, measurements required to calculate soil productivity indices on individual fields are expensive and time consuming, since site evaluation through soil sampling followed by intensive laboratory analysis is required. Hence, spatially-dense soil sampling has not been widely adopted by crop producers.

Spatially referenced soil sampling either by random soil sampling or on a regular grid is now routinely used to create maps for soil variability for variable-rate fertiliser and lime application. Another method to map soil variability is from direct measurement of spatial crop productivity by yield monitoring. However, yield maps are confounded by many potential causes of yield variability like pest incidence, nutrients, and management variations. Averaging multiple years of yield maps has been suggested as another way of establishing stable yield productivity patterns related to soil properties [20,26,32]. However, in some regions, high producing fields during the wet seasons can be adversely affected in dry seasons. Averaging yield maps may neutralise the information needed to better understand the interaction between soil properties and climate for crop production.

Recent technological advances in computer hardware and software, global positioning systems, and a wide array of new electronic, mechanical and chemical sensors for field-scale measurements offer inexpensive and accurate methods (within 0-1 meter accuracy) for measuring within field productivity variation patterns.

Soil electrical conductivity (EC) is one of the simplest, cost-effective soil measurements available to measure and map soil physico-chemical properties. Soil EC measurements integrate many soil properties affecting crop productivity including soil texture, cation exchange capacity, drainage conditions, organic matter level, salinity, and subsoil characteristic. With field verification, soil EC have been related to specific soil properties that affect crop yield, such as topsoil depth, pH, nutrient concentrations, and water holding capacity. Rapid spatial measurement of soil EC can be accomplished using mobile electromagnetic induction sensing [10,18,25] or EC measurement [11]. It has been reported that the spatial measurement of soil EC have potential for predicting crop production variation caused by soil property differences [10,21], and thus, as a surrogate measure of more costly soil chemical and physical measurements that directly affect plant growth and yield [9].

Studies showed that rice productivity was strongly influenced by soil texture, nutrient concentration and organic matter [5]. Rice yield from more sandy paddy fields is much lower than the fields with high clay and organic matter. Reduction in crop yield from sandy paddy fields has been attributed to a problematic water management and a root zone soil that is less than ideal for nutrients retention.

Even though soil ECa has been used widely in advanced countries for upland crops, research results on paddy soils are lacking. Therefore, there is an urgent need to apply soil ECa measurements on Malaysian paddy fields so that the rice industry can benefit from the rapid fertility assessment for better crop management. This paper describes the findings of research conducted on the relationships between soil ECa and physico-chemical properties of paddy fields and soil ECa to potential rice yield.

In order to distinguish the EC measured by the Veris unit from the soil science definition of EC (based upon conductance of a saturated soil paste extract), we will term the Veris EC measurement as apparent EC (ECa).

MATERIALS AND METHODS

Site descriptions

The research project was conducted at MARDI Seberang Perai research station located at the northern part of Peninsular Malaysia. The station is situated on latitude of 5.54˚N, longitude of 100.46˚E, and elevation of 10 m above sea level. The air humidity is always above 80%. The study area has an equatorial climate with uniform temperatures throughout the year. Temperatures range from 32˚ C during the day to 22˚C during the night. Rainfall is common throughout the year averaging 2400 mm a year. The monthly rainfall pattern shows two periods of high rainfall separated by two periods of low rainfall. The first wet season occurs from October to November, and the second from April to May. The driest months occur from January to February, and again from June to July (intermonsoon).

The site of MARDI Seberang Prai station was previously a rubber estate before it was converted into paddy fields. Rice has been planted in the area since its conversion in the seventies. Two separate research plots within the station were used to carry out research activities. One of the research plots is equipped with subsurface drainage facilities whereas the other is a single large contiguous plot of 9 ha. (9-ha plot) free of farm encumbrances. In-field improvements that have been done to the 9-ha plot include land levelling, upgrading of water control and management structures, water supply as well as waterways (perimeter drains and canals) construction.

Single plane large contiguous 9 ha plot

From the composite soil textural analysis, the 9 ha plot can be classified as sandy clay loam with proportions of sand, silt and clay estimated at 63, 13 and 24 % respectively. The plot is situated in the middle of the research station.

The plot was developed from three strips of land consisting of 12 plots without any infield obstruction. Operations such as the relocation of farm roads, flattening all the existing bund (batas), digging out and removal of all the irrigation and drainage facilities like irrigation piping, distribution boxes, delivery canals, drains and drainage boxes were all completed in 2002.

Subsurface drainage plot

The subsurface drainage facilities were installed in 1997. Over the duration of various subsurface drainage studies, the same research plot has been upgraded gradually and systematically. The soil texture of the subsurface drainage plot is classified as sandy clay loam with proportions of sand, silt and clay estimated at 60, 11 and 29 % respectively.

Measuring of soil ECa

Conductivity is a measure of the ability of a material to transmit an electrical charge. The measurement of soil electrical conductivity (EC) involves applying a voltage into the ground through metal electrodes and measuring the resistance to the electric current flow.

The most common method of measuring soil ECa is called the four-electrode configuration, originally suggested by a scientist named Wenner in 1915 [2]. The Veris 3100 Soil EC Mapping System uses the same method, but six-electrode configuration to measure soil ECa. The six electrodes have been replaced by rotating discs which are placed about 6 cm into the soil. As the Veris unit is pulled through the field, one pair of disk-electrodes (number 2 and 5 in Figure1) injects electrical current into the soil, while the change in voltage is measured across the other disk electrodes. Knowing the amount of current, the change in voltage and the distances between the disks, computer program in Veris then calculates soil ECa. While the Veris disk-electrodes only penetrate the soil a few centimetres during measurement, the electrical

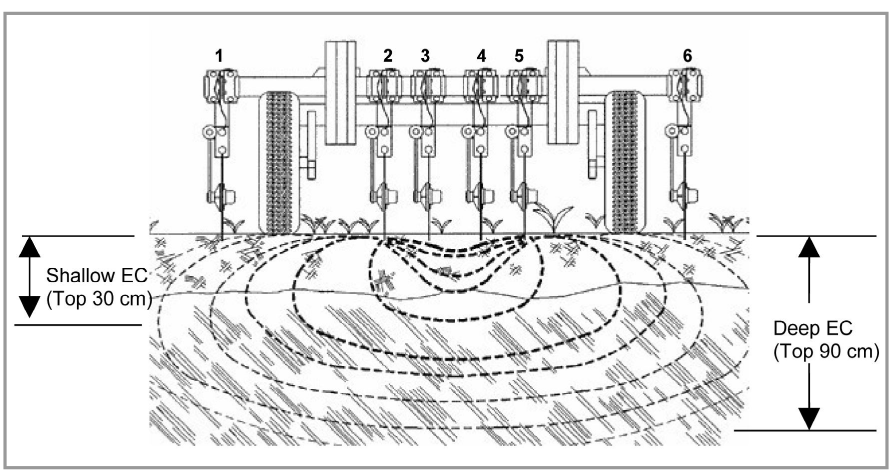

Figure 1: Veris 3100 soil ECa mapping system (Courtesy Broughton et al., 2002)

network (Figure 1) travels much deeper in the soil. Disks 3 and 4 are closer to each other and measure soil ECa for the top 30 cm. Disk 1 and 6 are farther apart and measure soil ECa for the top 90 cm of soil. A field is usually mapped by driving back and forth through the field on parallel transects of 15 m swaths apart at speeds up to 24 km/h. The system produces between 125 to 500 soil ECa readings per ha.

The setting up of the Veris 3100 together with the DGPS system attached to a tractor is shown in Figure 2 below. The instrument (Veris 3100) was calibrated, as per manufacturer instructions, prior to data collection. The Veris 3100 Sensor Cart was pulled through the field behind a tractor in a series of parallel transects spaced of about 15 m apart for the 9-ha plot. For the subsurface drainage plot, it was pulled in a narrow transects in each subplot. As the cart was pulled through the field, the Veris soil ECa mapping system acquired ECa data from the field rapidly and geo-referenced them using the DGPS receiver.

Figure 2: A GPS mounted on Veris 3100 unit attached to a tractor set for soil ECa survey at MARDI Seberang Prai

The ECa and GPS data are recorded on the Veris instrument flash memory in an ASCII text format, and downloaded onto a diskette at the user discretion. These data can then be transferred to the available geospatial or GIS software such as Surfer, GS+ or ArcView GIS to generate colour maps of field's soil ECa showing different colours representing differences in soil properties within the field. The statistical analyses of the collected ECa measurements can be used to reveal the basic features of the soil changes.

Soil ECa measurements were taken before land preparation of the off-season paddy crop to obtain a good hydraulic contact in a relatively dry field that was below saturation point for each planting season. This situation usually coincides with the dry period in the cropping season. Although absolute soil ECa readings may vary from measurement to measurement at different times of measurements, similar trends of ECa measurements were expected in the same paddy field under such similar field conditions.

Soil variable and yield measurements

Composite soil samples were taken at two separate depths (0-20 and 30-50 cm) using soil auger at 30 m regular grid intervals throughout the 9-ha plot. For the subsurface drainage plot, soils were sampled at 12 m regular grid intervals of the same depths. These samples were sent to soil laboratory for its physico-chemical properties (pH, N, P, K, CEC, organic carbon, clay, silt, and sand) and electrical conductivity analyses. These properties were determined using the standard procedure stated in Methods of soil Analysis [6]. The latitude and longitude of each sampling locations were acquired with a hand-held DGPS meter.

Random soil samplings along the transect lines were taken at two separate depths of 20 cm and 40 cm to determine the soil moisture content using the gravimetric method. This data collection was taken on the same day as ECa data collection. The DGPS of these sample points were determined and recorded with a hand-held DGPS system. Grain yield were obtained by 3 m x 3 m crop cutting test at the same soil sampling locations and corrected to 14 % moisture content.

RESULTS AND DISCUSSION

Soil ECa measurements

The total time taken for Veris 3100 to survey the 9-ha plot on transects of 15 m swaths and logged in more than 5000 data points 'on-the go' where each data point consists of DGPS values (latitude and longitude), shallow and deep ECa values and elevations took about two hours only. The subsurface drainage plot took only 30 minutes to accomplish more than 300 same set of data point measurements. Should other methods such as grid or random sampling been used, much more time were required to cover the same acreages and data sets. During the ECa measurements, the soil moisture contents of the field were determined and ranged from 22 to 24 % on dry basis.

Spatial ECa maps of 9-ha plot

The ECa data collected from fields can be used to generate different types of maps using the available geospatial software. The commonly generated maps are post maps, ECa maps and wireframe maps. A post map shows paths of vehicles passes used to measure soil ECa within the farm field. An ECa map is a colour map depicting spatial soil ECa measurements and a wireframe map is basically a three-dimensional soil ECa map.

Figure 3 is a typical post map that shows pattern of vehicle passes used to measure soil ECa within the 9-ha plot. Different colours along the passes represent different ranges of ECa values showing differences in soil properties.

Figure 4 shows krigged ECa maps of the 9-ha plot generated from Surfer program. The areas with darker colour indicate higher ECa values and vice versa. From the ECa maps, it can be observed that the north-eastern area has higher ECa values corresponding to the filled areas. The southern part has lighter colour corresponding to the cut area. Hence, the ECa

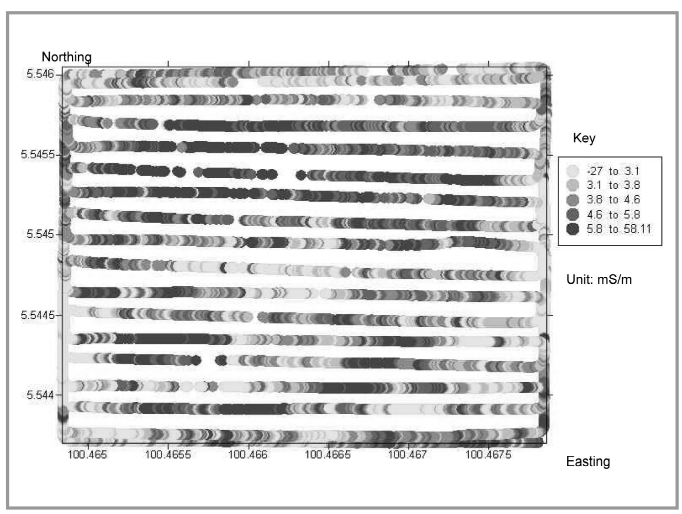

Figure 3: Typical pattern of tractor passes used to measure soil Eca within the 9-ha plot at MARDI, Seberang Perai

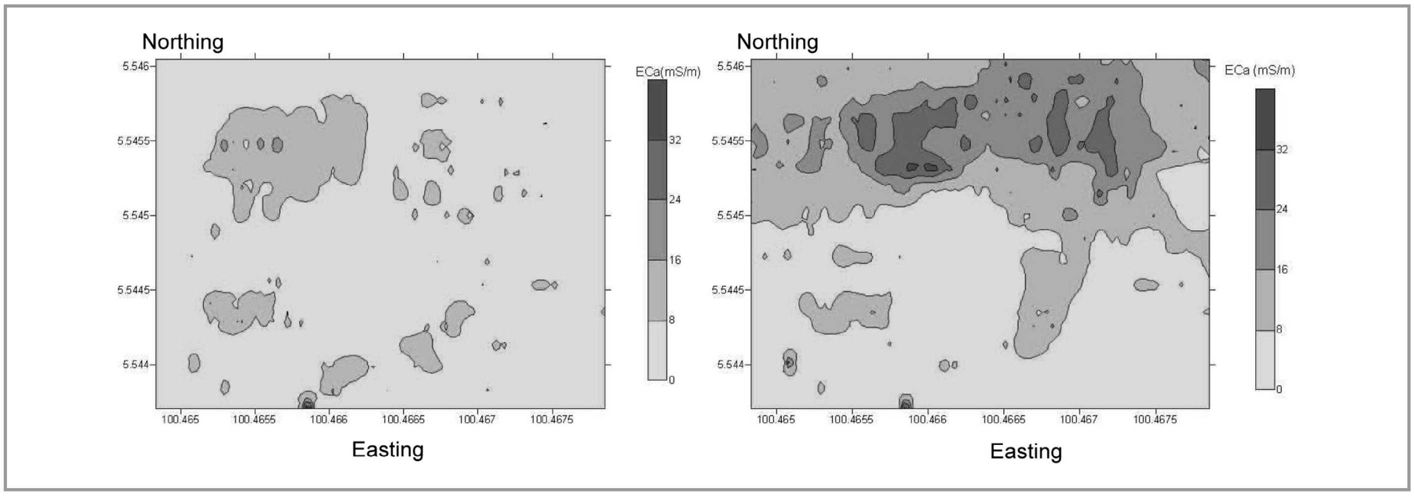

Figure 4: Soil ECa measurements obtained with Veris 3100 for both shallow (left) and deep (right) readings on the 9-ha plot at MARDI Seberang Prai, 2002

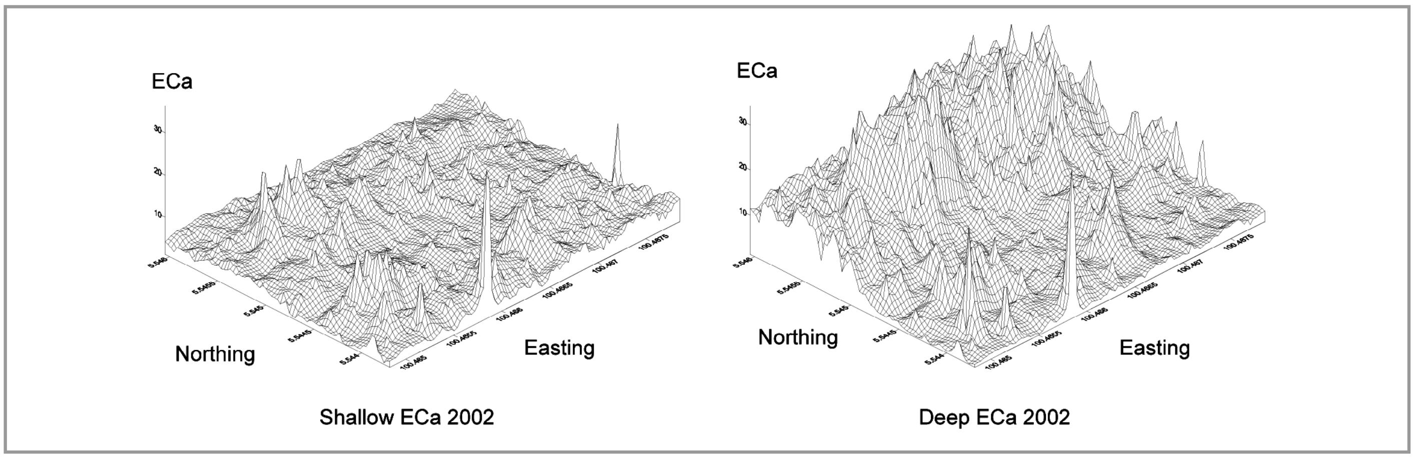

Figure 5: Spatial ECa maps obtained with Veris 3100 readings on the 9-ha Plot at MARDI, Seberang Prai

maps are able to show the history of the surveyed areas from the differences in soil physico-chemical properties.

Figure 5 is a typical three-dimensional wireframe map plotted using the same data set as for the ECa maps. The only difference is that the wireframe map uses Z axis to represent the magnitude of ECa measurements instead of different colours. It also gives a better visual effect to distinguish areas with high and low ECa values in three-dimensional form.

The result of volumetric water content obtained indicated that the field soil moisture was relatively constant. Thus, the spatial variation of ECa could have been caused by factors other than soil moisture. While collecting ECa data, extreme values were occasionally encountered, as can be seen from the high spikes in Figure 5. Field investigations failed to establish any reasonable causes, and thus it gave an indication of possible erroneous measurements.

In Figure 5, the shallow (0-30 cm) soil ECa map revealed a similar pattern as that of the deep (0-90 cm) ECa map although not identical. In fact, they were significantly correlated (r= 0.52, 2002). The significant differences were the magnitude of ECa recorded. The mean values of the shallow ECa was 4.9 mS/m compared to the deep ECa of 9.3 mS/m.

Spatial ECa maps of 9-ha plot

Figure 6 is a typical post map of the subsurface drainage plot that shows the pattern of vehicle passes used to measure the soil ECa, whereas shallow and deep ECa for off-season 2003 are showed in Figure 7. The typical three dimensional maps for the corresponding season are revealed in Figure 8. From visual observation of the ECa maps, these maps show that the subsurface drainage plot has more uniform ECa profile. The mean values for shallow and deep ECa are 24.8 and 24.6 mS/m, respectively. The two valleys that appear clearly in the shallow ECa map (Figure 8) were the result of two in-field open ditches.

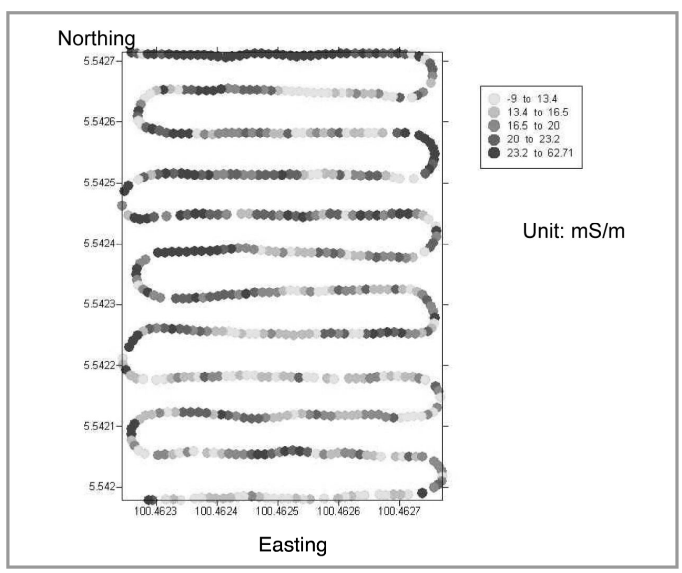

Figure 6: Typical pattern of tractor passes used to measure soil ECa within the subsurface drainage plot at MARDI, Seberang Perai

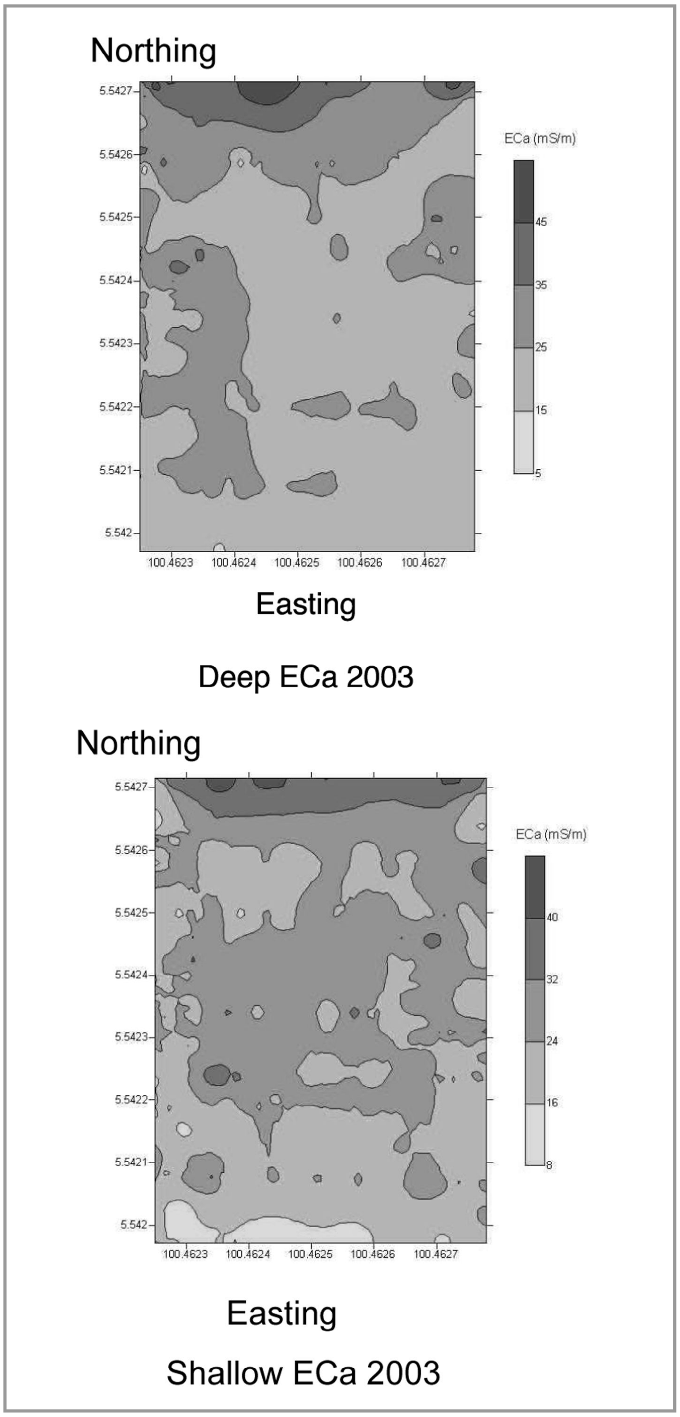

Figure 7: Soil ECa maps for the subsurface drainage plot at MARDI Seberang Prai

ANALYSES OF SOIL PROPERTIES

9-ha Plot

After field consolidation and levelling, soils at upper (0-20 cm) and lower (30-50 cm) layers were sampled for soil physico-chemical properties analysis. From Table 1, it can be noticed that the differences of soil properties between upper and lower layers were small as the result of field consolidation. The mean values of N, P, K, OC, CEC, pH for the upper soil layer were 0.10 %, 7.75 ppm, 0.18 me %, 0.71 %, 8.21 me % and 4.65, respectively. Among all the measured soil properties, K showed the highest variation of coefficient of 30 %. Generally, clay content of 22 % or less would be considered too low for rice cultivation while the optimum clay level should be around 40 % with low infiltration rate of less than 1 cm/day [15]. The analyses showed marginally fertile soil and such was marginally suitable for paddy planting.

The higher values of ECa at the lower soil layer than the upper layer could be attributed to higher soil bulk density. The bulk density of the soil taken at the lower layer averaged at 1.42 g/cm^3 whereas the upper layer was 1.28 g/cm^3.

Subsurface drainage plot

Subsurface drainage plot was developed in 1997. Before project implementation in 2002, soil samples from upper and lower layers were taken for soil properties analysis. The descriptive statistics of these properties together with ECa were tabulated in Table 2.

Table 1: Descriptive statistics of soil properties and ECa of 9-ha plot after land consolidation

	Upper soil layer (0-20 cm)									
	N (%)	P (ppm)	K (me %)	OC (%)	CEC (me %)	pH	Clay (%)	Silt (%)	Sand (%)	ECa
Mean	0.10	7.75	0.18	0.71	8.21	4.65	21.68	13.80	64.52	4.88
Std Dev.	0.02	0.82	0.05	0.08	1.03	0.12	3.55	2.28	3.80	1.70
Range	0.09	3.70	0.26	0.37	4.80	0.66	15.00	8.80	17.30	9.30
Minimum	0.06	6.40	0.09	0.54	6.40	4.24	13.80	9.90	56.40	2.20
Maximum	0.15	10.10	0.35	0.91	11.20	4.90	28.80	18.70	73.70	11.50
C. V.	21.94	10.52	30.94	11.29	12.55	2.54	16.37	16.49	5.90	34.80
	Lower soil layer (30-50 cm)									
	N (%)	P (ppm)	K (me %)	OC (%)	CEC (me %)	pH	Clay (%)	Silt (%)	Sand (%)	ECa
Mean	0.10	7.88	0.17	0.73	8.51	4.85	24.19	13.09	62.72	9.29
Std Dev.	0.02	0.79	0.05	0.12	1.23	0.44	6.16	3.39	5.63	6.07
Range	0.08	3.70	0.25	0.45	5.20	1.54	38.30	18.40	28.70	28.00
Minimum	0.07	6.50	0.08	0.53	6.40	4.40	11.60	3.50	45.10	1.10
Maximum	0.15	10.20	0.33	0.98	11.60	5.94	49.90	21.90	73.80	29.10
C. V.	21.83	10.06	30.72	15.83	14.45	9.08	25.45	25.93	8.98	65.39

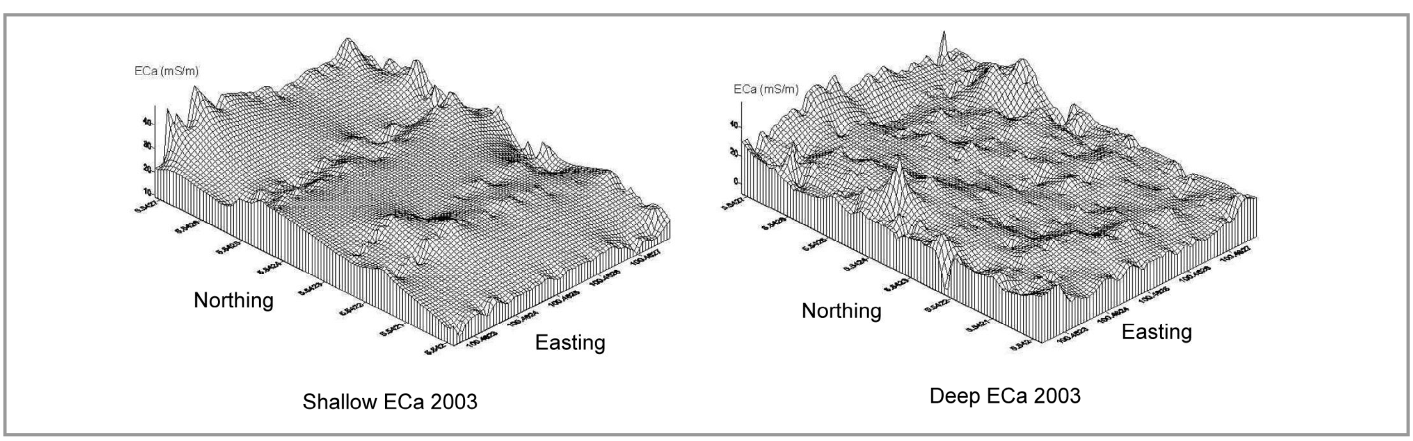

Figure 8: Spatial ECa three-dimensional maps for the subsurface drainage plot at MARDI Seberang Prai

Table 2: Descriptive statistics of soil properties and ECa of subsurface drainage plot before project implementation

	Upper soil layer (0-20 cm)									
	N (%)	P (ppm)	K (me %)	OC (%)	CEC (me %)	pH	Clay (%)	Silt (%)	Sand (%)	ECa (mS/m)
Mean	0.13	8.23	0.33	0.91	9.26	5.90	22.05	16.25	61.71	24.88
Std Dev.	0.02	0.84	0.07	0.06	0.94	0.05	4.55	2.70	5.39	5.37
Range	0.06	2.60	0.27	0.19	3.70	0.18	17.70	9.10	23.40	22.40
Minimum	0.10	6.80	0.18	0.80	7.50	5.80	12.90	13.00	47.30	14.90
Maximum	0.16	9.40	0.45	0.99	11.20	5.98	30.60	22.10	70.70	37.30
C. V.	13.21	10.23	20.48	6.97	10.13	0.86	20.62	16.64	8.73	21.57
	Lower soil layer (30-50 cm)									
	N (%)	P (ppm)	K (me %)	OC (%)	CEC (me %)	pH	Clay (%)	Silt (%)	Sand (%)	ECa (mS/m)
Mean	0.10	7.92	0.15	0.86	9.39	5.60	31.01	9.73	59.26	24.61
Std Dev.	0.02	0.59	0.03	0.07	0.98	0.24	7.57	3.20	8.30	6.63
Range	0.07	2.00	0.11	0.21	3.70	0.70	29.80	10.90	26.50	27.10
Minimum	0.07	7.10	0.09	0.77	7.90	5.24	20.10	3.50	45.10	16.10
Maximum	0.14	9.10	0.20	0.98	11.60	5.94	49.90	14.40	71.60	43.20
C. V.	19.51	7.43	22.66	8.62	10.47	4.28	24.41	32.88	14.00	26.93

By comparing the soil properties of upper and lower layer soils (Table 2), it can be seen that higher amounts of N, P, K, OC, pH and silt were found at the upper layer than the lower layer. However, clay content was higher in the lower layer. There were negligible differences in CEC, sand, and ECa between the two layers. The mean values of N, P, K, OC, CEC, pH in the upper soil layer were 0.13 %, 8.23 ppm, 0.33 me %, 0.91 %, 9.26 me % and 5.90 respectively. For all the variables analysed, the highest CV found was the K (22%) of the lower layer followed by the K (20%) of the upper layer. The soil was moderately fertile and suitable for paddy cultivation.

The above analyses showed that the upper layer of subsurface drainage plot was more fertile. This observation may be due to accumulation of applied commercial fertilizers, crop residues, parent materials, green and farm manures and ammonium and nitrate salts [19,23]. Continued cultivation also increases soil organic matter content and other elements from additional root mass even if grain straw is burnt and removed [27]. N is the most volatile in the soil, apart from the uptake by the plant, most of the N is lost from the soil by leaching and denitrification processes [23]. K and OC are relatively immobile and always remain at the top soil layer except deep ploughing or excessive soil movement [27]. Likewise, P does not move far from the point of placement [3,13].

CORRELATION BETWEEN GRAIN YIELD AND SOIL VARIABLES

9-ha Plot

From the 9-ha plot, a total of 198 soil samples were collected for soil analyses. Correlation analyses showed that correlation coefficients between yield and soil parameters were generally low and inconsistent (Table 3), although most correlation coefficients of greater than 0.21 were found to be significant. Correlations which ranged from negative to positive were also generally inconsistent between seasons and depths.

Yield and soil variable correlations for the upper soil layer of cropping season OS-02 exhibited relatively more consistent trend with positive correlation coefficients for all of the soil cations except for soil organic carbon. The coefficients for N and CEC were significantly positive. However, correlations between yield and soil variables for the lower soil layer (same cropping season OS-02) were low and were all non-significant. Correlations obtained for cropping season OS-03 were similar to those obtained in cropping season OS-02 lower soil layer. Low and non-significant correlations to soil cations were obtained except for N which showed significant negative correlation. Soil organic matter showed significant positive correlation with yield, but this relationship was insignificant in the upper soil layer of cropping season OS-02. Cropping season OS-04 also exhibited inconsistent correlation trend of low and non-significant correlations except for CEC that showed significant positive correlation similar to the upper soil layer of cropping season OS-02. Correlations between yield and ECa for both deep and shallow soil layer were mostly negative and low except for ECa deep in OS-02 which was significantly positive. Correlations obtained for soil physical properties were low and inconsistent for all cropping season.

Table 3: Correlation between grain yield and soil variables of the 9-ha Plot

C. S.	n & Depth	pH	N	P	K	Soil OC	CEC	Clay	Silt	sand	Soil EC Shallow	Soil EC Deep
OS 02	99-S	0.052	**0.235***	0.106	0.023	-0.092	**0.239***	0.161	-0.124	-0.062	-0.087	-
OS 02	99-D	0.040	0.049	0.013	-0.106	0.017	-0.008	0.000	0.069	-0.046	-	**0.255***
OS 03	99-S	0.069	**-0.279***	-0.116	-0.030	**0.417***	0.043	0.098	-0.021	-0.038	-0.037	-0.035
OS-04	99-S	-0.014	-0.065	0.004	0.190	0.141	**0.262***	-0.028	-0.071	0.069	-0.021	-0.078

* Significant at P ≤ 0.05 level C.S. = Cropping season S = Upper soil layer D = Lower soil layer
n = Total number of data points

Subsurface drainage plot

From the subsurface drainage plot, a total of 60 soil were collected for soil analyses. Correlation between yield and soil variables (Table 4) were also low and non-significant, except for soil organic carbon (OS-03, shallow) and K (OS-04, shallow) where significant positive correlation coefficients greater than 0.35 were found. Correlations were also generally inconsistent between seasons and depths.

Yield and soil variable correlations for cropping season OS-02 were low and non-significant for both upper and lower soil layers. Similar trend was exhibited in cropping season OS-03 as no significant correlation was observed between yield and soil physico-chemical properties except soil organic carbon. Cropping season OS-04 exhibited a slightly more consistent trend with positive correlation coefficients for soil organic carbon and soil cations. Further more, correlation of yield with K was significantly positive. Correlations between yield and ECa for shallow as well as deep soil layers were positive for cropping season OS-02 but negative for cropping seasons OS-03 and OS-04. However, they were low and non-significant for all cropping seasons.

Table 4: Correlation between grain yield and soil variables of the subsurface drainage plot

C. S.	n & Depth	pH	N	P	K	Soil OC	CEC	Clay	Silt	sand	Soil EC Shallow	Soil EC Deep
OS 02	30-S	-0.129	0.241	-0.209	-0.213	-0.059	-0.056	0.098	-0.198	-0.017	0.211	-
OS 02	30-D	0.011	0.256	-0.164	-0.017	-0.020	-0.132	0.065	-0.001	-0.060	-	0.154
OS 03	30-S	-0.123	0.150	0.197	0.116	**0.361***	-0.058	-0.049	0.024	0.030	-0.224	-0.020
OS-04	30-S	0.094	0.242	0.281	**0.470***	0.038	0.294	0.197	0.306	-0.320	-0.118	-0.152

* Significant at P ≤ 0.05 level C.S. = Cropping season S = Upper soil layer D = Lower soil layer
n = Total number of data points

Pooled analyses of 9-ha and subsurface drainage plots

Prior to pooled analysis, the correlation coefficients (r) between soil variables and grain yield for both the 9-ha and the subsurface drainage plots for all seasons and depths were subjected to the test of homogeneity. The results showed that there were no significant difference between the coefficients (Table 5) except for N (OS-03). Hence, all the homogeneous correlations soil variables can be combined for pooled analysis. Further more, the same variety was planted during the same time period under the same management practices. The two plots were also closed to each other and experienced the same climatic conditions and classified under the same soil series. The only obvious difference is the time of development of the plots: the 9-ha plot was developed and levelled in 2000 compared to the subsurface drainage plot which had been developed and cultivated since 1997. The past cultivation activities have caused the fields to be different in its soil physico-chemical properties, drainage conditions and soil texture which effect soil productivity. Nevertheless, these factors were integrated and measured as soil ECa values and become part of the experimental variables in this study.

Table 5: Homogeneity test of correlations (r) between grain yields and soil variables for the 9-ha and subsurface drainage plots

C. S.	n & Depth	pH	N	P	K	Soil OC	CEC	Clay	Silt	sand	Soil EC Shallow	Soil EC Deep
OS 02	129-S	0.696	0.001	2.138	1.207	0.023	1.894	0.087	0.122	0.043	1.915	NA
OS 02	129-D	0.018	0.954	0.671	0.168	0.029	0.328	0.089	0.104	0.004	NA	0.235
OS 03	129-S	0.783	**4.038** *	2.106	0.452	0.092	0.215	0.458	0.043	0.098	0.768	0.005
OS-04	129-S	0.247	2.051	1.709	2.127	0.228	0.025	1.092	3.160	3.384	0.201	0.119

* Significant at $P \leq 0.05$ level C.S. = Cropping season S = Upper soil layer D = Lower soil layer
n = Total number of data points

After combining the data from both the subsurface drainage and 9-ha plots, the total data points increased to 129 each for both upper (0-20) and lower (30-50) soil layers. Correlation coefficients obtained between yield and soil parameters for the pooled analyses (Table 6) were high and significant. Also, correlations were consistent between growing seasons and depths.

Table 6: Correlation between grain yield and soil variables for pooled analyses of the 9-ha and subsurface drainage plots

C.S	n & Depth	pH	N	P	K	Soil OC	CEC	Clay	Silt	Sand
OS 02	129-S	0.891 **	0.397**	0.218*	0.642**	0.711**	0.404**	0.026	0.367**	-0.240 *
OS 02	129-D	0.889 **	0.361**	0.153	0.627**	0.661**	0.326**	-0.002	0.294**	-0.186 *
OS 03	129-S	0.775 **	NA	0.206*	0.695**	0.644**	0.359**	0.029	0.282**	-0.192 *
OS 04	129-S	0.581 **	0.247**	0.194*	0.579**	0.510**	0.438**	0.050	0.256**	-0.195 *

* Significant at $P \leq 0.05$ level: **Highly significant at $P \leq 0.01$ level
n=Total number of data points C.S. = Cropping season S = Upper soil layer D = Lower soil layer

Yield and soil variable correlations for all four cropping seasons were consistent and mainly significant. Correlations for soil variables pH, K, soil organic carbon, CEC and silt were positive and highly significant for all analyses. Correlations between yield and P were significantly positive only for three cropping seasons. Correlation with respect to sand was significantly negative for all cropping seasons. The correlation between yield and clay were mostly positive but of low coefficient values for all cropping seasons.

Correlations of grain yield with soil ECa

Correlation coefficients obtained between grain yield and soil ECa (shallow and deep) exhibited consistent trend with positive and highly significant coefficients ranging from 0.26 to 0.85 (Table 7) for all the three cropping seasons.

Table 7: Correlation between grain yield and soil ECa

Cropping season	n	EC Shallow			EC Deep		
		02	03	04	02	03	04
OS 02	129	0.846**	-	-	0.674**	-	-
OS 03	129	-	0.693**	-	-	0.416**	-
OS 04	129	-	-	0.497**	-	-	0.264**

**Highly significant at $P \leq 0.01$ level n = Total number of data points

Figure 9 illustrates the relationships of soil ECa and crop yields from the pooled analyses. Generally, it showed that most of the high yield areas correspond to areas with high soil ECa values and the low crop yield areas correspond to areas with lower soil ECa values. Even so, it is clearly shown that the areas with extreme ECa values at both ends failed to produce anticipated extreme low or high yields.

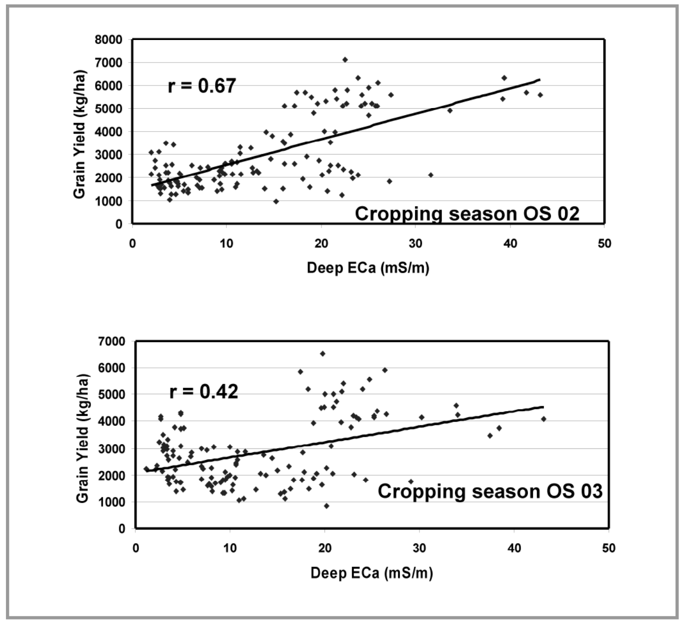

Figure 9: Grain yield in relation to deep soil ECa for cropping seasons off-season 02 and 03 at MARDI, Seberang Perai

From the results obtained above, it is clearly revealed that fields with mark contrasting soil physico-chemical properties were needed to obtain required relationships between grain yields and soil variables. For a single contiguous field, the fields need to be heterogeneous in order to obtain meaningful correlations between grain yield and soil variables or soil ECa.

This simple correlation analysis is an assessment of the linear relationship between variables. If nonlinear relationships exist between yield and yield-limiting factors, this correlation analysis may miss important relationships. Further more, when dealing with entire production fields, multiple and interacting yield-limiting factors are likely to be present (Sudduth et al., 1996).

Correlation coefficients between soil ECa and mapping dates

Different sets of ECa measurements from the same field were correlated. The results showed that the average correlation coefficients between ECa and different mapping dates of subsurface drainage and 9-ha plots were highly significant (Table 8). This indicates that the ECa values may change with each mapping exercise but the patterns of the ECa maps within the field do not tend to change significantly over time. Generally, once an ECa map has been made, it will remain relatively accurate unless significant soil movement occurs such as with land levelling, farm facilities (farm road, irrigation and drainage) construction.

Table 8: Average correlation between soil ECa and mapping dates

Field	Shallow ECa	Deep ECa
9-ha plot	0.676**	0.862**
Subsurface drainage	0.768**	0.844**

**Highly significant at P ≤ 0.01 level

Developing the relationship of yield to soil ECa

The growth and yield of the rice crop is markedly influenced by soil physical and chemical properties above the plough pan that is within the rhizosphere of the rice plant. Owing to this strong relationship, potential theoretical relationships between ECa and crop productivity can be hypothesized.

The relationship was studied by Webb [28] where yield and soil ECa on these data sets were explored using the concept of an upper 'boundary line'. It was found that the method could further improve the correlations. Boundary line analysis works best when the data sets are large. The boundary line analysis procedure assumes that there is a significant biological response between the potential limiting factor and the response variable in order to imply the cause-and-effect relationship [28,29]. Based upon the investigations, a log-normal peak function was chosen to fit the boundary data subset and generate a boundary line. The log-normal peak function was flexible in representing various respond combinations to soil ECa values [24].

The log-normal peak function is as follows:

$$YP = a + be^{-0.5[\ln(x/c)/d]^2}$$

Where, YP is yield, x is ECa, a is the lower limit of yield, b is the height of the peak above a, c is the value of x over which the peak is centred, d is a curve-fitting parameter giving shape and width to the peak, and e is the base of natural logarithms. For each log-normal equation an adjusted r2 value was calculated.

Integration of the relationship of yield and soil ECa

The log-normal regression boundary line for each cropping season along with the data used to create the boundary lines

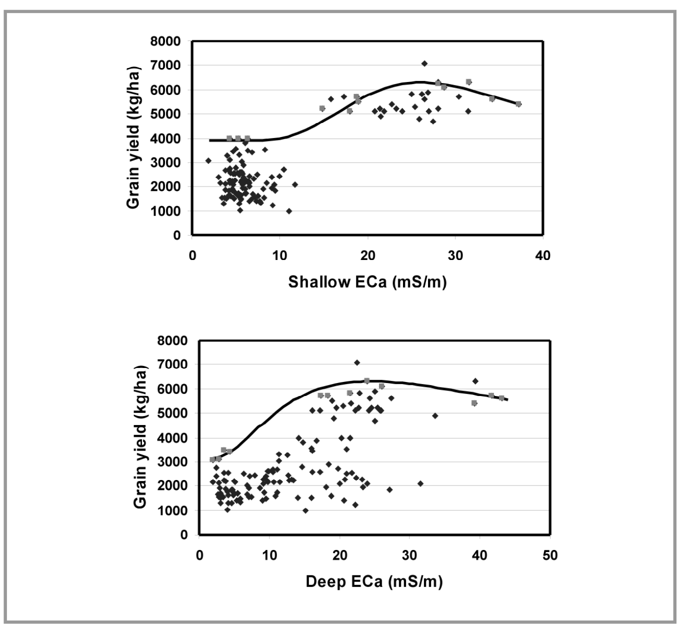

Figure 10: Scatter plots of ECa and yield for cropping season OS-02, where yield decreased with decreasing ECa

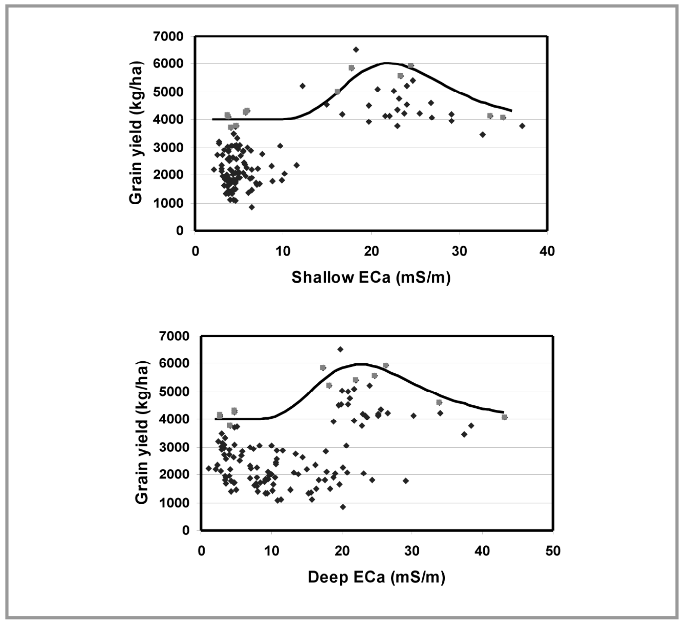

Figure 11: Scatter plots of ECa and yield for cropping season OS-03, where yield was less at low and high ECa values and higher at some mid-range of ECa

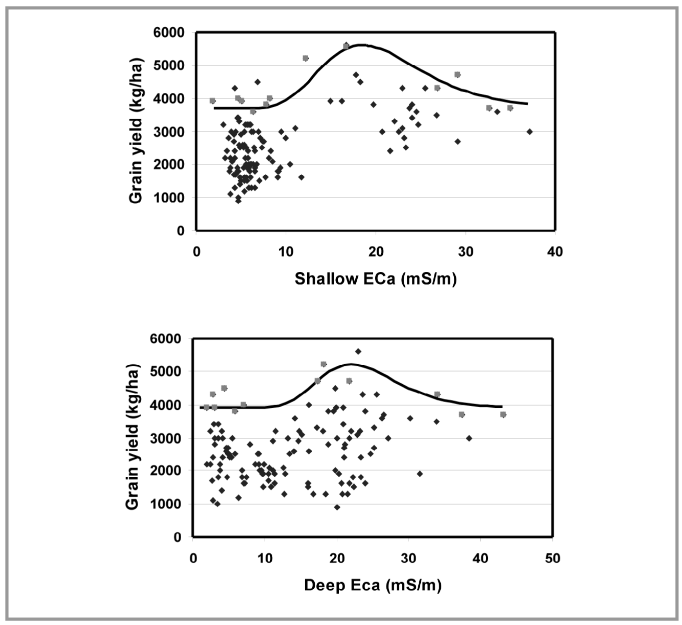

Figure 12: Scatter plots of ECa and yield for cropping season OS-04, where yield was less at low and high ECa values and higher at some mid-range of ECa

(red colour points) are shown in the scatter plots of Figures 10 to 12, and the regression parameters are given in Table 9. The log-normal function fits the upper boundary of ECa and yield data well with r^2> 0.8 in four out of six investigations (Table 9). Generally, the cropping seasons with low r^2 values also exhibited relatively small changes in yield over the observed range of ECa. Additionally, it can be noticed from Table 10 that the standard deviations were also correspondingly lower. Since the data used in this analysis were taken from MARDI Station Seberang Perai, application of this equation to other locations with different soil series and climatic conditions need further field investigations and verification.

The investigation from the boundary line plots (Figures 10 to 12) showed that the log-normal peak values varied from year to year and with soil depths. The relationship also revealed that yield was less at low and high soil ECa values and peaked at

Table 9: Boundary line regression parameters and statistics for paddy fields to predict potential yield at a given ECa

			Log-normal equation parameters				
Year	N	n	a	b	c	d	r^2
	ECa shallow						
2002	129	12	3900	2400	26.0	0.372	0.94
2003	129	12	4000	2000	22.0	0.258	0.87
2004	129	12	3700	1900	18.5	0.300	0.76
	ECa deep						
2002	129	12	3100	3200	24.5	0.796	0.98
2003	129	12	4000	1950	22.5	0.320	0.86
2004	129	12	3900	1300	22.0	0.250	0.61

Table 10: Descriptive statistics of yield derived from boundary-line analyses

	Shallow 02	Deep 02	Shallow 03	Deep 03	Shallow 04	Deep 04
Mean	5072	4593	4580	4695	4455	4375
Std Dev.	1036	1412	846	824.8	537	399
Range	3184	3567	2199	2160	1650	1250
Minimum	3066	2733	3711	3750	3900	3900
Maximum	6250	6300	5910	5910	5550	5150
C. V.	20.4	30.7	18.5	17.6	12.1	9.1

some mid-range (from 18.5-26 mS/m) over the range of 5 to 43 mS/m. Overall comparison showed that the peaks for cropping seasons OS-02 were relatively small and not so significant compared to the other cropping seasons.

It is important to note that crop yields are not always higher in high soil ECa areas. In some parts of the field, crop yields could be lower in high ECa areas. There are many factors that could cause the crop yield and soil ECa to respond differently. For example, in some fields, higher soil ECa values may indicate higher clay and organic matter contents and thus a more productive soil. In other fields, the higher soil ECa values may indicate shallow thick impermeable plough pan and hence shallow root zone, which in turn resulted in a shallow productive soil with a limited crop yield. Consequently, it may be more economical to increase agricultural inputs in high productive areas to improve crop yields, and in areas where the soil is poor and cannot effectively store nutrients, reduce the amount of agricultural inputs. In both cases, a soil ECa map of the field is essential to identify those areas that require a change in agricultural inputs.

Low soil ECa areas could be associated with less fertile soil which could be having higher sand content, lower organic matter, and are poorer to store nutrients. The study showed that usually the best yielding areas have average soil ECa values. Compared to findings elsewhere, the optimum soil ECa values for crop production not only depend on the crops planted, soils and climate, but also precipitation during crop growth. Hence, development of the relationship between yield and soil ECa for crop yield prediction is both crop and site specific.

Soil ECa as a paddy soil productivity index

The dispersed natures of data in the scatter plots were indicative of the existence of multiple yield-controlling factors during the crop growth cycle. Soil suitability for crop growth is a composite of many measurable properties, much more than what ECa can represent. Soil ECa is only a partial indicator of that suitability.

While the primary value of ECa as examined using boundary line analysis can be used to diagnose soil problems associated with field conditions and management practices and to estimate the magnitude of yield loss due to less than ideal soil property conditions, it does not help to identify directly specific potential corrective measures for the soil. It indicates the direction for improved site-specific management. Thus, even though the boundary line analysis did show significant relationships between ECa and yield in all cropping seasons (r=0.61 to 0.98), the interpretation of this relationship should be aided by more information on specific field characteristics.

Developing a simple and rapid technique to analyse soil productivity

Crop yields determined from crop cutting test were considered as observed yields (Yob). The predicted potential yields (Ypo) were derived from the log-normal equation based on shallow ECa for 2004 was as follows:

$$Ypo = 3900 + 1300\ e^{-0.5[\ln(x/22.0)/0.25]^{\wedge}2}$$

Where Ypo is the potential yield (kg/ha), and x is the measured ECa.

Since the values of Ypo depended solely on the measured ECa values, it could be used as a value of soil fertility index. This will greatly simplified the classification of soil fertility as the spatial variation of soil properties is very complex. When the values of Ypo and Yob were compared, four possible classes of plots can be identified:-

(i) Ypo and Yob are both high
(ii) Ypo is high and Yob is low
(iii) Ypo is low and Yob is high
(iv) Ypo and Yob are both low

For each class, different input management options can be planned to maximise the soil productivity. Class i is the most productive farm area where soils were fertile and observed yields were high, and it deserves to be given either a higher fertilizer rate or maintain the present fertilizer rate. For class ii, the yield-constraining factors such as soil physical conditions and soil properties should be investigated and it is possible to overcome them. In the case of class iii, more site-specific soil analyses and site investigations should be done to explain the contrasting phenomenon. For class iv the soil yield-limiting factors responsible for low yield performance should be identified. This approach enables a classification of farm areas into productivity units and allows for site-specific and variable-rate input application. Over-fertilization is damaging as it results in varying degrees of surface and groundwater pollution. On the contrary, accurate fertiliser application means less wastage of the applied nutrients, less pollution to the environment, and lower input cost.

CONCLUSIONS

Soil ECa measuring devices provide the simplest, and quickest way of generating maps that can be used to provide an estimate of the within-field soil differences associated with soil physical and chemical properties. As such, soil ECa measurements can be used as a surrogate measure of soil properties affecting crop productivity like soil texture, soil nutrients, cation exchange capacity, drainage conditions, organic carbon, salinity and subsoil characteristics. It can also be a measure of root-zone suitability for crop growth and yield. When used in conjunction with a differential Global Positioning System (DGPS) receiver, ECa can be geo-referenced to create maps for precision agriculture application.

The results showed that in both the 9-ha and subsurface drainage plots, the upper soil layer (0-20 cm) are more fertile compared to the lower layer (30-50 cm). the fertility could be the result of accumulated applied fertilizers, crop residue, green and farm manures. However, between the two plots, a lower soil nutrient concentration was observed from the 9-ha plot as a result of field consolidation. Within the 9-ha plot, the filled areas have higher soil ECa measurements than the cut areas indicating soil texture and fertility differences.

The results of correlation studies showed that the coefficients (r) between yield and soil variables for cropping season off-season 02, 03 and 04 were generally low, non-significant and ranged from negative to positive for both the 9-ha and the subsurface drainage plots.

When the data for the two plots were pooled and correlated, the coefficients between yield and most of the soil variables were high, significant and consistent in trend. The analyses showed that a mark contrast of soil properties is needed to signify the relationship between yield and soil variables. Other correlation studies found to be significant were between ECa and different mapping dates.

The relationship between grain yield and soil ECa was explored in scatter plots. A boundary line using a log-normal function was fitted to the upper edge of the data representing the potential yield at a given range of soil ECa measurements. A significant relationship between potential grain yield (Ypo) and soil ECa was shown. The log-normal function fitted well the upper boundary of the soil ECa and yield data scatter plot, with r2 > 0.8 in four out of six cropping seasons. The relationship also revealed that yields were less at low and high soil ECa values and peaked at some mid-range (from 18.5-26 mS/m) over the range of 5 to 43 mS/m. This pointed out that soil suitability for crop growth is the composite of many measurable properties, much more than what soil ECa can represent. Soil ECa is only a partial indicator of that suitability. Nevertheless, the use of the boundary line analysis helped to determine the magnitude of potential yield loss due to less than ideal conditions in the root zone.

The comparison between calculated Ypo and observed yield (Yob) indicated that areas can be classed according to where (i) Ypo and Yob are both high, (ii) Ypo is high and Yob is low, (iii) Ypo is low and Yob is high and (iv) Ypo and Yob are both low. This approach enables a classification of farm areas into management units and allows for discriminate fertilizer application, thus avoiding under or over-fertilization. These findings also pave the way for using ECa as a prescription map for variable-rate applications of fertilizer, seed and pesticides and it appears to be a promising technology and merits additional investigation.

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