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Dimensional analysis of soil properties after treatment with the rotary paraplow, a new conservationist tillage tool

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Abstract

This study examined a new conservation tillage tool, the "rotary paraplow". Emphasis was placed on evaluating the tool's conservation potential using dimensionless graph analysis. The dynamic conditions of the soil were investigated in terms of physical soil properties. Having determined the variables to be measured, dimensional analysis was used to plan the experiments. Two variations were considered for each dependent variable (linear speed, working depth, and rotation velocity), totaling eight treatments, allotting in each an experimental strip with five data collection points. This arrangement totaled 16 experimental strips, with 80 data collection points for all variables. The rotary paraplow generates a trapezoidal furrow for planting with a very wide bottom and narrower at the top. The volumetric subsoiling action generates cracks on the sides of the band. Because of their specific geometry the blades of rotary paraplow generate a soil failure according to its natural crack angle, optimizing the energy use, while preserving the natural soil properties. Results showed the conservation character of the rotary paraplow, capable of breaking up clods for planting without changing the original physical soil properties.

Additional key words: dimensionless chart; soil dynamics; strip till.

Resumen

Análisis dimensional de las propiedades del suelo después del tratamiento con el Paraplow rotativo, una nueva herramienta de labranza conservacionista

En este estudio se examinó una nueva herramienta de labranza en un sistema conservacionista, el "paraplow rotativo". Se hizo hincapié en la evaluación del potencial conservacionista utilizando un análisis de gráficos adimensional. Se investigaron las condiciones dinámicas del suelo en términos de propiedades físicas del suelo. Habiendo determinado las variables que deben medirse, se utilizó un análisis dimensional para planear los experimentos. Se consideraron dos variaciones para cada variable dependiente (velocidad lineal, profundidad de trabajo y velocidad de rotación), con un total de 8 tratamientos, teniendo cada tratamiento asignada una parcela experimental con 5 puntos de recogida de datos. Se utilizaron 16 parcelas experimentales, con 80 puntos de recogida de datos para todas las variables. El paraplow rotativo genera un surco trapezoidal, además de las grietas en los laterales del surco formado por la acción de una labranza profunda. Debido a su particular geometría, las cuchillas del paraplow rotativo rompen el suelo en su ángulo natural de ruptura. Esta grieta se produce de forma natural en áreas del suelo de menor resistencia, por lo que la ruptura del suelo se realiza de manera más eficiente, y debido a que se requiere menos energía para generar estas grietas, la descompactación del suelo con paraplow no modifica sus propiedades físicas. Los resultados demuestran que el paraplow rotativo es una herramienta de labranza conservacionista.

Palabras clave adicionales: cultivo en faja; dinámica del suelo; gráfico adimensional.

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Abbreviations used: C (cohesion); L (lenght); M (mass); OCI (original cone index); Rot (rotating speed); T (time); Ts (theorical forward speed); U (water content); Wd (working depth); WMD (weighted mean diameter); γ (bulk soil density).

Introduction

Great attention is currently given to soil preparation tools adequate to conservation of initial soil conditions, to prevention of erosion and to preservation of soil for future generations. Many studies have proposed new conservation tillage tools and much effort has been applied to assess their actual advantages and optimal operating variables experimentally (Albiero, 2010).

The impact of agricultural equipment (machinery and implements) on the soil entails changes in its natural properties, with either beneficial or adverse physical, mechanical, chemical or biological effects (Volpato *et al.,* 2001).

Conservation soil tillage reduces the degree and intensity of soil preparation and retains residues and wastes, forming a surface layer of plant matter, which can lead to a surface accumulation of organic materials in a 5 to 10-cm layer, with major benefits for the soil as to improving its structural stability and physical properties (Carter, 2004). Such techniques can also increase the association of minerals and organic particles, resulting in organic-mineral microstructures (Carter, 2004), and in increased soil biological activity, allowing underground macro-fauna to help complementing soil tillage (Carter, 2004).

According to Albiero and Maciel (2011), the rotary paraplow is intended to be a new strip-tillage tool to be adopted in seeding machines consistent with the conservationist strip-tillage practice of preserving residues on the soil surface, while increasing subsurface disturbance, cutting weeds, enhancing strip porosity and distributing fertilizers.

A type of rotary paraplow was developed by Chang (2004), being a combination of a vertical rotary hoe and a paraplow. Types of paraplows were developed that did not require the application of an external vertical force, which proved to save energy, reduce compaction, and generally improve tillage.

Within this context, this work was aimed at evaluating variations in soil physical properties after treatment with the rotary paraplow, a tillage tool that offered good subsurface preparation in the furrow, while leaving the surface largely undisturbed (Albiero, 2010). This evaluation would help assess the value of the same device as a tool for conservation soil preparation, and help specify the best operation configuration in terms of soil conservation.

According to Mialhe (1996), the intrinsic goal of tillage machinery evaluation is to measure changes occurring in the soil because of the force applied when using tillage machinery or implements. Changes are characterized by the guided application of such forces under different soil and climatic conditions to obtain qualitative, quantitative and operational performance measurements.

Dimensional analysis identifies qualitatively the variables that influence soil preparation, as well as determines in quantitative terms the occurrence of the interrelationship between the variables established by this phenomenon (Maciel, 1993). As Langhaar (1951) stated, dimensional analysis captures differences between treatments with great accuracy and little effort.

Variables to evaluate the rotary paraplow were selected and then used them to prepare dimensionless charts, before and after operation, whereby it was possible to evaluate the tool in terms of conservation-related aspects of soil property variables.

Material and methods

The study was conducted at the experimental field in the Faculty of Agricultural Engineering/UNICAMP, Campinas-SP, Brazil (22° 48’ 57” S, 47° 03’ 33” W, 640 m asl).

The experiment was carried out in a clayey-textured Orthox Oxisol soil (Bras. “Dystroferric Red Latosol”; Freire, 2006) typical of the Campinas (SP) region its particle size distribution: 59% clay, 15% silt, 16% sand and 3% organic matter. Field was last planted 7 years prior to the experiment, with maize (*Zea mays*). The area was highly compacted with cone index values greater than 4,000 kPa, in surface compaction at a depth range between 0 and 100 mm, on the upper portion of a 3% sloping, and infested with the Guinea grass (*Panicum maximum* Jacq.) and signal grass (*Brachiaria decumbens* Stapf.) weeds.

The rotary paraplow used in this experiment (Fig. 1), was first described by Albiero and Maciel (2011). It was operated by a power tiller (walking tractor, powered by an one-cylinder diesel engine with rated power of 8.9 kW at 3,000 min^{-1}, two power take-off rotation speeds, 62.8 rad s^{-1} (600 min^{-1}) and 94.2 rad s^{-1} (900 min^{-1}), coupled to a tool holder on a chassis, and a 1.75:1 bevel reduction gear assembly.

In this experiment, gears 1 and 2 were used, to develop speeds of 0.36 and 0.7 m s^{-1} on a concrete track. Rotation speeds 1 (62.8 rad s^{-1}) and 2 (94.2 rad s^{-1}) were used, which after reduction by the rotary paraplow

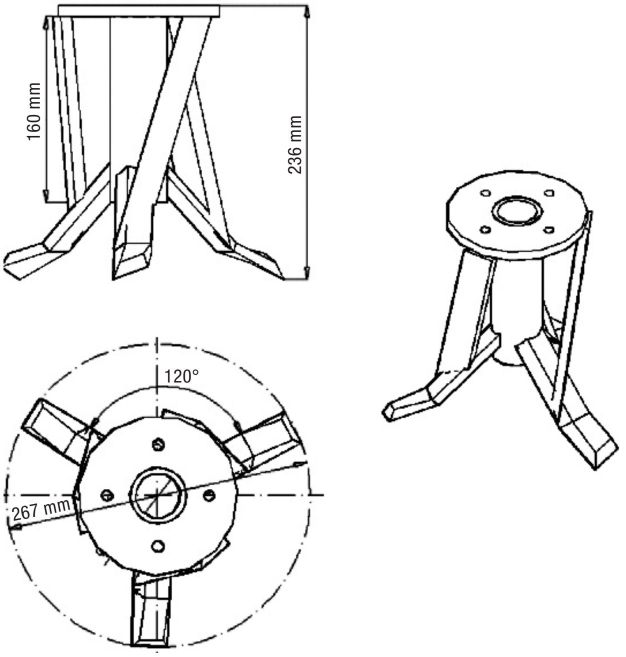

Figure 1. Rotary paraplow used in experiments.

transmission gave the following tool rotations: 1 (35.6 rad s^{-1}) and 2 (53.8 rad s^{-1}).

Dimensional analysis methodology and experimental design

The calculation methodology used in dimensional analysis was predicted by Murphy (1980) and Szucs (1980), and applied by Maciel (1993) to soil tillage machinery.

Due to the great variety of variables referring to various phenomena, quantifications and standards, it was adapted the variables to the same system of units, for the sake of simplifying the treatments and calculations, and in this case the system of units best suited to the study was the CGS system [centimeter (cm), gram (g), second (s)]. Thus, the variables pertinent to the experiment were converted into generic variables broken down into their basic characteristic dimensions (Table 1).

The basic dimensions considered were mass (M), given in g, length (L) in cm and time(T), in s. All the dimensions of the variables were converted into these three basic forms, and the dimensions that had components of force were converted into $(M).(L)^{-1}.(T)^{-2}$ due to Newton's second law.

The dependent variables in this work —theoretical forward speed, Ts (36 and 70 cm s^{-1}), working depth setting, Ws (15 and 20 cm), and tool rotation speed, Rot (35.6 and 53.8 rad s^{-1})— and the operating specifications of the Bertolini Model 318 Power tiller, provided two variations of such variables, totaling 8 operating combinations (or treatments), as shown in Table 2. Each treatment was applied twice, making 16 experiments. Each experiment had 5 data collection points, totaling 80 sampling points for all the variables considered as independent for dimensional analysis. The treatments were denominated Exyz, where x was the theoretical speed, y the tool rotating speed, and z the depth setting (Table 2).

In this context, and based on studies performed in the light of theories and bibliographic references (Langhaar, 1951; Gill and Vanden Berg, 1968; Koolen and Kuipers, 1983; Updahyaya *et al.,* 1994) in relation to evaluation of conservation tillage machinery, the following variables were chosen (Table 1): cohesion (C), with a view to learning about soil conditions in terms of this dynamic property; this variable was obtained with a bevameter projected by Maciel (1993) and the methodology follows recommendations by Updahyaya *et al.* (1994); the original cone index (OCI) of the test area before the operation in order to infer resistance to root penetration and degree of compaction was obtained with a digital penetrometer model DLG PNT 2000 and the methodology followed recommendations by Silva (2002); soil bulk density (γ), obtained in accor-ance with the volumetric ring method (Kiehl,

Table 1. Dimensional conversion of variables evaluated

Name	Abbreviation[1]	Resulting dimension	Dimension CGS	Basic dimension
Soil cohesion	C	kPa	kgf cm^{-2}	$[M].[L]^{-1}.[T]^{-2}$
Original cone index	OCI	kPa	kgf cm^{-2}	$[M].[L]^{-1}.[T]^{-2}$
Weighted mean diameter	WMD	mm	cm	[L]
Apparent soil density	γ	g cm^{-3}	g cm^{-3}	$[M].[L]^{-3}$
Water dimensional	Du	g	g	[M]

[1] C: cohesion. OCI: original cone index. WMD: weighted mean diameter. γ: bulk soil density. Du: soil water dimension.

Table 2. Combinations of dependent variables in the work

Treatment	Ts[a]	Rot[b]	Wd[c]
E111	1	1	1
E112	1	1	2
E121	1	2	1
E122	1	2	2
E211	2	1	1
E212	2	1	2
E221	2	2	1
E222	2	2	2

[a] Theorical speed (Ts) index: Ts1 = 36 cm s^{-1}; Ts2 = 70 cm s^{-1}. [b] Tool rotation speed (Rot) index: Rot1 = 35.6 rad s^{-1}; Rot2 = 53.8 rad s^{-1}. [c] Work depth (Wd) index: Wd1 = 15 cm; Wd2 = 0 cm.

1979); water content (U) obtained following Hillel (1980); and the weighted mean diameter (WMD), to assess the stability of wet aggregates, following Kiehl's (1979) methodology. All these variables, which were considered independent for the purposes of dimensional analysis, varied freely and their values were collected from experiments.

The test area was divided into 16 experimental strips, each with a useful evaluation length of 10 m, plus 2 m of buffer space, and 2 m for reaching steady operating conditions. Randomly spaced data collection points were marked by 5 stakes on each experimental strip. The totally randomized experimental design is shown in Table 3. The experimental outline for this research sought to evaluate the rotary paraplow in all possible operational combinations, so as to achieve a complete characterization of the soil decompacting it performs. Therefore, a totally randomized experimental project [defined by Cochran and Cox (1957) as the simplest type of experimental arrangement in which the treatments are allocated to their units of variation in a completely random manner] was followed.

Table 3. Totally randomized experimental design

Line	Ts[a]	Rot[b]	Wd[c]
1	1	2	2
2	2	2	2
3	1	1	2
4	2	2	1
5	1	1	1
6	2	1	1
7	2	1	2
8	1	2	1
9	1	2	1
10	2	2	1
11	1	2	2
12	2	1	1
13	2	1	2
14	1	1	1
15	1	1	2
16	2	2	2

[a,b,c] See Table 2.

A dimensional matrix was assembled with these variables, representing a vector subspace of the experiment, thus defining a system of homogeneous linear equations, the solution of which defined the experiment solution matrix from which the P terms were obtained, as mentioned by Langhaar (1951). Having defined the P terms, it became necessary to determine the correlation between them in order to establish which dimensionless charts correlated best in terms of behavior, to facilitate data interpretation.

When choosing the best correlated P-terms for building dimensionless graphs of the treatments sets, the greatest correlation coefficients of each treatment were considered for each pair of P-terms after operating the rotary paraplow, and the correlation coefficient considered was the product of Pearson R^2 (this addressed the variances of the correlated values).

Specified form of the selected P-terms

$$\Pi_3 = \frac{OCI}{C} \qquad [1]$$

The relationship between the original cone index of the test area (OCI) and the soil cohesion (C), means physically that behaved in a manner inversely proportional to the original cone index, thus defining shear stress in the failure plane that remained after the operation, indicating soil decomposition. The OCI could be considered a property of undisturbed soil, that is, that had no relation with the action of rotary paraplow; therefore, this P-term was dependent only on the variation of cohesion, since the cone index could be considered a constant.

$$\Pi_{13} = \frac{Du}{\gamma\,(WMD)^3} \qquad [2]$$

The relationship between soil water dimension (Du), density (γ) and weighted mean diameter (WMD) permitted an assessment of the effects of water content on bulk density and soil stability, resulting in a dimensionless number that was a characteristic of the soil in relation to its physical properties and mechanical behavior after tillage. The water quantity in the soil was not related to the action of rotary paraplow; therefore, as the original cone index, we could consider it as a constant (both before and after the operation), so this P term had a dependent variation only in relation to soil bulk density and average diameter of moist aggregates.

Results and discussion

The dimensionless charts Π_3 x Π_{13} represent intrinsic soil behavior as a function of dynamic characteristics (compactness and cohesion). Figure 2a-h show this relationship, before and after the operation of the rotary paraplow, for each treatment.

Soil dynamic properties are manifested in the soil movement and are essentially: soil stress, soil deformation, stress/deformation relationship (soil strength and stress distribution), deformation distribution, soil yield strength, and rigid body movement (Gill and Vanden Berg, 1968). The relationship defined by the P term (Eq. [1]) is a function of the OCI (before the operation) and the inverse of the soil shear stress variation, defined by Gill and Vanden Berg (1968) as soil cohesion, since a soil failure under shear occurs on a shear plane where the shear stress reaches a constant value (C); thus P term describes the variation of this dynamic property which is directly related to soil compaction.

In general, the ideal condition of a soil after being worked with a tool, is not undergoing any physical change that might modify its dynamic characteristics, as reported by Koolen and Kuipers (1983) and Gill and Vanden Berg (1968).

It should be noted that both P terms have in their denominators components of variation because Π_{13} has a variable as numerator that undergoes no change after operation (*Du*-water quantity) and Π_3 too, because the numerator is the OCI of area, which is also unchanged by the operation.

The charts should be interpreted by comparing the straight line obtained from the “after” data with the straight line obtained from the “before” data. Ideally, the “after the operation” line should have the same range in terms of soil physical properties (Π_{13}), while the ratio of OCI to cohesion should vary. In these terms, the best performances can be seen in 2b (treatment E222), and Figure 2c (treatment E121).

Because of the same variation in physical properties (Π_{13}), these treatments display approximately the same range of variation in compactness, as measured by the decrease in cohesion coefficient and the increase in the P term, Π_3, indicating the operation’s predictable mechanical behavior of decompacting the soil in terms of its initial physical characteristics.

The angular coefficient of the straight lines represents the division of cohesion by the bulk density and the average diameter of moist aggregates, since the OCI and the amount of soil water are considered as constants therefore, comparing the treatment straight lines before and after, the cone index and the amount of water can be neglected. Thus, with the higher angular coefficient concluded that there was a greater decompression with less change in soil physical properties, hence the straight line obtained after the operation with a small range of angular coefficient is preferable.

In Figure 2a (E111) we see that there is a big change in the physical properties of soil after using the rotary paraplow. The angular coefficient is different between the lines before and after treatment. This indicates that this provision has its effects on the relationships with soil physical properties.

Figure 2b (E222) presents a different aspect compared to Figure 2a (E111), because we can observe that there was a big change in soil physical properties after a minor operation of rotary paraplow, due to the range amplitude of P-term Π_{13}. This configuration has a faster action in deeper soil, thus lesser disruption of the soil, while the decomposition is significant (a greater angular coefficient after the operation).

In Figure 2c (E121), this configuration has a combined action of slow progress with high rotation in a shallow soil, thus, the disruption of the soil is less intense that observed in treatment E111 (Fig. 2a), but more intense that of observed in treatment E222 (Fig. 2b), indicating that it is an intermediary treatment between the two (E111 and E222).

Figure 2d and 2e show that these combinations does not have a proper conservationist action. These configurations presented a very slow action in a body with deeper soil, decreasing dramatically the WMD, that has a great influence in P-term (Π_{13}), thus indicating that the soil disruption is magnified.

Figure 2f shows that this treatment E211 induced a significant change in the soil physical properties because of the same decomposition, thus it did not have an adequate conservationist performance.

Treatment E212 (Fig. 2g) had very similar effects to those of E111 (Fig. 2a), but having a greater variation of the angular coefficient (34) than treatment E111 (22). This can be explained by the faster action of the tool (higher speed) in a body of higher ground site (greater depth) at lower speed (less vibration).

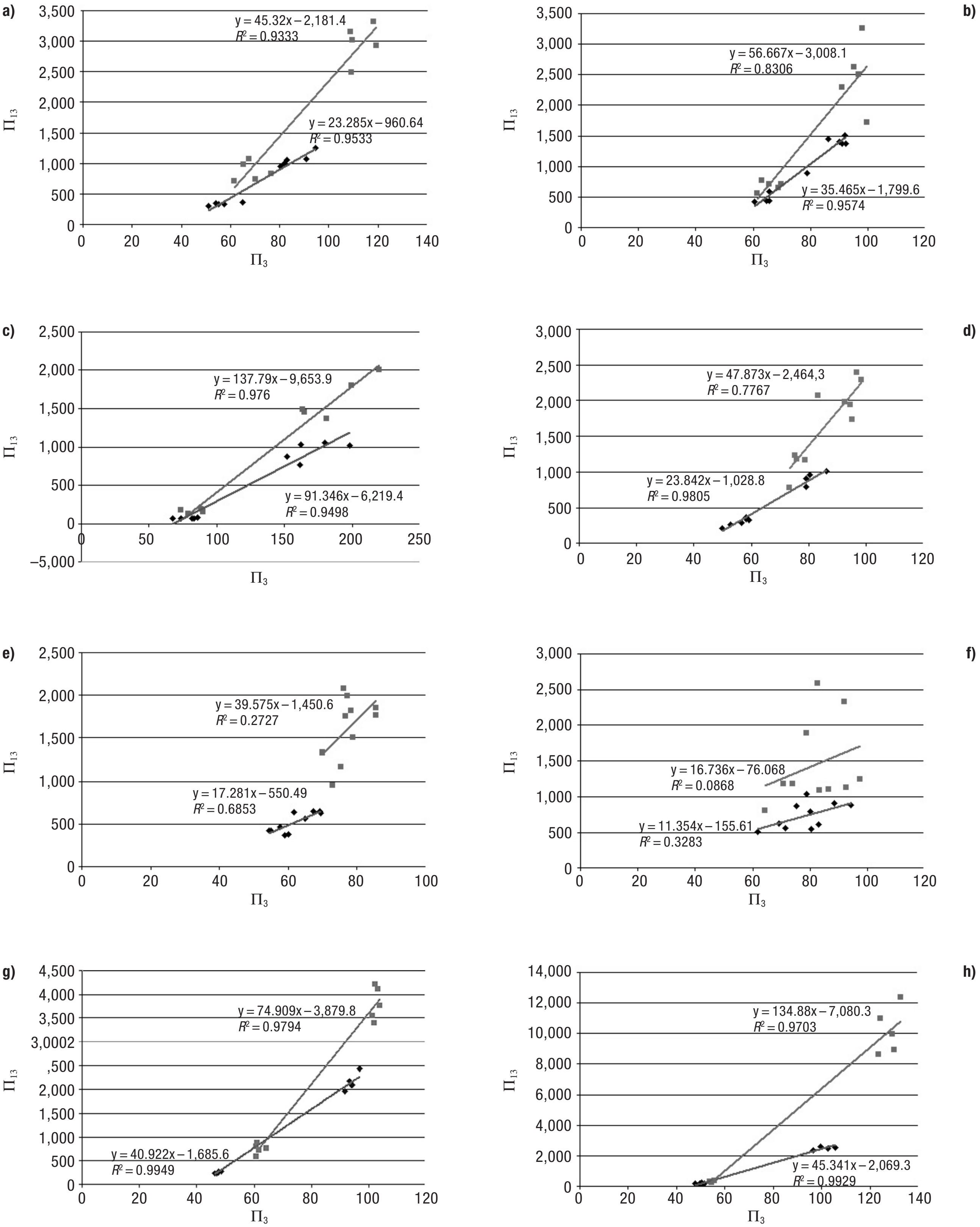

Figure 2. Dimensionaless charts $\Pi_3 \times \Pi_{13}$, showing treatments (before and after): (a) E111A × E111D, (b) E222A × E222D, (c) E121A × E121D, (d) E122A × E122D, (e) E112A × E1112D, (f) E211A × E211D, (g) E212A × E212D, (h) E221A × E221D.

Among all treatments, E221 (Fig. 2h) exhibited the biggest difference between angular coefficients, indicating that this treatment produced more efficient soil decomposition. However, the range of variation of physical properties (Π_{13}) is very large, indicating that there was an excessive change in soil structure, especially in relation to WMD.

The results corroborated the conclusions reached by Albiero (2010) regarding the conservation characteristics of the rotary paraplow. The clear experimental demonstration of changes in soil behavior as a function of the operating settings chosen (theoretical speed, tool rotating speed and depth setting) was reflected in the sets of charts depicting the overall analysis of soil behavior after tillage. It was possible to determine the best combination of these operating variables for the soil under study in order to optimize conservation requirements. All settings and findings relate exclusively to the texture of the soil being tested, in this case a Red Orthox Oxisol, Freire (2006), since the trends of all experimental variables are connected to the physical, chemical and dynamic characteristics of the specific texture and its extremely high clay content.

Albiero and Maciel (2011) concluded that the rotary paraplow produced a well-prepared range of soil of a trapezoidal shaped furrow of a small surface width and a larger subsurface area, which means less exposure of surface soil to erosion while having a larger area of well-prepared soil for plant roots in the subsurface. The cracks generated on the sides of the groove had a dual function, first they allow water infiltration, reducing the risk of erosion and, secondly, they reduce the compaction of the area by facilitating the action of roots penetrating the soil, to obtain nutrients.

Soil mechanical behavior is governed by several physical factors: soil type, water content, organic matter and bulk density, and these coupled behaviors depend on the density/water content ratio. Bulk density is influenced by cohesion and adhesion, which in turn depend on the soil internal friction and of soil bulk density itself Mouazen (2002). Another variable directly connected with soil mechanical behavior, according to Javarez (1996) is the weighted average diameter of moist aggregates, which is influenced by differing organic matter content, biological activity, temperature oscillations and water content. Soil aggregation state, according to Maia (1999), is especially important in the study of physical properties and can limit plant growth, even in ideally fertile soils. P term Π_{13} (Eq [2]), concentrates these variables, offering an actual measure of modifications to the soil mechanical behavior as a function of its physical variables.

The rotary paraplow has these effects mainly due to its action of volumetric subsoiling. The blades of the rotary paraplow, due to their specific geometry, generate a soil breaking phenomenon in their natural angle of fracture. This fracture occurred naturally in soil areas of lower resistance. So soil disruption was performed more efficiently, because it required less energy to generate the fractures. These regions of soil natural fracture, according to Albiero (2010), depend on the conformation of the aggregates, the amount of organic matter, the internal variations of texture, the internal variations of aggregates size, and so on.

Similarly, when the rotary paraplow was applied to the soil, its action equaled that of the conventional paraplow, in which the disruption is generated in naturally settled regions (Tupper *et al.,* 1998), it is not “unnatural” disruption, in other words, the breaking is by mechanical action.

Therefore there is not an excessive reduction of aggregate WMD, so it is possible to reduce soil compaction without reducing WMD. It is important to consider that WMD is raised to three in the numerator of Π_{13}. Thus any variation in WMD generates big changes in this P term. Considering oxisols the rotary paraplow enabled to reduce soil apparent depth and compaction, keeping WMD rating within conservationist patterns (little change in WMD implies less disruption of soil; Javarez, 1996).

Hillel (1980) stated that soil tillage depth greatly influences soil structure, which depends essentially on water quantity, soil type and tillage system. This can be seen in the differences between the dimensionless charts where the only operational variable that changed was the working depth level, as in treatments E111 and E112 (Fig. 2a and 2e), E222 and E221 (Fig. 2b and 2h), E122 and E121 (Fig. 2c and 2d) and E211 and E212 (Fig. 2f and 2g). Treatments at smaller depths can be seen clearly to produce more extensive changes in physical properties (Π_{13}) and a high degree of decomposition, which is not ideally conservationist.

These shallow operational combinations caused a greater disintegrating volumetric action in the soil region, where the rotary paraplow was applied; this occurs due to the less soil volume suffering the vector action of the shearing force generated by the rotary paraplow (Albiero, 2010); this volumetric action refers to the oscillatory cut action in the soil caused by tool rotation (Mouazen, 2002).

If the soil site undergoing these effects is very small, the vibration in this soil area will be stronger, increasing the disintegration effect. When this volumetric action happens with low speed and less depth, but high rotation, for example, in treatment E121 (Fig. 2c), the soil structure receiving these vibrations (high rotation + low speed) undergoes big impact that the maximum effect takes place due to the longer time of exposure (low speed + time spent) and less soil resistance (smaller depth + easier soil mobilization). Now, evaluating the opposite situation, of greater speed and a smaller depth, but with little rotation, for example, the E212 treatment (Fig. 2g), it is possible to notice similar effects, since the soil receives the same vibrations, because it has the same rotation, but in less time (greater speed); therefore, this situation can be considered with the same frequency, generating the same effects in higher depths.

The dynamic effects of tools moving at high speeds in the soil can be defined by two mechanisms that cause the main effects on forces required to move the soil: continuous acceleration of soil masses and changes in soil strength at high shear rates (Colouma *et al.,* 2005).

According to Wells and Treesuwan (1978), a successful methodology to predict soil deformation characteristics in terms of humidity and bulk density should be based on the soil cone index, because soil resistance to tool penetration depends on soil mechanic and physical properties, which affect compactness, bulk density and humidity. The dimensionless chart $\Pi_3 \times \Pi_{13}$ allows complete analysis of soil tillage tools characteristic effects in terms of soil conditions before and after their operation.

Conclusions

The dimensionless chart $\Pi_3 \times \Pi_{13}$ provided information to analyze the dynamic behavior of the tested soil in terms of its physical properties by quantifying the changes in these properties and relating them qualitatively to the various linear data patterns.

Dimensional analysis stated that, in conservation terms, the best results were provided by treatments E121: forward speed 1 (36 cm s^{-1}), tool rotating speed 2 (53.8 rad s^{-1}), working depth setting (15 cm); and E222: forward speed 2 (70 cm s^{-1}), tool rotating speed 2 (53.8 rad s^{-1}), working depth setting (20 cm). In these configurations, the changes in physical properties as a function of cohesion occurred according to conservationist variables specified in the literature, characterizing the rotary paraplow as a soil conservation tillage tool.

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