SOILS2004 CONFERENCE PROCEEDINGS

INNOVATION IN SOIL SCIENCE FOR SUSTAINABLE AGRICULTURE

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PERSATUAN SAINS TANAH MALAYSIA
MALAYSIAN SOCIETY OF SOIL SCIENCE
MSSS

THE MALAYSIAN SOCIETY OF SOIL SCIENCE

PROCEEDINGS
SOILS2004
CONFERENCE

Bayview Beach Resort, Batu Ferringhi, Penang
April 13-14, 2004

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MALAYSIAN SOCIETY OF SOIL SCIENCE (MSSS)

ISBN 967-9945-26-X

Published by:

Malaysian Society of Soil Science
Locked Bag 254, 43409 UPM Serdang
Selangor

Printed by:

Baraplas Kreatif Enterprise
3358A,Jalan 18/31,Taman Sri Serdang,
43300 Seri Kembangan,Selangor.
(Tel: 03-8941 0053)

Proc. Soils2004 Conference. April, 2004. Penang, Malaysia. Malaysian Society of Soil Science (MSSS)
(Editors: ZZ Zin, SK Balasundram, KJ Goh, MM Hanafi, I Ahmad, CI Fauziah and MS Halimi)

Paper 2

DEVELOPMENT OF A SOIL TILTH INDEX AND ITS RELATIONSHIP WITH RICE YIELD IN A MALAYSIAN PADDY FIELD

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Introduction

An increase in rice productivity in Malaysia has been achieved through the introduction of high-yielding varieties and improved crop management practices. Suhaimi et al. (1986), however, stated that there still exists wide differences in yield among the major rice growing areas, i.e. the granary areas, of up to about 50%, and to some extent between seasons (about 10%). Ismail et al. (1991) pointed out that the factors that differentiate rice productivity in these granary areas are climate, soil and crop management. They opined that, as most of the granary areas are irrigated, the effects of regional climatic differences are expected to be minimal. Available classification systems that provide means of estimating and evaluating the productivity of rice lands are subjective and qualitative in nature and do not provide any means of predicting rice yield quantitatively (Ismail et al., 1991).
Tillage treatments have been an integral part of many soil- and crop-management studies of the multifaceted concept of soil tilth. Although an experienced person may tell by sight and feel if a soil is in good or poor tilth, there is still no readily available method of quantifying and measuring it, particularly under irrigated farming conditions. Therefore, gaining a quantitative understanding of soil tilth and evaluating the effects of tillage systems on soil tilth are needed. If soil tilth can be quantified, tillage indices could be used in scheduling farming operations and to improve soil management, which will consequently lead to sustainable productive and profitable agriculture. Tilth indices could also be used for yield prediction as well as in optimizing energy use for tillage by indicating when additional tillage may not be necessary. The objectives of this study were: i) to develop a soil tilth index based on changes in some soil physical properties due to rotary tillage in a paddy field; and ii) to quantitatively compare rice yields and created soil conditions as measured by the developed tilth index.

The soil tilth index concept

The term 'soil tilth' has been used to describe a given soil structural state and its direct and indirect effects on the physical, chemical and biological processes occurring in the soil (Hadas, 1997). Soil tilth is a dynamic characteristic and thus subject to change due to natural forces as well as to modification by artificial means such as plowing and cultivation (Karlen et al., 1990; Singh et al., 1992). When tillage effects on soil tilth are evaluated, it is critical to know both the initial soil characteristics and which tilth factors are being altered by tillage (Buckland and Pawluk, 1985).
Several attempts have been made by many soil scientists and agricultural engineers to quantitatively describe soil tilth by formulating indices, which are sometimes correlated to crop yields. Neill (1979) assumed that soil is a major determinant of crop yield because of the environment it provides for root growth (other factors being climate, management, and plant genetic potential). A positive relationship has been found to exist between extensive root growth and crop yield. Many models have been developed for predicting soil tilth (Colvin et al., 1984; Singh et al., 1992; Christopher and Mokhtaruddin, 1995; Tapela and Colvin, 1998),

and soil productivity (Neill, 1979; Pierce et al., 1983; Kiniry et al., 1983; Larson et al., 1983; Gantzer and McCarty, 1987; Gale et al., 1991; Mulengera and Payton, 1999) which take into account the physical properties (available water capacity, bulk density, cone index, aggregate uniformity coefficient, plasticity index, electrical conductivity, humus, porosity, sand and clay content, row topography, residue cover, surface roughness, and tillage depth) and chemical properties (pH and organic matter content) of the soil. These soil parameters have been considered because of the ease with which they can be measured in the field and are more likely to be accepted for management use by farmers (Singh et al., 1992). Christopher and Mokhtaruddin (1995) also observed that the better the soil structure (humus, porosity and bulk density) the better the soil tilth, but extreme values of consistency (sand and clay content) are detrimental to soil tilth.

Soil conditions created by different tillage tools may vary from farm to farm depending on soil type, soil water content at time of tillage, tool adjustment, and speed of tool operation. The important soil conditions affected by tillage are those that either directly or indirectly affect plant growth and/or soil erosion (Colvin et al., 1984). Different soils do not necessarily respond similarly to common tillage practices (Triplett et al., 1970). Regardless of tillage practice, high yields are obtained on soils having favorable physical conditions (Browning and Norton, 1947). No single tillage implement is satisfactory under all conditions, and crop response varies with soil type, season, and crop variety. Browning and Norton (1947) emphasized that, although tillage implements play a very important role in the preparation of a favorable seedbed, it should be recognized that the implements are only part of the overall program needed for developing and maintaining favorable soil tilth. It is widely believed that the same tillage practice carried out at different times may produce varying forms of soil structural states. Likewise, different tillage sequences and/or passes with different implements may end up producing the same 'soil tilth'. These phenomena have complicated the quantification of soil structural state following tillage and relate it directly to crop yields. Great variability in correlations between crop yields and 'soil tilth index', determined at different times of the cropping season, have been reported by many soil scientists and agricultural engineers (Hadas, 1997). This has necessitated the difficult task of continuously collecting pertinent data on soil properties throughout the cropping season (if they are to be correlated with yield), with respect to fluctuating weather conditions and varying management practices. Hadas (1997) noted that the choice of the most effective tillage practice to attain a given soil tilth not only vary between different agro-ecological environments, but also within the same ecological environment.

Modification of the soil tilth index model

The soil tilth index (TI) as originally developed by Singh et al. (1992) and subsequently modified by Tapela and Colvin (1998) is:

$$TI = CF_1 * CF_2 * CF_3 * CF_4 * CF_5 \qquad [1]$$

where: TI = soil tilth index ($0.00 \leq TI \leq 1.00$); CF_1 = tilth coefficient of bulk density; CF_2 = tilth coefficient of cone index; CF_3 = tilth coefficient of plasticity index; CF_4 = tilth coefficient of aggregate uniformity coefficient; CF_5 = tilth coefficient of organic matter content

The proposed general form of equation for tilth coefficients was:

$$CF_x = A_0 + A_1 * X + A_2 * X^2 \qquad [2]$$

where: CF_x is the tilth coefficient for the soil property (X); A_0, A_1, A_2 are constants.

The tilth coefficients were normalized to range between 0.00 and 1.00, so as to also obtain tilth index between 0.00 and 1.00. A value of 0.00 indicated an absolutely limiting level of a soil property and a value of 1.00 indicated the optimum level.

We modified the basic form of the TI model (Singh et al., 1992; Tapela and Colvin, 1998) to include RI_i, the root-weighting factor of the ith soil layer. This consideration was made based on the fact that the value of each soil depth increment as an environment for roots is not equal, the importance of each layer being weighted towards the surface with a gradual decrease with depth (Neill, 1979). We further modified Eq. (1) by using geometric mean of the individual tilth coefficients to arrive at a soil layer rating (Gale et al., 1991). One disadvantage of the original TI model is that the rating for an individual soil layer could be lower than the tilth coefficient for any soil property considered within that layer. For instance, if the factors CF_1, CF_2, CF_3, CF_4 and CF_5 in Eq. (1) were all equal to 0.80, the aggregate multiplicative rating would be 0.33. But, using the geometric mean of the individual tilth coefficients, the aggregate multiplicative rating for the soil layer would be 0.80. The geometric mean gives equal weight to proportional differences in factor coefficients and not to absolute differences (Gale et al., 1991) as in the original tilth index model. Since each tilth coefficient corresponds to a different soil characteristic, absolute differences in the tilth coefficient for one characteristic, although standardized from 0.00 to 1.00, do not reflect the same absolute difference in other factor coefficients. The tilth coefficient for a particular soil factor is based on the level at which it is optimum or limiting to root growth, independent of other factors (Gale et al., 1991). The concept of geometric mean has been commonly used in other fields, such as in econometrics to 'average' price indices developed from different bases.

The modified tilth index (MTI) model is as shown in equation [3] below.

$$MTI = \sum_{i=1}^{n} [(CF_1 * CF_2 * CF_3 * CF_4 * CF_5)^{1/5} * RI]_i \qquad [3]$$

where: MTI = Modified tilth index ($0.00 \leq MTI \leq 1.00$); CF_1 = tilth coefficient of bulk density;
CF_2 = tilth coefficient of cone index; CF_3 = tilth coefficient of plasticity index; CF_4 = tilth coefficient of aggregate uniformity coefficient; CF_5 = tilth coefficient of organic matter content
RI = root weighting factor (of an ideal soil); n = the number of soil layers of the root zone depth under consideration.

The weighting factor, RI, was based on estimation of the root distribution in an ideal medium developed from water depletion studies by Horn (1971), and work latter extended by Kiniry et al. (1983), who assumed that the relative root mass at depth D is equal to the fraction of available water depleted at that depth. Horn's prediction equation for the fraction of available water depleted versus depth for a recharged soil (Gantzer and McCarty, 1987) is:

$$L_D = 0.152 \ln \{R + (R^2 + 6.45)^{0.5}\} - 0.152 \ln \{D + (D^2 + 6.45)^{0.5}\} \qquad [4]$$

where: L_D = fraction of available water depleted at depth D; D = depth within the profile, cm; R = total rooting depth, cm.

The integral of equation [4] estimates the fraction of the total root mass contained in a given depth increment (say D_1 to D_2), which gives the RI of equation [3] (Gantzer and McCarty, 1987), such that:

$$RI = \int_{D_1}^{D_2} [0.152 \ln \{R + (R^2 + 6.45)^{0.5}\} - 0.152 \ln \{D + (D^2 + 6.45)^{0.5}\}]\, dD \qquad [5]$$

where: RI is the fraction of total water depletion from a given soil depth, D; R is the maximum plant rooting depth.

The relationships for tilth coefficients corresponding to soil parameters were developed using yield data obtained from field experiments in the study area and target potential yield of rice of 10 ton/ha in granary areas of Malaysia. The following equations were obtained:

$$CF_{BD} = -13.595*BD^2 + 21.415*BD - 7.768 \quad [6]$$
$$CF_{CI} = 1.8747*CI^2 - 1.3082*CI + 0.8208 \quad [7]$$
$$CF_{PI} = -0.0026*PI^2 + 0.0477*PI + 0.4743 \quad [8]$$
$$CF_{AUC} = 0.0926*AUC^2 - 1.7183*AUC + 8.5503 \quad [9]$$
$$CF_{OM} = 0.1675*OM^2 - 1.8763*OM + 5.8422 \quad [10]$$

where: CF_{BD}, CF_{CI}, CF_{PI}, CF_{AUC}, and CF_{OM}, are the tilth coefficients for bulk density, cone index, plasticity index, aggregate uniformity coefficient, and organic matter, respectively.

After the soil physical measurements for two soil layers (0-100 mm and 100-200 mm) were made, tilth coefficients were assigned to the individual measurements (Eqs. 6-10). The computed tilth coefficients were then normalized to range between 0.00 and 1.00 so that the corresponding tilth indices calculated would also range between 0.00 and 1.00.

Evaluation of the modified soil tilth index (MTI)

Experimental area

Data for the development and evaluation of the MTI were obtained from field experiments conducted during the 2003 cropping seasons at the Sungai Burong Compartment of the Tanjong Karang Rice Irrigation Scheme in the Northwest Selangor Integrated Agricultural Development Project (PLBS) located on $3^0$35"N and $101^0$05"E in the Kuala Selangor and Sabak Bernam Districts, Malaysia. Mean annual rainfall in the study area was about 1600 mm. Climate, in general, is semi- and sub-tropical continental with mean monthly temperature of about 28^0C. The soil type in the experimental plots is predominantly silty clay, belonging to the Selangor soil series with mechanical analysis of 1.1% sand (> 50 microns), 45.4% silt (2-50 microns) and 53.5% clay (<2 microns) on average.

Data collection procedure

The field with continuous rice has been managed with the same tillage treatment for over four decades. A two-factor experiment in a completely randomized design, replicated over two cropping seasons, was set up. The factors and their levels were: Transmission Gear ratio – Gear 1 High (G1), Gear 2 Low (G2), Gear 3 Low (G3), and Gear 4 Low (G4), and rotor speed – 140 rpm (R1), 175 rpm (R2), and 200 rpm (R3). The treatments were a combination of these factors in a factorial manner as follows: G1R1, G1R2, G1R3, G2R1, G2R2, G2R3, G3R1, G3R2, G3R3, G4R1, G4R2, and G4R3. Tillage operations were carried out with an 80" rotavator (for first rotavation) and a 110"-rotavator (for second and third rotavations), attached to a FIAT 640 diesel tractor, operating at 2400 rpm under standard conditions. Seedlings of the rice variety MR 219 were transplanted using a Kubota rice transplanter SPA 65 at a spacing of 300 x 200 mm. All the plots used in this study were fertilized at the same levels under irrigated conditions in order to reduce the significance of differential fertility on crop yield.

Prior to tillage operations, undisturbed core soil samples were taken from three locations within each experimental plot with 70 mm x 40 mm brass ring core samplers at two depths (0-100 mm and 100-200 mm) and used in the determination of dry bulk densities using the technique described by Brady and Weil (1999). Bulk soil samples were also collected for the purpose of characterizing the soil in the study area. Before harvest, three measurements each of bulk density, aggregate uniformity coefficient, organic matter, soil pH, and plasticity index from the 0-100 mm and 100-200 mm depths were again made in crop rows, in each plot. The samples for aggregate uniformity coefficient, organic matter, pH, and plasticity index were mixed and one representative sample for each tillage treatment was analyzed. A Standard

ASAE cone penetrometer, having a cone of base diameter 4 mm and a tip angle of 60^0, was used to take soil penetrometer resistance measurements at 9 locations in each plot at 25.40 mm (1 inch) increments to a depth of 152.40 mm (6 inches). Values of the cone index were then computed following ASAE standard procedure and guidelines. Organic matter content of each soil sample was assessed using the method of Walkley and Black (1934). Particle-size distribution was performed using the Pipette method (Day, 1965). Gravimetric water content of the soil under field conditions were determined by drying it in an oven at 105^0C for 24 hours.
Yield components and yield data were collected at harvest. Daily weather data (maximum and minimum temperatures, solar radiation, rainfall, and relative humidity) from the day of transplanting to harvest were obtained from a nearby weather station.

Data analysis

An analysis of variance was performed to determine if there was any significant difference among the mean yields. Correlation analysis was performed between the developed MTI and yield. Different types of curves were fitted to the data set in order to determine the one that gives a better correlation between MTI and yield

Results and discussion

Yield analysis

The rice yield harvested averaged about 6.65 Mg ha^{-1}. However, there were some differences in the mean yields. Accordingly, variations in the mean yields were all attributed to the treatment effect (tillage practices). An analysis of variance was performed on these means to determine if there was any significant difference among the yield means. The p-value was 0.0020 while the coefficient of variation was 24.6%. Duncan's multiple range test for differences ($\alpha = 0.05$) showed that treatment G4R2 had the highest mean yield which was significantly different from G1R1, G1R2, G2R1, G2R3, G3R3 and G4R1, but not significantly different from G1R3, G2R2, G3R1, G3R2 and G4R3. The analysis of variance also showed that there were no individual significant effect of gear ratio G ($F = 1.87$, $p = 0.1405$) and rotor speed R ($F = 2.10$, $p = 0.1283$) on yield, but there was highly significant interaction effect ($F = 5.19$, $p = 0.0001$) of the two parameters on yield.

Validation of the modified tilth index

The mean values of the soil properties measured before tillage operations and before harvesting, respectively, are presented in Table 1.

Table 1. Mean values of soil properties in experimental plots before tillage (BT) and before harvesting (BH)

Tillage treatment	Bulk density ($Mg\ m^{-3}$)		Cone index (MPa)		Plasticity index (%)		Aggregate uniformity coefficient (%)		Organic matter (%)	
	BT	BH	BT	BH	BT	BH	BT	BH	BT	BH
G1R1	0.87	0.83	0.25	0.18	6.98	3.27	9.75	9.05	4.90	4.85
G1R2	0.86	0.75	0.14	0.18	8.32	5.78	9.48	9.73	6.25	4.56
G1R3	0.84	0.80	0.28	0.19	11.16	2.10	9.17	9.68	5.65	6.08
G2R1	0.84	0.75	0.16	0.18	7.02	6.27	9.45	9.50	5.72	5.41
G2R2	0.85	0.83	0.14	0.19	6.29	4.84	8.13	11.15	4.77	4.27
G2R3	0.85	0.79	0.24	0.22	8.06	4.05	10.61	9.20	5.63	6.00
G3R1	0.86	0.89	0.11	0.15	3.32	7.14	9.44	9.90	4.48	4.29
G3R2	0.82	0.86	0.24	0.23	10.85	5.81	9.88	9.53	5.36	5.29
G3R3	0.91	0.76	0.14	0.17	9.98	1.87	9.13	9.61	5.35	4.60
G4R1	0.87	0.80	0.16	0.10	8.40	3.53	9.02	9.81	5.11	4.15
G4R2	0.90	0.81	0.20	0.19	3.60	15.03	8.96	9.49	4.90	5.04
G4R3	0.90	0.78	0.15	0.17	7.31	12.93	10.72	9.45	4.55	4.03

In general, it is difficult to quantify soil property changes imposed by tillage. However, the effect of tillage on the soil properties was evident in the measurements taken before harvesting. A paired t-test showed that there was a decrease in bulk density, cone index, plasticity index and organic matter. The decrease in bulk density was highly significant, while organic matter was barely insignificant at the 5% level (Table 2). The exceptional case of increased values of aggregate uniformity coefficient may have resulted from other practices such as irrigation and fertilization, or conditions induced by natural processes such as rainfall or desiccation during the growing period.

Table 2. Paired T-test comparison of mean soil parameter values before tillage (BT) and before harvesting (BH)

Parameter	Mean	SD	SE	T	Prob > |T|
Bulk density	0.6000	0.0577	0.0167	3.6033	0.0041
Cone index	0.0050	0.0470	0.0136	0.3685	0.7195
Plasticity index	1.5558	5.9062	1.7050	0.9125	0.3811
Aggregate uniformity coefficient	-0.1967	1.1498	0.3319	-0.5925	0.5655
Organic matter	0.3417	0.5985	0.1728	1.9774	0.0736

Having developed the MTI, it was necessary to validate it. The initial assumption was that as the MTI value increases, the associated yield should increase accordingly. To verify this, correlation analysis between the MTI and yield was performed. Different types of curves were fitted to the data set of MTI and yield (Table 3) in order to determine the one that gives a better correlation between MTI and yield. It was found that the quadratic functions (Figures 1 and 2) gave the best correlations for soil measurements before tillage and before harvesting, respectively, which were in agreement with the observation of Tapela and Colvin (1998) that found good quadratic correlation between their MTI and yield. The regression analysis performed to evaluate the MTI resulted in Eqs. (11) and (12). Regression lines for Eqs. (11) and (12) are illustrated in Figures 1 and 2, respectively.

Table 3. Mean values of MTI and yield as affected by tillage and time

Tillage treatment	Modified Tilth Index (MTI)		Yield
	Before tillage	Before harvesting	(Mg ha^{-1})
G1R1	0.59	0.63	6.24
G1R2	0.69	0.67	5.00
G1R3	0.64	0.62	7.41
G2R1	0.65	0.61	5.77
G2R2	0.68	0.75	7.18
G2R3	0.72	0.63	6.08
G3R1	0.64	0.68	7.66
G3R2	0.66	0.61	7.70
G3R3	0.63	0.64	5.73
G4R1	0.63	0.72	5.69
G4R2	0.64	0.60	8.48
G4R3	0.67	0.69	6.81

$$Yield = -236.61*MTI^2 + 307.86*MTI - 93.25$$
(for soil sampling before tillage)
($r^2 = 0.1256$, $p = 0.6466$, $n = 12$) [11]

$$Yield = 247.81*MTI^2 - 336.84*MTI + 120.42$$
(for soil sampling before harvesting)
($r^2 = 0.2734$, $p = 0.2376$, $n = 12$) [12]

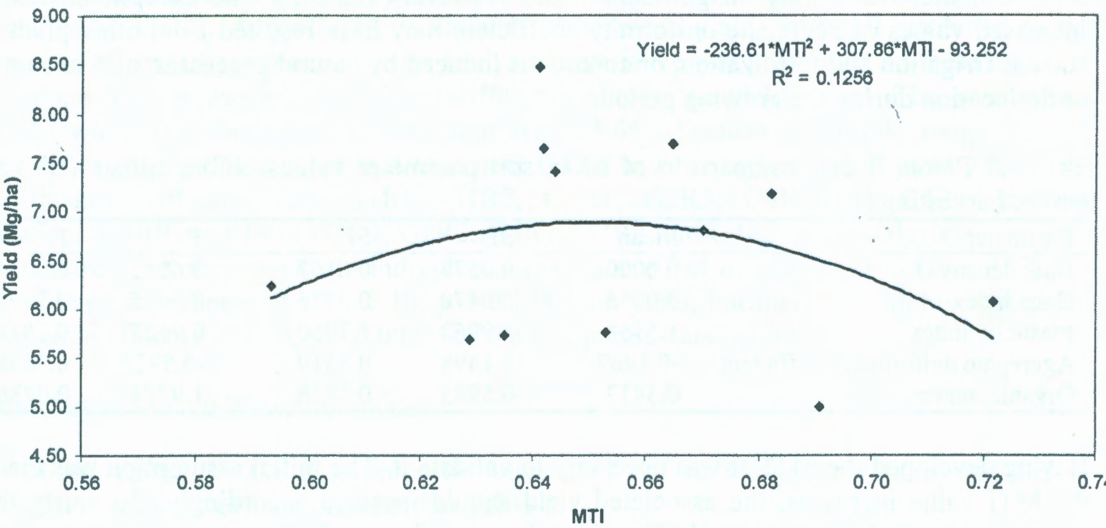

Figure 1. Relationship between rice yield and MTI for soil sampling before tillage

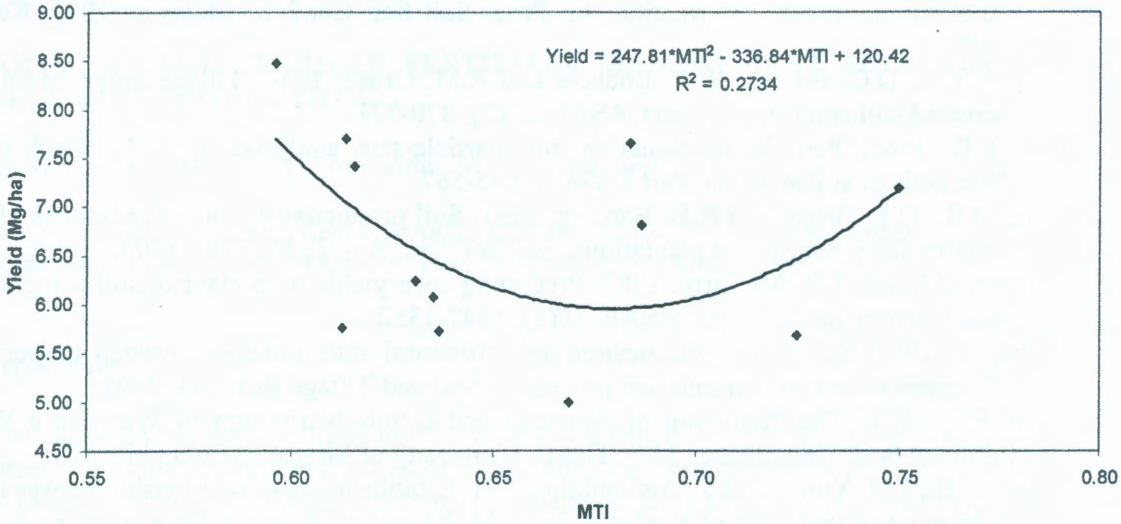

Figure 2. Relationship between rice yield and MTI for soil sampling before harvesting

Conclusions and recommendations

1. In field verification, the developed MTI correlated positively with rice yield, with coefficient of determination ranging from 0.13 to 0.27 depending upon time of season when the tilth index was calculated. The tilth index provided a better correlation with the rice yield for soil sampling before harvesting (r=0.52) than for soil sampling before tillage (r=0.36), depicting the effect of the tillage treatments applied.
2. The data used in the development and evaluation of the MTI was obtained only from the Tanjong Karang rice growing area of Malaysia, and thus was limited. Further investigation for a wide range of crops, soil and climatic conditions, and management practices are therefore needed to ascertain the accuracy of the MTI and possibly improve the methods used to estimate its parameter values and/or change its structural form.
3. The results of the study suggest that the tilth index may assist in yield prediction by comparing measured soil conditions to known or projected optima for a paddy field.
4. Investigation into the possibility of obtaining non-limiting, critical and root-limiting values of soil physical properties in paddy fields under varying tillage systems is recommended.

Acknowledgement

The authors are grateful to the Malaysian Government for the financial support given to the lead author of this paper to pursue his studies at the Universiti Putra Malaysia. Special thanks are due to Tn. Hj. Nasir bin Waris and his staff, particularly Mr Kamaruddin Sujang and Mr Saiful Baharim, at the Sungai Burong Rice Seed Production Centre of the Department of Agriculture Malaysia for their help during the field experimentation. The assistance of Mr Abd. Aziz Abdullah and other technical staff of the Soil Physics Laboratory in the Faculty of Agriculture, UPM is also acknowledged.

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