ISSN: 1394 7990
Malaysian Journal of Soil Science Vol. 9: 53-63 (2005) Malaysian Society of Soil Science

Soil Tilth Index for Malaysian Paddy Fields

S.M. Bockari-Gevao[1], W.I. Wan Ishak[1], Y. Azmi[1] & C.B.S. Teh[2]
[1]*Department of Biological and Agricultural Engineering*
Faculty of Engineering
Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

[2]*Department of Land Management, Faculty of Agriculture*
Universiti Putra Malaysia 43400 UPM, Serdang, Selangor, Malaysia

ABSTRACT

Tillage treatments have been an integral part of many soil and crop management studies on the multifaceted concept of soil tilth. If soil tilth can be represented as a tillage index, it could be used to schedule farming operations and to improve soil management, which will consequently lead to sustainable, productive and profitable agriculture. This study was undertaken 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 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 an overall decrease in bulk density, cone index, plasticity index and organic matter, after tillage treatments. Analysis of variance indicated significant differences ($p<0.01$) among the rice yield means. Bulk density, cone index and plasticity index were identified to have fairly high positive correlation with the yield ($r>0.30$). A tilth index was consequently developed with bulk density, cone index and plasticity index which gave a better linear relationship ($R^2 = 0.56$) with 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 on 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 (Hadas 1997). 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 (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).

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 is needed. If soil tilth can be quantified, tillage indices could be used in scheduling farming operations and improving 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 optimising energy use for tillage by indicating when additional tillage may not be necessary (Singh *et al.* 1992).

Several attempts have been made by 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; 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 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 (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.

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 (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.

The main objectives of this study were: (i) to investigate the effect of rotary tillage on some soil physical properties and rice yield in a paddy field; (ii) to develop a soil tilth index based on the changes in these soil properties; and (iii) 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.* (1992) and subsequently modified by Tapela and Colvin (1998) 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 the tilth coefficient of bulk density, CF_2 the tilth coefficient of cone index, CF_3 the tilth coefficient of plasticity index, CF_4 the tilth coefficient of aggregate uniformity coefficient, and CF_5 the tilth coefficient of organic matter content. Singh *et al.* (1992) 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.* (1992) 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 to 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 plant will not normally survive (Tapela and Colvin 1998). 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 normalised to a 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 (Singh *et al.* 1992; Tapela and Colvin 1998) 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 $Mgcm^{-3}$), 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 (Neill 1979). We further modified Eq. (1) by using the geometric mean of the individual tilth coefficients to arrive at a soil layer rating (Gale *et al.* 1991). 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 (Gale *et al.* 1991).

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 later 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 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) (Gantzer and McCarty 1987).

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

$$CF_{BD} = -1.5337\ BD + 2.0009 \qquad (5)$$
$$CF_{CI} = 0.249\ CI + 0.8191 \qquad (6)$$
$$CF_{PI} = 0.0016\ PI + 0.7721 \qquad (7)$$
$$CF_{AUC} = 0.0761\ AUC + 0.0295 \qquad (8)$$
$$CF_{OM} = 0.0994\ OM + 0.1761 \qquad (9)$$

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 Tanjung Karang Rice Irrigation Scheme in the Northwest Selangor Integrated Agricultural Development Project (PLBS) located at 3°35'N and 101°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 a mean monthly temperature of 28°C. 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 two-factor experiment arranged in a completely randomised 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 first rotavation) and a 282 mm-rotavator (for second rotavation and third rotavation), attached to a FIAT 640 diesel tractor, operated with a PTO speed of 540 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 fertilised at the same levels under irrigated conditions in order to reduce the significance of differential fertility on crop yield.

Prior to tillage operations 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 (1999). Bulk soil samples were also collected for the purpose of characterising 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 analysed. 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 152.40 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 was determined by drying it in an oven at 105°C for 24 hours. Yield data were collected at harvest on 4 June and 11 December 2003 in the off-season and main season, respectively.

An analysis of variance was performed to determine whether 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

Effect of Rotary Tillage Practice on Soil Parameters

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

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

BT = before tillage, BH = before harvesting

T-test results showed that there was an overall decrease in bulk density, cone index, plasticity index and organic matter content, possibly as a result of the tillage treatments applied. The decrease in bulk density was highly significant ($p<0.01$); organic matter was barely insignificant at the 0.05 level. The exceptional case of overall increase in values of aggregate uniformity coefficient may have stemmed from other practices such as irrigation and fertilisation, or conditions induced by natural processes such as rainfall or desiccation during the growing period. Several researchers (Salokhe *et al.* 1993) have reported a decrease in bulk density and cone penetration resistance in lowland soils due to puddling or rotary tillage.

TABLE 2
Mean values of the modified tilth index (MTI) and Duncan's multiple range test for rice yield means

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]

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

Effect of the Rotary Tillage Practice on Yield

The rice yield harvested in the off-season of 2003 averaged about 6.65 Mg ha^{-1}. However, there were some differences in the mean yields. An analysis of variance performed indicated significant differences ($p<0.01$) among the yield means. Accordingly, variations in the mean yields were all attributed to the treatment effect (tillage practices). Duncan's multiple range test for differences ($\alpha = 0.05$) showed that tillage treatment G4R2 had 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 (Table 2). 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 MTI and yield was very low ($R^2 = 0.13$). The range of the MTIs was also small, but this seemed reasonable because the MTI was designed to cover a wide range of soil conditions while the ranges of soil conditions and yields were fairly small in this experiment. A similar observation of low correlation ($R^2 = 0.02$) was made by Tapela and Colvin (1998) for their modified Tilth Index values versus corn yields in an experiment conducted at Iowa State University, USA.

TABLE 3
Correlation matrix of rice yield and selected soil properties

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

To improve the MTI as an indicator of soil tilth, correlation between each soil property and yield was done (Table 3). It was found that bulk density, cone index and plasticity index had fairly high positive correlation with yield (r>0.30). This meant that yield increased with an increase in these soil parameters. The observed relations between yield and bulk density, cone index and plasticity index may be true for irrigated paddy soils, which having high moisture content, require increased compaction (bulk density and cone index) in order to provide the necessary mechanical support needed by 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.

Figure 1 illustrates the linear relationship between yield and MTI developed for soil sampling before harvesting. It can be observed from *Figure 1* that rice yield decreases with an increase in MTI, depicting the effect of the tillage treatment. The benefit of the MTI is that it summarises the contributing effects of bulk density, cone index and plasticity index to yield variability in the paddy field. The distribution of the estimation errors of yield for soil sampling before harvesting is illustrated in *Figure 2*.

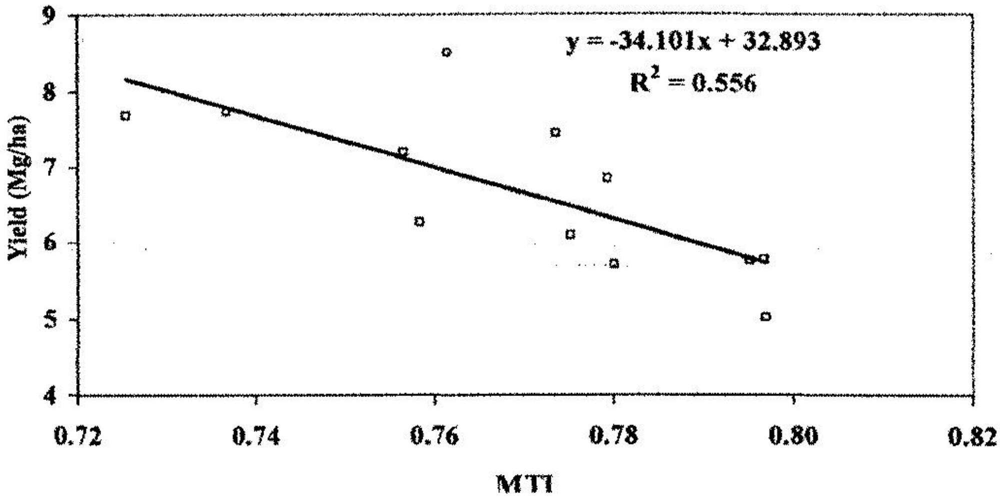

Fig.1: Relationship between yield and MTI for soil sampling before harvesting

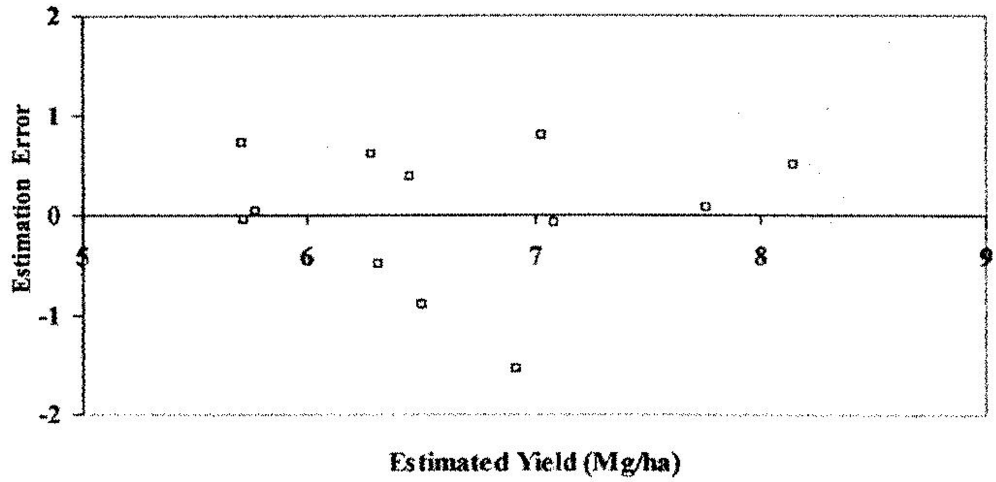

Fig. 2: Distribution of estimation errors of yield for soil sampling before harvesting

CONCLUSIONS AND RECOMMENDATION

Experimental results indicated a general decrease in bulk density, cone index, plasticity index and organic matter content, possibly as a result of the tillage treatments applied. An analysis of variance performed indicated 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 provided a better correlation ($R^2 = 0.56$) with 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 into the possibility of obtaining non-limiting, critical and root-limiting values of soil physical properties in paddy fields under varying tillage systems is also recommended.

REFERENCES

BRADY, N.C. and R.R. WEIL. 1999. *The Nature and Properties of Soils*. 12th ed. London: Prenctice-Hall.

BUCKLAND, G.D. and S. PAWLUK. 1985. Deep plowed Solonetzic and Chernozemic soils:II. crop response characteristics. *Can. J. Soil Sci.* **65**: 639-649.

CHRISTOPHER, T.B.S and A.M. MOKHTARUDDIN. 1995. Using factor analysis in soil science: a tool to summarize information. In *Proc. of the Soil Sci. Conf. of Malaysia 1995, ed.* Aminuddin, B.Y., A.B. Ismail, A.R. Ahmad and M.Z. Ghazali. Langkawi, Malaysia.

COLVIN, T.S., D.C. ERBACH, W.F. BUCHELE and R.M. CRUSE. 1984. Tillage Index based on created soil conditions. *Trans. of the ASAE* **27**: 370-371.

DAY, P.R. 1965. Particle fractionation and particle-size analysis. In *Methods of Soil Analysis. Part I. Agronomy,* ed C.A.Black, **9**: 545-567.

GALE, M.R., D.F. GRIGAL and R.B. HARDING. 1991. Soil Productivity Index: predictions of site quality for White Spruce plantations. *Soil Sci. Soc. Am. J.* **55**: 1701-1708.

GANTZER, C.J. and T.R. MCCARTY. 1987. Predicting corn yields on a claypan soil using a Soil Productivity Index. *Trans. of the ASAE* **30**: 1347-1352.

HADAS, A. 1997. Soil tilth – the desired soil structural state obtained through proper soil fragmentation and reorientation processes. *Soil & Tillage Res.* **43**: 7-40.

HORN, F.E. 1971. The Prediction of Amounts and Depth-distribution of water in a well-drained soil. M.S. Thesis. University of Missouri, Columbia, MO.

KARLEN, D.L., D.C. ERBACH, T.C. KASPAR, T.S. COLVIN, E.C. BERRY and D.R. TIMMONS. 1990. Soil tilth: a review of past perceptions and future needs. *Soil Sci. Soc. of Am. J.* **54**: 153-161.

KINIRY, L.C., C.L. SCRIVNER and M.E. KEENER. 1983. A Soil Productivity Index based upon predicted water depletion and root growth. University of Missouri-Coumbia. Coll. of Agr., *Agr. Exp. Sta. Res. Bull. 1051.*

MULENGERA, M.K. and R.W. PAYTON. 1999. Modification of the productivity index model. *Soil & Tillage Res.* **52**: 11-19.

NEILL, L.L. 1979. An evaluation of soil productivity based on root growth and water depletion. M.S. Thesis, University of Missouri, Columbia.

PIERCE, F.J., W.E. LARSON, R.H. DOWDY and W.A. GRAHAM. 1983. Productivity of soils: assessing long-term changes due to erosion. *J. Soil Water Conserv.* **38**:39-44.

SALOKHE, V.M., M. HANIF MIAH and M. HOKI. 1993. Puddling effects on some physical properties of Bangkok clay soil. *J. Agric. Engg.* **2**: 59-71.

SINGH, K.K., T.S. COLVIN, D.C. ERBACH and A.Q. MUGHAL. 1992. Tilth Index: an approach to quantifying soil tilth. *Trans. of the ASAE* **35**: 1777-1785.

TAPELA, M. and T.S. COLVIN. 1998. The Soil Tilth Index: an evaluation and proposed modification. *Trans. of the ASAE* **41**: 43-48.

WALKLEY, A. and I.A. BLACK. 1934. An examination of the effect of Dejareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* **37**: 29-38.