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A Modified Soil Tilth Index and Its Relationship with Rice Yield

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ABSTRACT: This study was conducted to investigate the effect of rotary tillage on some soil physical properties (bulk density, cone index, plasticity index, aggregate uniformity coefficient) and organic matter, and to develop and evaluate a soil tilth index based on changes of these soil properties. The tillage treatments were 4 x 3 factorial combinations of forward speeds obtained with four selected tractor transmission gears (Gear 1 High, Gear 2 Low, Gear 3 Low and Gear 4 Low), and three rotary tilling speeds (140 rpm, 175 rpm and 200 rpm) of commonly used tillage implements in Malaysian paddy fields. Experimental results indicated a significant decrease in bulk density of the soil due to rotary tillage. The other soil parameters were not significantly affected by the tillage operation. Analysis of variance indicated significant difference ($p<0.01$) among the rice yield means. Bulk density was identified to have a high positive correlation with the rice yield. A tilth index consequently developed with bulk density, cone index and plasticity index gave better predictability ($r^2 = 0.56$) of rice yield than when individual soil properties were considered. Results of the study suggest that tilth index may assist in yield prediction by comparing measured soil conditions in a paddy field.

KEYWORDS: Rotary tillage, soil physical properties, tilth index, crop yield, paddy field.

INTRODUCTION

Tillage treatments have been an integral part of many soil- and crop-management studies of the multifaceted concept of soil tilth. 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[1]. Soil tilth is dynamic and thus subject to change due to natural forces, as well as to modification by artificial means such as plowing and cultivation[2,3]. 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[4].

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 is 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[3].

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[5] 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 between extensive root growth and crop yield. Many models have been developed for predicting soil tilth[3,6,7,8] and soil productivity[5,9,10,11,12,13], which take into account the physical properties (available water capacity, bulk density, cone index, aggregate uniformity coefficient, plasticity index, electrical conductivity, humus content, 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[3]. Christopher and Mokhtaruddin[7] also observed that the better the soil structure (high humus, porosity and bulk density) the better the soil tilth, but extreme values of consistency (sand and clay content) are detrimental to soil tilth.

Great variability in correlations between crop yields and a 'soil tilth index', determined at different times of the cropping season, have been reported by many soil scientists and agricultural engineers[1]. 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.

The main objectives of this study were: 1) to investigate the effect of rotary tillage on some soil physical properties and rice yield in a paddy field; 2) to develop a soil tilth index based on the changes in these soil properties; and 3) to compare rice yields and the developed tilth index.

MATERIALS AND METHODS

Modification of the Soil Tilth Index

The soil tilth index (TI), as originally developed by Singh *et al.*[3] and subsequently modified by Tapela and Colvin[8], is:

$$TI = CF_1 * CF_2 * CF_3 * CF_4 * CF_5 \quad (1)$$

where TI is the soil tilth index ($0.0 \le TI \le 1.0$), CF_1 to CF_5 are the tilth coefficients of bulk density, cone index, plasticity index, aggregate uniformity coefficient, and organic matter content, respectively. Singh *et al.* [3] proposed a quadratic relationship for the tilth coefficients for each soil factor. The proposed general form of equation was:

$$CF_x = A_0 + A_1 * X + A_2 * X^2 \quad (2)$$

where CF_x is the tilth coefficient for the soil property (X) and A_0, A_1, A_2 are empirical constants. Singh *et al.*[3] derived this relationship simply by examining each soil factor separately according to defined criteria. The defined criteria in each case involved setting three important levels for each soil property that were critical in the growth of a crop. These were non-limiting (sufficient level), critical and limiting points. The non-limiting condition is the optimal level for maximum plant growth, while the limiting level is the level above which the plants will not normally survive[8]. These values were then plotted on a graph and the best fitting polynomial curve determined to define a regression equation to establish other values within the range. The tilth coefficients were normalized to range between 0 and 1, so that a tilth index of 0 indicated an absolutely limiting level of a soil property and a value of 1 indicated the optimum level.

We modified the basic form of the TI model[3,8] to include RI_i, the root-weighting factor of the *ith* soil layer. The modified tilth index (MTI) model is as shown in equation (3) below.

$$MTI = \sum_{i=1}^{n} [(CF_{BD} * CF_{CI} * CF_{PI} * CF_{AUC} * CF_{OM})^{1/5} * RI]_i \quad (3)$$

where MTI is the modified tilth index ($0.0 \le MTI \le 1.0$); CF_{BD}, CF_{CI}, CF_{PI}, CF_{AUC}, and CF_{OM}, are the tilth coefficients for bulk density (BD in Mgm^{-3}), cone index (CI in MPa), plasticity index (PI in %), aggregate uniformity coefficient (AUC, dimensionless), and organic matter (OM in %), respectively; RI root weighting factor of an ideal soil; and *n* the number of soil layers of the root zone depth under consideration.

The root weighting factor RI was included because 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[5]. We further modified Eq. (1) by using the geometric mean of the individual tilth coefficients to arrive at a soil layer rating[12]. 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 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 as in the original tilth index model[12].

The weighting factor, RI, was based on estimation of the root distribution in an ideal medium developed from water depletion studies by Horn[14] and later extended by Kiniry *et al.*[10], 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[11] is:

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

where L_D is the fraction of available water depleted at depth D; which is the depth within the profile in centimeters, and R the maximum plant rooting depth in centimeters. The integral of equation (4) estimates the fraction of the total root mass contained in a given depth increment, which gives the RI of equation (3)[11].

In the proposed modified tilth index model, the relationships between tilth coefficients and soil parameters were developed using yield data obtained from field experiments in the main cropping season (July to December) in 2003. Individual yield obtained from each experimental plot was expressed as a fraction of the maximum yield obtained in that season. The ratios so obtained were regressed against corresponding measured soil parameter values for each plot to obtain a relationship between the yield ratios and the tilth coefficients of the soil parameters. The following linear equations were formulated:

$$CF_{BD} = -1.5357BD + 2.009 \quad (5)$$
$$CF_{CI} = -0.249CI + 0.8191 \quad (6)$$
$$CF_{PI} = -0.0016\,PI + 0.7721 \quad (7)$$
$$CF_{AUC} = 0.0761AUC + 0.0295 \quad (8)$$
$$CF_{OM} = 0.0994OM + 0.1761 \quad (9)$$

where CF_{BD}, CF_{CI}, CF_{PI}, CF_{AUC}, and CF_{OM}, are as previously defined.

Evaluation of the Modified Soil Tilth Index (MTI)

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 at 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 subtropical continental with a mean monthly temperature of 28^0C. The soil type in the experimental plots is silty clay, belonging to the Selangor soil series (Vertic to Typic Dystropept) with a mean texture of 1.1% sand (> 50 µm) and 53.5% clay (< 2 µm).

A 4 x 3 two-factor experiment arranged in a completely randomized design was set-up and conducted twice over the off-season (January to June) and main season (July to December) in 2003. 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. Three tillage operations were carried out using a 203 mm-rotavator (for the first rotavation) and a 282 mm-rotavator (for the second and third rotavations), attached to a FIAT 640 diesel tractor, and operated with a PTO speed of 540 rpm under standard conditions. Seedlings of a high-yielding rice variety, MR 219, with a short growth duration of 105 to 111 days, were transplanted using a Kubota rice transplanter SPA65 at a spacing of 300 x 200 mm. All the plots used in this study were fertilized at the same level under irrigated conditions, in order to reduce the significance of differential fertility on crop yield.

Prior to tillage operation in the off-season, undisturbed core soil samples were taken from three different locations within each experimental plot with 70 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 density and soil moisture content, using the technique described by Brady and Weil[15]. Bulk soil samples were also collected to characterize the soil in the study area. A week before harvest, three measurements each of bulk density, aggregate uniformity coefficient, organic matter, soil pH, and plasticity index from the topsoil depth (0-100 mm) and subsoil depth (100-200 mm) 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°, 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 152.4 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[16]. Particle-size distribution was performed using the Pipette method[17]. Gravimetric water content of the soil under field conditions was determined by drying it in an oven at 105°C for 24 hours. Yield data were collected at harvest on the 4th of June and 11th of December 2003 in the off-season and main season, respectively.

A pair-comparison t-test was used to detect the significance of differences between the soil properties before tillage and before harvesting in the off-season, across all tillage treatments. An analysis of variance was performed to determine whether there was any significant difference among the mean yields. Correlations in rice yield with soil properties were calculated, while regression of rice yield on the developed MTI was performed. 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. The distribution of estimation errors of the estimated yield for soil sampling before harvesting was also illustrated.

Results and Discussion

Effect of the Rotary Tillage Practice on Soil Parameters

The mean values of the soil properties measured before tillage operations and before harvesting in the

Table 1. Mean values of soil properties in experimental plots in the off-season.

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
Average	**0.86**	**0.80**	**0.18**	**0.18**	**7.61**	**6.05**	**9.48**	**9.68**	**5.22**	**4.88**

BT = before tillage, BH = before harvesting

off-season are presented in Table 1. These values were used to check through t-test comparison, the significance of the rotary tillage on the soil properties. The t-test results given in Table 2 showed that there was an overall decrease in bulk density, cone index, plasticity index and organic matter, possibly as a result of the tillage treatments applied. The decrease in bulk density was highly significant ($p<0.01$), while that in organic matter was almost significant at the 0.05 level. The exceptional case of an overall increase in values of aggregate uniformity coefficient may have stemmed from other practices such as irrigation and fertilization, or conditions induced by natural processes such as rainfall or desiccation during the growing period. It has been reported a decrease in bulk density and cone penetration resistance in lowland soils due to rotary tillage in flooded soil, called 'puddling'[18].

Effect of the Rotary Tillage Practice on Yield

The rice yield harvested in the 2003 off-season averaged about 6.65 $Mg\ ha^{-1}$. However, there were some differences in the mean yields. An analysis of variance performed indicated significant difference ($p<0.01$) among the yield means. Accordingly, variations in the mean yields were all attributed to the treatment (tillage practices) effect. Table 3 gives the comparison of rice yield means from the various tillage treatments. Duncan's multiple range test for differences (± = 0.05) showed that tillage treatment G4R2 gave the highest mean yield, which was significantly different from treatments G1R1, G1R2, G2R1, G2R3, G3R3 and G4R1, but not significantly different from treatments G1R3, G2R2, G3R1, G3R2 and G4R3. The experimental design used in the present study did not permit the investigation of the interaction effects of gear ratio (G) and rotor speed (R) on the yield, as the individual tillage treatments were not replicated, but instead, yield sampling was replicated within each treatment.

Validation of the Modified Tilth Index

Having developed the tilth index (MTI), it was necessary to validate it. The linear relation between the MTI and yield based on Equation [3] was very weak with a low coefficient of determination ($R^2 = 0.13$). The range of the MTIs was also small, but this seemed reasonable because the MTI was designed to cover a

Table 2. Paired t-test comparison of mean soil parameter values before tillage and before harvesting in the off-season.

Soil Parameter	Mean	Std dev	Std error	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

Table 3. Mean values of the modified tilth index (MTI) and Duncan's multiple range test for rice yield means in the off-season.

Tillage treatment	MTI	Mean yield†(Mg/ha)
G4R2	0.76	8.48[a]
G3R2	0.74	7.70[ab]
G3R1	0.73	7.66[ab]
G1R3	0.77	7.41[abc]
G2R2	0.76	7.18[abc]
G4R3	0.78	6.81[abc]
G1R1	0.76	6.24[bcd]
G2R3	0.78	6.08[bcd]
G2R1	0.80	5.77[cd]
G3R3	0.80	5.73[cd]
G4R1	0.78	5.69[cd]
G1R2	0.80	5.00[d]
Average	**0.77**	**6.65**

†Means with the same letters are not significantly different at the 0.05 level.

wide range of soil conditions, while the ranges of soil conditions and yields were fairly small in this experiment. A similar observation of low coefficient of determination (R^2 = 0.02) was made by Tapela and Colvin[8] for their modified Tilth Index values versus corn yields in an experiment conducted at Iowa State University, USA.

To improve the MTI as an indicator of soil tilth, correlation between each soil property and yield was done (Table 4). It was found that bulk density, cone index and plasticity index had fairly high positive correlation with rice yield. The correlation between bulk density and rice yield (r = 0.686) was significant at the 0.05 probability level. However, the correlations between cone index and rice yield (r = 0.303) and between plasticity index and rice yield (r = 0.501) were not significant. This meant that yield increased with the increase in these soil parameters. The observed relations between yield and bulk density, cone index and plasticity index may be true due to the fact that irrigated paddy soils, having high moisture content, require increased compaction (bulk density and cone index) in order to provide the necessary mechanical support needed by

Table 4. Correlation matrix of the selected soil properties and rice yield in the off-season.

Parameter	BD	CI	PI	AUC	OM
CI	0.060				
PI	0.054	0.060			
AUC	0.214	-0.148	-0.093		
OM	-0.120	0.637*	-0.260	-0.407	
Yield	0.686*	0.303	0.501	0.167	0.121

BD = bulk density, CI = cone index, PI = plasticity index,
AUC = aggregate uniformity coefficient, OM = organic matter.
* = significant at the 0.05 level.

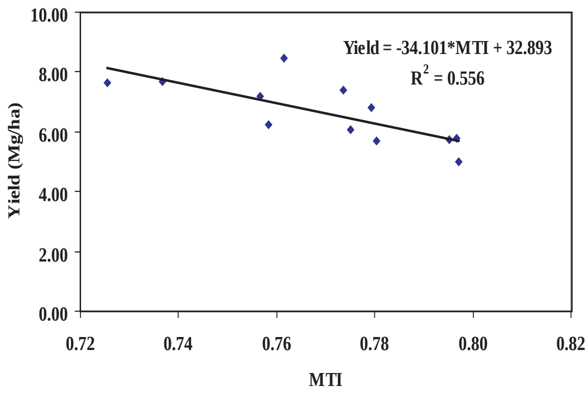

Fig 1. Linear regression of yield upon MTI for soil sampling before harvesting in the off-season.

the rice plant for proper anchorage. With only bulk density, cone index and plasticity index considered in the model, the inclusion of the root weighting factor (RI) also did not make any improvement in the predictability of yield with the MTI. For this reason, average soil parameter values of bulk density, cone index and plasticity index were eventually considered in the computation of the MTI by Equation (10) below, which gave a higher fit of r^2 = 0.56.

$$MTI = (CF_{BD} * CF_{CI} * CF_{PI})^{1/3} \quad (10)$$

where MTI, CF_{BD}, CF_{CI}, and CF_{PI} are as previously defined.

The linear relationship between rice yield and MTI developed for soil sampling before harvesting in the off-season is given in Equation 11 and illustrated in Figure 1. It can be observed from Figure 1 that rice yield decreases with increasing MTI, reflecting the effect of the tillage treatment. The benefit of the MTI is that it summarizes the contributing effects of bulk density, cone index and plasticity index to yield variability in the paddy field.

$$Yield = -34.101 * MTI + 32.893 \ (R^2 = 0.56) \quad (11)$$

The distribution of estimation errors of the estimated yield can be employed to check the goodness of fit of the regression model (Equation 11), as illustrated in Figure 2. The plot of the estimation errors against the estimated yield shows a random scattering of points in a horizontal band, which indicates a good yield prediction model from MTI.

Conclusion

Experimental results indicated a general decrease in bulk density, cone index, plasticity index and organic matter, possibly as a result of the tillage treatments

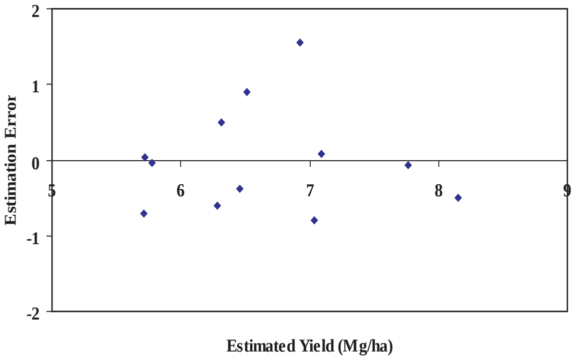

Fig 2. Distribution of estimation errors of yield for soil sampling before harvesting in the off-season.

applied. An analysis of variance performed indicated a significant difference ($p<0.01$) among the rice yield means. Bulk density, cone index and plasticity index were identified to have fairly high positive correlation ($r>0.30$) with the yield. The developed tilth index gave a better predictability ($r^2 = 0.56$) of the rice yield for bulk density, cone index and plasticity index. The results of the study suggest that the tilth index may assist in yield prediction by comparing measured soil conditions in a paddy field. A fairly good yield prediction of the soil tilth index model developed in this study may be due to the close similarity between the properties of soil used to develop and those used to test the model. However, because the approach used in this study is based on simple correlation and regression analyses, the predictive ability of the model cannot be guaranteed for soils whose properties fall outside the range of values used. Hence, the model is of limited applicability and its validity needs to be tested further on several other soils with a wider variation in intrinsic properties. Investigation of non-limiting, critical and root-limiting values of soil physical properties in paddy fields under varying tillage systems is also recommended.

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