Journal of Agricultural Research Advances
ISSN: 2582-7227

**Research Article**
Open Access

# Conceptual model for the development of a "tilth index" to quantify the quality of crop seedbed preparation

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Received on: 24/01/2022 Accepted on: 22/06/2022 Published on: 25/06/2022

## ABSTRACT

**Aim:** The main aim of this study was to develop a "tilth index" to quantify soil tillage operation by determining a set of appropriate soil property indicators (attributes), via scoping, screening, and scoring process, by integrating polynomial function for each indicator and developing a combined tillage implement-soil attribute weight using Analytical Hierarchy Process (AHP) to arrive for an overall soil quality index for each tillage operation, Secondly to validate the developed model in comparison to published tilth indices estimated from field studies.

**Materials and Methods:** The developed decision–support model, to determine the overall tilth index for each tillage implement, was based on a five-step procedure of Scooping potential soil physical properties; Screening of these soil property attributes to select the most responsive set to modeling. The third step was defining the polynomial functional relation for each soil attribute. The fourth step is to employ the Analytical Hierarchy Process (AHP) pair-wise weighting and additive integration to develop a combined attribute – alternative tillage implements weight. The fifth step was the development of an overall adjusted tilth indicator, rating of the alternatives, and selection of the most efficient alternative.

**Results:** A statistical analysis was made to validate the developed adjusted tilth index with crop yields. The trend of the newly estimated soil tilth index was found to compare well with obtained crop yields, and thereby helps the decision-maker in selecting the most effective tillage operation.

**Conclusion:** It was concluded that the indexing approach used in this study provides a practical and effective tool for quantitative evaluation of the quality of soil tilth for the fulfillment of contracts, and under different environments and types of soils.

**Keywords:** Analytical hierarchy process; tilth index; corn yield, soil attributes

**How to cite this article**: Abbas OM and Mohammed HI (2022). Conceptual model for the development of a "tilth index" to quantify the quality of crop seedbed preparation. J. Agri. Res. Adv., 04(02): 22-37.

## Introduction

Soil tilth describes the qualitative physical state of the soil (texture, structure, strength, organic matter and consistency) after seedbed preparation modification by tillage implements (SSSA, 1979; Hillel, 1982; Brady, 1984 and Plaster, 1985). It is dynamic and changes through time by natural elements, and man-made (Brady, 1984). Farmers and farm managers face many such situations in tilth level assessment and often wise decisions have to be made within a short time. Needful tool easily provide expertise to farmers when needed. Quantification of the processes of tilth can be used as a decision aid to help in selecting the suitable tillage implement to use and as an indicator to judge the quality of soil tilth achieved (Karlen et al., 1990).



Soils in good tilth are granular with stable soil aggregates, resist compaction, absorb water readily and store it for later plant use. It prevents erosion, floods, stream siltation, is free of crust, and improves crop yields (Erbach, 1989).

The rate of plant growth, in general, and yield obtained in particular can be used as an indicator of soil tilth because it integrates the effects of the crop, soil, and microenvironment (Karlen et al., 1990). Plant selection can influence soil tilth because some species can penetrate compacted soil layers, whereas others increase aggregate and macro-pore stability (Elkins, 1985).

The problem of tilth level assessment is a typical agricultural problem. Although an experienced person may tell by sight and feel if the soil is in "good" or "poor" tilth, no analytical procedure has yet been devised to quantify and measure it. In practice, tilth levels are often assessed using judgmental or subjective logic. Therefore, gaining a quantitative understanding of soil tilth and determining how it can be managed for optimum productivity are needed. Once the soil tilth condition is known, specific measures may be undertaken to improve or maintain the tilth.

Singh et al (1992) stated that tilth is a blanket term describing the soil conditions determining the degree of fitness of soil as an environment for the growth and development of a crop plant. He stated further that soil with an ideal tilth should (i) offer minimal resistance to root penetration, (ii) permit free intake and moderate retention of rainfall, (iii) provide an optimal soil air supply with a moderate gaseous exchange between soil and atmosphere, (iv) hold to a minimum, competition between air and water for occupancy of the pore space, (v) provide maximal resistance to erosion, (vi) facilitate the placement and coverage of green manures and organic residues, (vii) promote microbial activity, and (viii) provide stable traction for farm implements. Poor soil tilth rust and compact easily, resist water intake, induce runoff and erosion, and frequently reduce crop yields by preventing plants from using the nutrients and soil moisture present.

Soil compaction, aggregate stability, and structure influence tilth by affecting pore size distribution, and thus soil aeration can be taken to express their action. Even small changes in these physical parameters can affect soil tilth by influencing soil microbial processes (Doran and Smith, 1987), as well as by changing infiltration and thus runoff or soil erosion (Foster et al., 1985). Plant growth can be used as an indicator of soil tilth because it integrates the effects of the crop, soil, and microenvironment (Karlen et al, 1990). Plant selection can influence soil tilth because some species can penetrate compacted soil layers, whereas others increase aggregate and macro-pore stability (Elkins, 1985).

Knowledge of determining soil tilth conditions enables decision-makers to assess accurately the better crop management decisions to take regarding tillage, crop rotation, fertilizer management, and yield goals can be made. thus determining optimal management policies that promote the continuous use and maximize the protection of soil and water resources.

Bockari-Gevao et al, (2006) indicated that many attempts have been made by some scholars to quantitatively describe soil tilth by formulating indices, which are sometimes correlated to crop yields. Neill (1979) developed, as a pioneer work, a soil "productivity index" based on the assumption that soil is a major determinant of crop yield because of the environment it provides for root growth, and other factors (climate, management, and plant genetic potential) are not included in her model. She considered available water capacity, bulk density, aeration, 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 as the parameters most influencing root growth. Each parameter was evaluated in terms of root response, and each soil layer was weighted according to an ideal rooting distribution. Her model defines soil capability for crop production rather than soil status due to changes made by tillage implements.

Karlen et al. (1990) defined tilth as "the physical condition of a soil described by its bulk density, porosity, structure, roughness, and aggregate characteristics as related to water, nutrient, heat, and air transport; stimulation of microbial and microfauna populations and processes; and impedance to seedling emergence and root penetration." This definition is in line with Neill (1979) considering productivity of the soil itself rather than changes made by tillage systems.

Pierce et al. (1983) modified the productivity index developed by Neill (1979) to include some additional concepts and to use the soil and land-use databases compiled by the Soil Conservation Service. Following Neil (1979) the assumption of evaluating the productive potential of soils in terms of the environment provided by the soil for root growth is adopted.
Development of soil tilth index rather than soil productivity index is started by Singh et al (1992) when he reduced the tilth indicators into a meanable size and proposed functional forms to describe tilth index based on observations and field trials using corn crop for only one season in Iowa state-USA.

Tapela and Colvin (1998) modified Singh et al. (1992)'s linear correlation model to a new quadratic relationship. However, neither model could consistently distinguish which tillage method produced better tilth. This confirmed that their methods needed further refinement and investigation.

Given these negative impacts, past and current research has been geared towards limiting tillage to the level that is necessary for optimizing crop yield. Some studies have shown that crop yield can be increased by plowing the soil, but the amount of tillage needed to obtain optimum yield is not known. The major obstacle to determining this is that soil condition following tillage cannot be adequately evaluated (Dexter, 1988). Consequently, it is difficult to judge how much tillage is required to improve the seedbed condition of a particular soil to get optimum yield.

The traditional method of seedbed evaluation is to make a visual assessment of the adequacy of the soil to support a planted crop. The method is qualitative and leads to arbitrary and subjective classification (Tapela and Colvin, 1998), such as "good tilth" or "poor tilth". The problem with subjective evaluation methods is that they cannot be used reliably to make management decisions regarding tillage. Thus, there is a need to develop quantitative evaluation methods that are more predictable. Karlen et al. (1998) pointed out that soil quality cannot be measured directly, but must be inferred or estimated by key indicators. Although an experienced person may tell by sight and feel if the soil is in 'good' or 'poor' tilth, there was no available method to quantify and measure it. Therefore, gaining a quantitative understanding of soil tilth and evaluating the effects of tillage systems, crop rotations, and seasonal variations on soil tilth were needed. The main objectives of this study were to develop a 'tilth index' to quantify soil tilth and to verify the proposed tilth index by field data.

## Materials and Methods

*Development of the conceptual model*

*The model Rationale:* Soil tilth is assumed to be a compound soil property, it is thus proposed that soil tilth can be characterized by the integration of soil physical properties such as tillage depth, compaction, strength, aggregate characteristics (Karlen et al., 1990); organic matter content (Knuti et al., 1979); and consistency (Plaster, 1985). The model rationale is based on a proposed modification for improving the method suggested by Singh et al (1992), and modified by Bockari-Gevao et al, (2006). The intended adjustments are based on proposing a set of schemes for selecting soil attributes that truly express the functions of tillage operations, defining each soil property by suitable polynomial functional relation, the estimate of a multiplicative tilth index for each candidate tillage implement and expressing the relative differences in the characteristics of the soil evaluation attributes and tillage implements These were made by determining a combined adjustment weighting factor using Analytical Hierarchy Process (AHP) for purpose of developing an overall tilth index to rank tillage implements and select the most efficient one. The rationale in the election of each soil attribute is based on their power of expression tillage intended functions, while the modifications in the definition of the functional relations for each indicator of each soil attribute is based on the principles of quality control used in the industry by determining upper, mid, and lower limits (Neill, 1979; Pierce et al. 1983, and Singh et al 1992). However, the list of proposed soil characters usually included as indicators to express and define both soil quality and the tilth index reported in the literature is usually long. This will make indicator measurement and their practical use to evaluate the quality of seedbed preparation in the field a difficult task. This calls for determining criteria for selecting the relevant indicator to include as part of the tilth index. The rationale to define the functional relationship of each soil attribute is to adopt the polynomial relation on basis of the rate of diminishing return (El Nady, 2015).

In the late 1970s, Saaty (1977) developed the analytic hierarchy process (AHP) as a robust approach to multi-criteria decision-making. It is applied in diverse areas to rank, select, evaluate, and benchmark decision alternatives (Waisil et al 2003; Golden et al, 1989). In the AHP, the decision-maker models a problem as a hierarchy of criteria, sub-criteria, and alternatives. After the hierarchy is constructed, the decision-maker assesses the importance of each element at each level of the hierarchy to aid in making proper decisions.

**The model Structure and Processes:**

The model general flow chart which consists of five – steps procedure was depicted.

*Step 1: Scoping of indices:* Quality of soil tilth refers to the ecological equilibrium and the functionality of soil and its capacity to maintain a well-balanced ecosystem with high biodiversity above and below the surface, and productivity. To understand and use soil tilth as a tool for improved and sustainable crop production, and for optimum utilization of farm machinery, soil physical properties must be determined, collected, and employed to verify which one responds to the proposed tillage operation within the desired timescale. Hence, soil attributes with a rapid response to natural or anthropogenic actions are considered good indicators of soil quality. These soil tillage attributes or indicators can be collected by primary or secondary data. The former can be generated from field experiments, while the latter can be deduced from many sources such as research articles and reports. However, running a field experiment is a difficult undertaking in terms of time, money, and effort. Using secondary data to generate soil attributes is referred to as the process of knowledge acquisition and simulation which is defined by Jones (1989) as being the process of extracting, structuring, and organizing knowledge from an expert source. This concise definition hides the complexity of the application. Singh et al (1992), Bockari-Gevao et al, (2006) Harris and Bezdicek (1994) stated that the main functions of any tillage operation are to prepare a fine seedbed, enhance water infiltration into the soil, facilitate seedling elongation, and root movement with less energy, destroy weeds, distribute residues and organic matter, conserve and store moisture, and minimize runoff. Among the physical indicators, soil texture, aggregation, moisture, porosity, and bulk density have been used. The first step in this model is the scoping of several candidate indicators that need to be proposed for describing and assessment of soil quality after conducting the tillage operation. These candidate indicators are expected to reflect soil properties and reflect the functions and purposes of conducting tillage activities as defined before and stated by Singh et al (1992). The raw initial set of proposed soil attributes to express tilth quality and diagnose impacts of tillage operations are suggested to include: (1) bulk density, (2) soil depth (3) infiltration, (4) penetration resistance "cone index", (5) soil porosity, (6) plasticity index, (7) soil roughness, (8) clod size "or aggregate uniformity coefficient", (9) organic matter, (10) weeding efficiency, and (11) water holding capacity " or water content", and (12) soil compaction.

*Step 2: Screening and pairwise comparison:* Singh et al (1992), Bockari-Gevao et al, (2006) Harris and Bezdicek (1994) indicated that soil quality indicators after tillage operations might be divided into two major groups, analytical and descriptive. Experts often prefer analytical indicators, while farmers and the public often use descriptive descriptions. As postulated in the scoping phase a wide range of indicators or soil properties may be proposed. For this model, ten soil property attributes are proposed as a possible alternative. In reality, it is impractical to use the whole set and they need to be screened out to keep minimum data set with the most essential ones.

The way to screen and select any one alternative index over another alternative is to be based on its degree of decision-maker satisfaction by fulfilling five acceptance scores (Sensitivity; Ease of understanding of indicator value; Ease and/or cost-effectiveness of measurement of soil indicator; Predictable influence of properties on soil, and plant growing system, and crop productivity; Relationship to ecosystem processes (especially those reflecting wider aspects of environmental quality and sustainability), and with its capability to achieve the reported tillage objectives. Lal (1994) and Doran and Prkin, (1996) recommended that to attain these acceptance scores the selection criteria should:

• ***Correlate*** well with natural processes in the ecosystem, natural environment, topography, and climate (this also increases their utility in process-oriented modeling)

.• ***Integrate*** soil physical, properties, and processes, and serve as basic inputs needed for estimation of tillage functions which are more difficult to measure directly.

• Be relatively ***cheap and easy to use*** under field conditions so that both specialists and producers can use them to assess soil quality.

• ***Precision and sensitivity*** to variations in measurement. The indicators should be sensitive enough to reflect the influence of management and climate on long-term changes in soil quality, but not be so sensitive that they are influenced by short-term weather patterns.

• Be the components of ***existing soil databases*** where possible.

In this study for indicators selection or rejection, and for developing pairwise comparison Cameron et al. (1998) equation is intended to be followed as an integral part of the scoring approach: $A = \sum(S, U, M, I, R)$

Where: A = Acceptance score for indicator; S = *Sensitivity* of indicator to degradation or remediation process; U =Ease of *understanding* of indicator value. M: *Ease and/or cost*-effectiveness of *measurement* of soil indicator I: Predictable ***influence*** of properties on soil, plant growing system, and crop productivity; R: ***Relationship*** to ecosystem processes (especially those reflecting wider aspects of environmental quality and sustainability).

Each parameter in the equation is given a score (1 to 5) based on the user's knowledge and experience of it. The sum of the individual scores gives the level of acceptance (A) score which can be ranked in comparison to other potential indicators, thus aiding

In developing a pair-wise comparison table to be used in the model step of using AHP. For example, soil bulk density may receive the following score: (S=4, U=4, M=5, I=3 and R=2) giving A values of (sum of scores to the total scores; i.e. =18/25 = (72%). Particle size, on the other hand, may only get an A value of 10/25 (40%) (S=1, U=3, M=2, I=2, and R=2). In this case, we should select soil bulk density to be one of the indicators for soil quality assessment and reject Particle size with a total score = A<50%

*Step 3: The Establishment of Indicators*

*Indicator Functional Relationships:* As stated in the model rationale the indicator to express each soil attribute can be defined quantitatively from the data of each measured soil parameter by employing a polynomial relationship (tilth coefficient) following the principle of diminishing return for crop growth rate by the following general relation format (Singh et al,1992; Conica, 2000):

$$CF(x) = Ao + A_1 * X + A2 * X^2 + ... + An * Xn, \quad ..........................................(2)$$

Where: CF(x) = tilth coefficient for the soil property attribute (X), and Ao, $A_1$, ……., An = empirical constants.

To derive the polynomial relationship for each proposed indicator it is essential to examine each screened and proposed property separately according to the concept of the control chart. The critical levels (or threshold levels), are: an upper control limit (UCL), a lower control limit (LCL) represent the minimum values within which soil quality must be kept for sustainable soil management, and in-between them is the middle (The mean). The non-limiting condition (the mean) is the optimal level for maximum plant growth (sufficient level), while the limiting level is the level above which the plants will not normally survive. These values were then be plotted on a graph and the best fitting polynomial curve was to be determined to define a regression equation to predict other values within the range.

Soil attributes differ widely in their magnitudes and the units used to express them. Since each indicator expresses the contribution of each soil attribute in the implemented final tilth indicator, it is thus necessary to consider the characteristics of each attribute in expressing each indicator by its normalization by unified scale or by using a non-dimensional scale. Singh et al (1992), Bockari-Gevao et al, (2006) Harris and Bezdicek (1994), and (Loveland et al., 2002) suggested a normalizing process by assigning one to the maximum value and zero to the lower minimum value and referring to these limits as trigger values or workable ranges. However, if the indicator for each attribute is expressed by functional relation with obtained yield is well established for the soil and crop under consideration (called sufficiency level in studies in the development of soil quality indicator), such indicator can be considered directly in the tilth model for the candidate implement. This approach is advocated in this model for the functional forms of the important soil attributes are recommended by Singh, et al, (1992) as follows:

*1-Bulk density (BD in Mgm OM):* Bulk density is defined as the mass of a unit volume of dry soil (Hillel, 1982; Brady, 1984; Plaster, 1985). It was identified to have a high positive correlation with wheat yield, and it is reported to express the soil resistance for root penetration into the soil. Based upon the review of literature observed upper and the lower pound of BD are 1.3 Mg/m^3 to 1.8 Mg/m^3 respectively (Neill, 1979; Hillel, 1982; Plaster, 1985). The recommended relation between the tilth coefficient [CF(BD)] and the bulk density (BD) is represented by equations 3.0 to 5.0 (Neill,1979).

CF (BD) = 1.0, for BD < = 1.3 Mg/m^3 …………………..... (3)

CF (BD) = - 1.5 + 3.87 * BD - 1.5 * BD^2; for 1.3 < = BD < = 2.1 Mg/m^3 …….(4)

CF (BD) = 0.0, for BD > = 2.1 Mg/m^ 3 …………..... (5)

2-Tillage depth (D in cm): Tillage depth is defined as the vertical distance from the initial soil surface to a specified point of tool penetration (Agricultural Engineers Yearbook, 1982). Tillage depth is the most easily field measurable soil attribute and is frequently used by farmers. The depth measured after tillage operation needs to be related to the expected root depth of an ideal crop. The expected ideal crop depth can be found in many irrigation references (Allen, 2000).

*3-Cone index (CI in MPa):* Cone index is considered as a measure of soil strength and an indicator of how easily roots can penetrate the soil, and thus, affect plant growth and crop yield. Many experiments have shown that crop yields decrease as the strength of soil layers increases. From the work reported by many investigators (Taylor and Gardner,1963; Taylor et al., 1966, and 1964; Parker and Taylor,1965; Taylor and Bruce, 1968; Tavemetti,1968; Taylor and Ratliff, 1969; Voorhees et al.,1975; Gerard et al.,1982; Bowen,1981; Fryrear and McCully, 1972), the relation proposed between the tilth coefficient [CF(CI)] and the cone index (CI) can be represented by equations 6,7, and 8 :

CF (CI) = 1.0, for CI < = 1.0 MPa ………….. (6)

CF (CI) = 1.012 - 0.002 » CI - 0.01 • CP,

For 1.0 <= CI < = 10.0 MPa ………………..(7)

CF (CI) = 0.0, for CI > = 10.0 MPa ……...(8)

*4-Aggregate uniformity coefficient (AUC, dimensionless) and Aggregate stability:* Aggregates are soil particles that are composed of smaller soil particles, which range in size from microns to millimeters. According to Singh et al (1992), and Sparling et al., 2003) the aggregate uniformity coefficient (CF (UC)] can be represented by equations 12 to 14.

CF (UC) = 1.0, for UC > = 5 ……….. (12)

CF (UC) = 0.348 + 0.245 * UC - 0.023 * UC^

For 2 < = UC < = 5 ……………………... (13)

CF (UC) = 0.75, for UC < = 2 ….... (14)

5-Porosity (P in %): The total soil porosity can be classified as textural, depending on the proportion of soil particles, and structural, depending on bio-pores and as macro-structures. The macro-pores are easily affected by soil use and management (Dexter, 2004). The ideal percentage of pores in agricultural soils, to be occupied by air and water, amounts to 40 % of the total volume of the soil, which can be considered as a base for a relative measure of porosity indicator.

*6-Weeding efficiency (We in %):* Weed infestation can be measured by running an intersect across and a long field in a diagonal direction, and measuring number of weeds in sampling one meter by one-meter rectangle before and after the tillage operation, and the relative percentage change is the indicator.

*7-Organic matter (OM in %):* Smith and Elliott (1990) reported that the organic matter content of agricultural soils is highly correlated with their potential productivity, tilth, and fertility. The amount of soil organic matter in most semiarid dryland soils is relatively low, ranging from 0.5 to 3%. Following Hillel, (1982); Brady, (1984), and Plaster, (1985) the curve of the limiting points for organic matter were similar to the bulk density curve. According to Singh et al (1992), the relation the tilth coefficient [CF (OM)] of organic matter (OM) is represented by equations 9 to 11

CF (OM) = 1.0, for OM > = 5% …………….. (9)

CF (OM) = 0.59 + 0.122 * OM - 0.008 * 0M ^2

For 1 <= OM <= 5% ………………. (10)

CF (OM) = 0.70, for OM < = 1% …………… (11)

*8-Available water content (%):* Water-holding capacity is the function of soil type, and reflects the capability of the soils to absorb, and retain rainfall before through-flow and run-off begin. It is positively correlated with soil organic matter but negatively correlated with bulk density, and it is a determining factor of traction and slippage. The minimum moisture content for a plant to survive should be above soil moisture at the wilting point and the maximum is at 80% of field capacity. Ideal mean soil moisture recommended being at 50% of the soil water holding capacity. Thus the tilth coefficient for soil moisture [CF (OM)] was its measured value related to soil mean value.

*9-Plant residues surface cover (%):* Soil erosion losses after planting are inversely related to the amount of soil surface covered by plant residues, regardless of pre-planting tillage operations (Laflen and Colvin, 1981). Similar, to the measurement of weed infestation residue cover, can be determined by the line transect method is the most accurate of the available methods. The tilth coefficient can be taken as the percentage of plant residues per unit area (Laflen et al., 1981).

*10- Plasticity index (PI):* The most common minimum and maximum values of the plasticity index from the Soil Survey report of Boone County, Iowa, were also 15 (medium plastic) and 40%, (high plastic) respectively, which were selected as the values corresponding to the non-limiting soil and soil unusable by plants (Casagrande,1948). In this model, the relation proposed between the tilth coefficient [CF (PI)] and the plasticity index (PI) is represented by equations 15 to 17 and shown in Figure A-4.

CF (PI) = 1.0, for PI < = 15% …... (15)

CF (PI) = 1.02 + 0.0009 • PI - 0.00016 *PI^2

For 15 <= PI <= 40% …………... (16)

CF (PI) = 0.80, for PI > = 40% …………… (17)

*Step 4: Development of Combined Relative Weight*

This step was based on running the Analytical Hierarchy Process (AHP), which is accomplished by generating entries of alternative tillage operations concerning the proposed tilth evaluation indicators in a pair-wise comparison matrix where elements were compared to each other. For each pair-wise comparison matrix, the decision-maker typically uses the eigenvector method (Saaty, 1977; Waisil et al 2003; Golden et al, 1989) to generate a priority vector that gives the estimated, relative weights of the elements at each level of the hierarchy. Weights across various levels of the hierarchy are then aggregated using the principle of hierarchic composition to produce a final combined weight for each alternative

The estimated overall tilth index for each implement combines the contribution of each soil attribute, and the behavior and characteristic of the implement itself compared to other alternative ones; to achieve tillage goals leading to maximizing crop yield. However, Singh et al (1992) no adjustment factor is used to reflect the relative weight of the indicator or the implement. While in Bockhari – Gevao et al, (2006) model Bockari-Gevao et al, (2006) layer root depth is used as a weight adjustment factor for the overall tilth index. In the development of the soil quality index El Nady (2015) used the root depth to adjust the overall index, which is the same technique followed in this model.

Ranking of alternative in this model was achieved by multiplication of the adjustment factor (score) developed by AHP with the multiplicative tilth index estimated by the indicator of soil attributes (this is explained mathematically in step five). In contrast to Singh et al (1992,) who used ANOVA and multiple range tests (LSD) Analytical Hierarchy Process (AHP) ranks tillage implemented in descending order according to the power of their estimated overall tilth index. This process quantifies the quality of seedbed preparation by each tillage implement and thereby aids the decision-maker to select the most effective tillage operation to use. However, if the decision-maker manages to establish the quantitative association between the tilth index of each tillage operation with crop yield under every crop and soil and by long-term research he can estimate the expected yield from doing certain tillage operations.

*Step 5: Development of The Tilth Index:*

In this model, it was recommended to use a linear multiplicative relation to express the details of each one of the proposed indices (tilth coefficient) to express the overall adjusted tilth index as:

$$ATI = (CF(x_1)* CF_{(X2)} * C\,F_{(x3)} * \ldots\ldots CF(xn_{-1}) * C\,F(xn))* Score \ldots\ldots\ldots\ldots (3)$$

Where: ATI = overall adjusted tilth index for tillage operation; CF (xi) = tilth coefficients for each of n soil indicator, and Score = the combined relative weight for the soil indicator – implement type determined by AHP.

To arrive at an overall tilth index for each indicator or coefficient a relative combined weight needs to be assigned to express its contribution. It was possible to define the weight using, AHP with pair-wise comparison, or Delphi. However, Bockari-Gevao et al, (2006) suggested adjusting the overall tilth index of each tillage operation by multiplication by an estimated root depth function to the soil layer. This proposal neglects the proportional differences in the characteristics tillage implements and the nature of each coefficient of the soil attribute and masks the relative effects of each one of them on the other to attain the objectives of the tillage operation.

In this model, it was recommended to take tillage attained depth directly as a field measurable indicator.

*Data Collection and Analysis*

*Case Study One: Corn Rotation Study Near Ames Iowa - Singh et al, (1992)*

Field experiments were conducted by Singh et al, (1992) during the 1989 and 1990 cropping seasons at the Agronomy-Agricultural Engineering

Research Center of Iowa State University, near Ames, Iowa. The soils were silty clay loam and Clarion loam on a slope of 0 to 3 percent with continuous com and corn-soybean rotations. Four replications in a randomized complete block split-plot design were used in both fields. The treatments were five levels of tillage; moldboard plow, chisel plow, spring disk, slot plant ridge, and till plant. For purpose of the verification of the developed model with that of Singh et al,(1992) the data for corn rotations (continuous com) in season 1989 will be will considered for comparative analysis and model validation. The soil characteristics of the experimental site was described as Silty clay loam with liquid limit = 35-60 %; Plasticity Index = 15 -30%; Organic matter = 6 – 8 %; Potential Corn yield = 7.2 Mg/ha; Potential Soybean yield = 2.8 Mg/ha. During 1989, in each crop rotation, four measurements of moisture content, bulk density, cone index, and uniformity coefficient were made from the 0-150 mm soil depth in the row from each plot. Samples were taken before tillage, after disking, after field cultivating, after planting, and before harvesting. The tilth indices of each of the four locations within a plot were averaged to provide a representative tilth index of each tillage treatment. Methods used to measure soil properties were given by Singh et al, (1992) following (ASAE Std. S312.2), and (Wray, 1986) recommendations. The values of the organic matter were taken from the soil survey report of Boone County (USDA-SCS, 1981). The reported data is taken as input to the model developed in this study to determine the new tilth indices.

*Case Study Two: Bockari-Gevao et al, (2006)*

Data for the development and evaluation of the tilth index 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), Kuala Selangor and Sabak Bernam Districts, Malaysia. Climate, in general, was semi- and subtropical. The soil is silty clay. The 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 in 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.

Measurements of soil properties were made following the technique described by Brady and Weil (1999) from the topsoil depth (0-100 mm) and subsoil depth (100-200 mm), Walkley and Black (1934), and the ASAE standard procedure and guidelines.

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 modified tilth index was performed.

The mean values of the soil properties measured before tillage operations and before harvesting were presented in Table 1. The modifications in Singh (1992) model as made by Bockari-Gevao et al (2006) include: First the basic form of the TI prediction by the model to include a root-weighting factor of the ith soil layer (RI); the modified tilth index (MTI) model was as shown in the equation.

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

Where: MTI= modified tilth index (0.0 < = MTI < +1.0); and

$CF_{(BD)} * CF_{(CI)} * CF_{(PI)} * CF_{(AUC)} * CF_{(OM)}$ = is 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. Secondly, Bockari-Gevao et al (2006) suggested using the geometric mean of the individual tilth coefficients to arrive at a soil layer rating. It was also raised the multiplicative value of soil indicators by a power of (0.2) without giving any reason. The weighting factor, (RI), is based on the assumption that the relative root mass at depth (D) is equal to the fraction of available water depleted at that depth. Thirdly 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, and expressed in the following linear forms:

CF BD = - 1.5357 BD + 2.009 ……….(5)

CF CI = - 0.249 CI + 0.8191……… (6)

CFPI = - 0.0016 PI 0.7721 ………….. (7)

CFAUC = 0.0761 AUC + 0.0295 ………… (8)

CF OM = 0.0994 OM + 0.1761 …………(9)

## Results and Discussion

*Verification of Tilth Indices Using Singh et al (1992) Corn Data:* Singh et al (1992) Tilth index for 1989 Cropping Season (Continuous Corn Rotation): As reported by Singh et al (1992) depicted the mean values of soil evaluation indicators, Model tilth index, Singh et al tilth index actual crop yield, and LSD-statistic for the continuous Corn Rotation in 1989.

*The actual average corn yields* of individual implements ranged from 8.73 Mg/ha for moldboard plow to 7.13 Mg/ha for till plant. Duncan's Multiple Range Test on the mean values of corn yield for the different tillage systems showed that moldboard plow, chisel plow, and till plant; chisel plow, till plant, and spring disk; and spring disk, and slot plant ridge system groups were not statistically different. The implements were ranked to their yield in descending order.

*Indices and yield:* comparison of the developed model tilth index with yield shows the same trend and same ranking sequence of tillage implement but using t-test they significantly differ in magnitude. This is difference is expected and in agreement with other indicators reported for soil quality or productivity (Kiniry et al, 1983, and Imoro et al, 2012).

Mean values of the tilth index developed by the study model were highest for moldboard plow among all the tillage practices. Mean values for chisel plow spring disk were equal but slightly lower for slot plant ridge and till plant. This result is similar to yield data and was confirmed by LSD test (Table 1).

The mean values of the tilth index determined by Singh et al (1992) for the different tillage systems showed a different trend from the corn yield. This is attributed by Singh et al (1992) to be due to the significant difference in the mean values, determined by Duncan's Multiple Range Test, between moldboard plowing and slot plant ridge systems. This requires, as intended in this study, the introduction of an adjustment factor to improve the predictability of crop yields.

Mean values of Singh et al (1992) tilth index were highest for moldboard plow among all the tillage practices. Mean values for till plant and chisel plow was equal but slightly lower than moldboard plow. Next in decreasing order of tilth index were spring disk and slot plant ridge. Crop yield and the two tilth indices follow perfect polynomial relations but with different degrees of association ($R^2$ ) equal to .0.968,0.953 and 0.935 for crop yield, modified tilth index, and Singh et al (1992) tilth index respectively.

As evident the developed model modified tilth index, However, other factors such as cost of energy, or availability of the required tractor draft need to be considered. Such a result is confirmed by the obtained yield data. *Verification of Tilth Indices Using Bockari - Gevao et al, (2006) Data:* The mean values of soil properties measured by Bockari-Gevao et al (2006) from replicated experimental plots for each tillage treatment were reported (Table 1). Experimental plots in the off-season. The results of the effect of the Rotary Tillage Practice on Soil Parameters examined Bockari-Gevao et al (2006), using t-test comparison, revealed a significant decrease of cone index, plasticity index, and organic matter parameters due to rotary tillage.

Table 1: Mean values of soil indicators, for the model, modified tilth index (MTI), the Singh et al (1992) tilth index, and com yields; and LSD-test for tillage treatments and the continuous com rotation in 1989.

| Tillage | System | Moisture Content (g/g) | Bulk Density (Mg/m^3) | Cone Index (MPa) | Uniformity Coefficient | Singh et al Tilth Index | Model Tilth Index | Actual Yield (Mg/ha) |
|---|---|---|---|---|---|---|---|---|
| Moldboard plow | MBP | 0.18 | 1.44 | 1.57 | 4.95 | 0.87 a | 0.93 | 8.78 a |
| Chisel plow | CP | 0.168 | 1.48 | 2.1 | 4.95 | 0.82 ab | 0.93 | 8.33 ab |
| Spring disk | TP | 0.206 | 1.38 | 1.74 | 3.86 | 0.82 ab | 0.89 | 8.27 ab |
| Slot plant ridge | SD | 0.154 | 1.55 | 2.4 | 4.71 | 0.78 ab | 0.73 | 7.57 ab |
| Till plant. | SPR | 0.148 | 1.57 | 2.29 | 4.95 | 0.77 b | 0.73 | 7.13 a |
| Same letters express the same significance difference due to LSD -test | | | | | | | | |

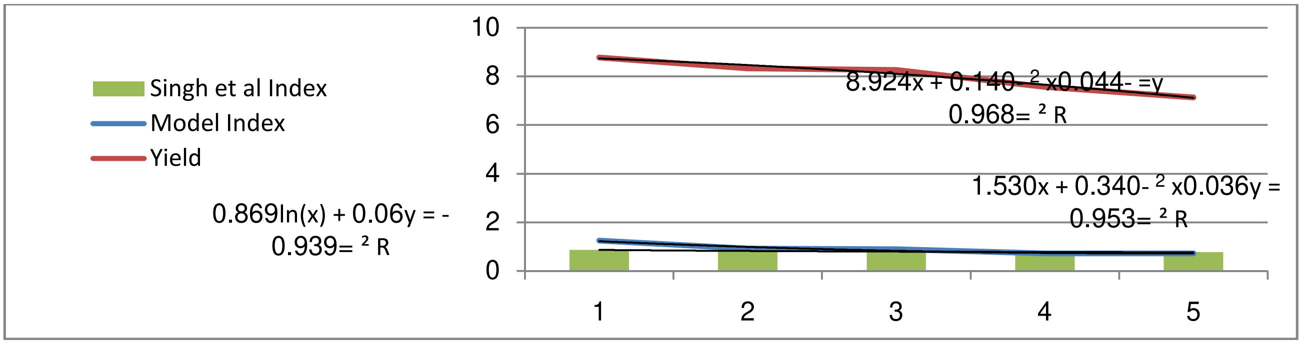

Fig 1 (a): Relation between, the model developed tilth index, Singh et al (1992) tilth index and crop yield

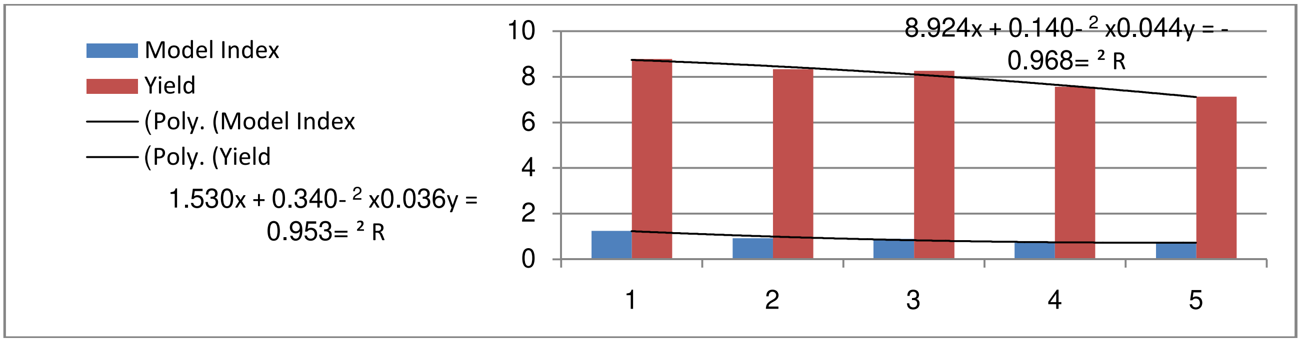

Fig 1 (b): Relation between, the model developed tilth index, and crop yield

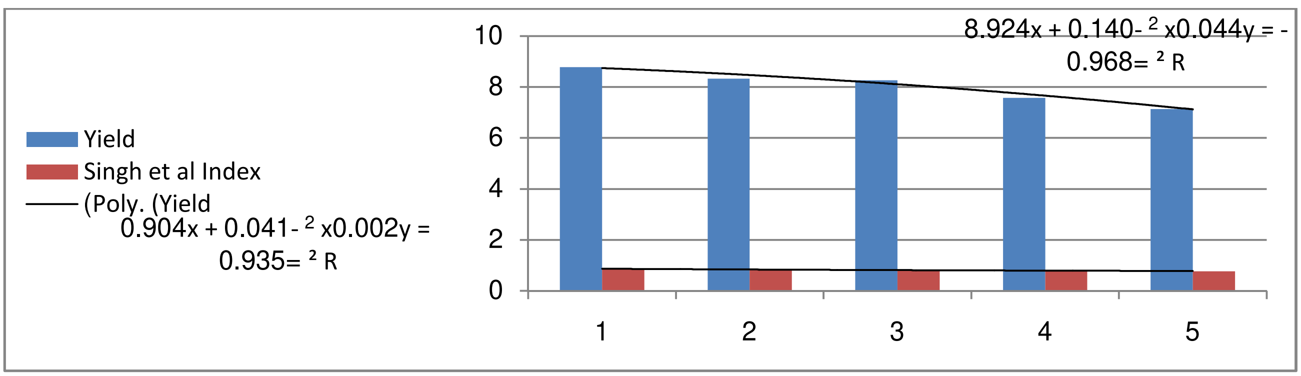

Fig 1 (c): Relation between, the model developed tilth index, and crop yield

Table 2: Mean values of soil properties measured from experimental plots of each tillage treatment

| Tillage | Bulk Density Mg /m3 | Cone Index Mpa | Plasticity Index % | Aggregate Uniformity Coefficient | Organic Matter % | (MTI) Tilth Index MTI | mean Yield Mg/ha | Model Adjusted Tilth Index |
|---|---|---|---|---|---|---|---|---|
| | AT | AT | AT | AT | AT | AT | AT | AT |
| G1R1 | 0.83 | 0.18 | 3.27 | 9.05 | 4.85 | 0.76 | 8.48 a | 0.003 |
| G1R2 | 0.75 | 0.18 | 5.78 | 9.73 | 4.56 | 0.74 | 7.70 ab | 0.008 |
| G1R3 | 0.8 | 0.19 | 2.1 | 9.68 | 6.08 | 0.73 | 7.66 ab | 0.014 |
| G2R1 | 0.75 | 0.18 | 6.27 | 9.5 | 5.41 | 0.77 | 7.41 abc | 0.020 |
| G2R2 | 0.83 | 0.19 | 4.84 | 11.15 | 4.27 | 0.76 | 7.18 abc | 0.025 |
| G2R3 | 0.79 | 0.22 | 4.05 | 9.2 | 6 | 0.78 | 6.81 abc | 0.030 |
| G3R1 | 0.89 | 0.15 | 7.14 | 9.9 | 4.29 | 0.76 | 6.24 bcd | 0.033 |
| G3R2 | 0.86 | 0.23 | 5.81 | 9.53 | 5.29 | 0.78 | 6.08 bcd | 0.038 |
| G3R3 | 0.76 | 0.17 | 1.87 | 9.61 | 4.6 | 0.80 | 5.77cd | 0.043 |
| G4R1 | 0.8 | 0.10 | 3.53 | 9.81 | 4.15 | 0.80 | 5.73cd | 0.047 |
| G4R2 | 0.81 | 0.19 | 15.03 | 9.49 | 5.04 | 0.78 | 5.69cd | 0.050 |
| G4R3 | 0.78 | 0.17 | 12.93 | 9.45 | 4.03 | 0.80 | 5.00d | 0.053 |
| Average | 0.8 | 0.18 | 6.05 | 9.68 | 4.88 | 0.77 | 6.65 | 0.000 |

It was reported a highly significant overall decrease in bulk density ($p<0.01$), with the decrease the organic matter was almost significant ($p<0.05$), while there is an exceptional overall increase in values of aggregate uniformity coefficient. These results imply that the reaction of the tillage operations on soil indicators is very variable and such variability needs to be considered in determining their overall impact. However, Bockari-Gevao, et al (2006) introduced root system depth (R) as an adjustment factor to express the effects of tillage operation.

Bockari-Gevao, et al (2006) reported that analysis of variance 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. Duncan's multiple range test for examination of the differences (± = 0.05) of yield means from the various tillage treatments showed that the response of tillage treatment varies significantly. This variability confirms the results of the t-test and calls for using a suitable adjustment factor Bockari-Gevao, et al (2006) related the association between tilth index and yield by a very weak linear relation (R2 = 0.13). These relations indicate that the tilth index to perfectly match crop yield needs to be adjusted by a suitable coefficient other than root depth. A similar observation of low coefficient of determination (R^2 = 0.02) was made by Tapela and Colvin for their modified Tilth Index values versus corn yields in an experiment conducted at Iowa State University, USA.

Correlation analysis between each soil property and yield was done by Bockari-Gevao, et al (2006) and given (Table 3). The table showed that there is a significant and fairly high positive correlation between bulk density, cone index, and plasticity index with rice yield, while aggregate uniformity coefficient and organic matter did not Bockari-Gevao et al (2006) attributed this variability to be due to the presence of high moisture content creating a favorable environment for improving the quality of bulk density, cone index, and plasticity index. Bockari-Gevao et al (2006) claim that when all soil indicators are considered in determining the modified tillage index (MTI), and with the inclusion of the root weighting factor (RI), there is no improvement in the predictability of yield. Even when only soil parameters that exhibit significantly positive correlation with yield (bulk density, cone index, and plasticity index) are considered, and by employing root correction factor the yield predictability of MTI is very low with the coefficient of determination of (R^2 =0. 56). They found that the resulting linear relation between MTI and cop yield failed to predict expected yield.

The input data of mean yield, and MTI for each tillage treatment, reported by Bockari-Gevao et al (2006) and given was entered in the developed model to generate the adjusted tilth index. By employing t-test and the graphical representation of the output it was possible to arrive at the following relations: Comparison of Bockari-Gevao, et al (2006) MTI with crop yield reveals significant differences with yield strongly follow polynomial relation with a high coefficient of determination (R^2 = 0.86), while MTI follows a low linear relation (R^2 = 0.556). This confirms the results of the correlation analysis and the t-tests reported by Bockari-Gevao et al (2006), which call for looking of more effective correction coefficient to remove the variability referred to before.

When the adjusted tilth index is determined by the developed model is compared to the obtained yield it is evident from figure (3b) that they follow the same trend with polynomial relation for both and a coefficient of variation of (R^2= o.99) for the adjusted tilth index.

Table 3: Correlation matrix of the selected soil properties and rice yield

| Parameter | Bulk Density | Cone Index | Plasticity Index | Aggregate uniformity coefficient | Organic Matter |
|---|---|---|---|---|---|
| | BD | CI | PI | AUC | OM |
| BD | 0.06 | | | | |
| CI | 0.054 | 0.060 | | | |
| PI | 0.214 | -0.148 | 0.093 | | |
| AUC | -0.12 | 0.637* | -0.26 | -0.407 | |
| OM | 0.680 * | 0.303 | 0.501 | 0.167 | 0.121 |
| * significant at 0.05 level | | | | | |

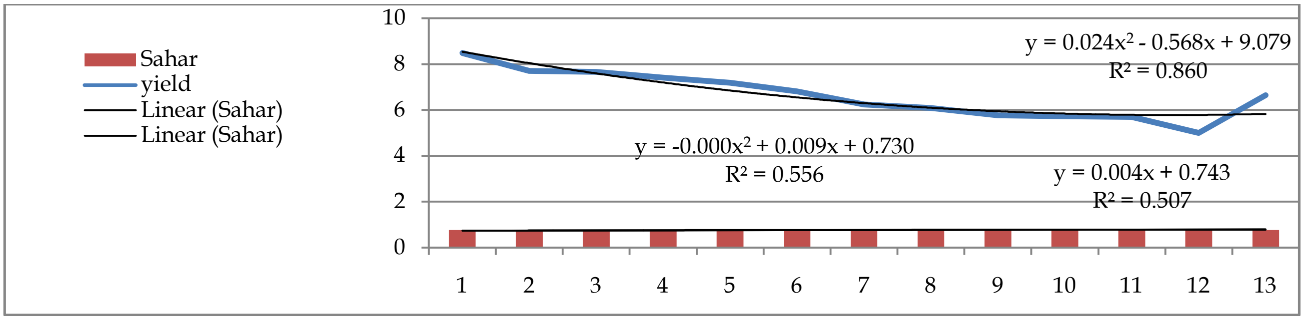


Fig 3 (a): The relation between MTI and crop yield

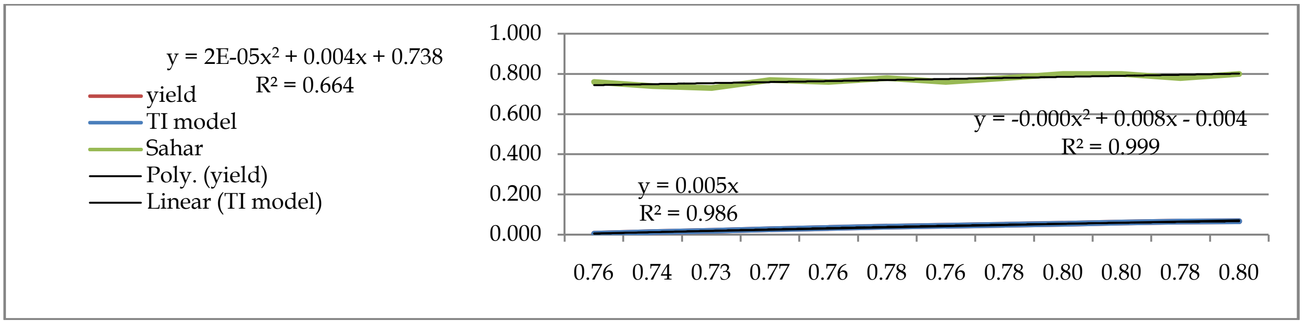


Fig 3 (b): The relation between MTI and crop yield

## Conclusions

The rationale of this study was a modified version from those tilth indices proposed by Singh et al (1992), and Bockari-Gevao et al (2006). The modifications include first the use of indicators scooping and screening processes. Secondly, to express the soil indicators in form of a polynomial functional relation on basis of principles of the rate of diminishing return and quality control limits. Thirdly, the assignment of relative weight to express the combined contributions of the indicators and tillage implements to attain the intended objectives of the tillage operation. Fourth, the consideration of the tillage depth as an integral part of the main soil evaluating indicators rather than adjustment weight. Fifth was the employment of AHP to define the combined weight. The application of the adjusted tilth index in the two case studies reveals the association between yield and the adjusted index. The development of the tilth index helps the decision-maker to select the most effective tillage operation to increase crop yield. The evaluation of the performance of tillage operation using the adjusted tilth index helps in the administration of tillage contracts in vast areas in a short period.

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