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Effects in mechanical properties and structure of the soil after tillage with rotary paraplow

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At present great emphasis is being put on soil preparation tools which conserve the initial conditions of soil structure, preventing erosion and preserving soil for future generations. A new conservational tillage tool – the rotary paraplow, it were carried out studies addressing the changes in structure and in mechanical properties of soil after tool operation. Dimensional analysis has been used as methodology since it calls for a judicious choice of dependent and independent variables of the studied phenomenon, followed by a method of algebraic calculation used to determine the components and essential combinations among the parameters, reaching the determination of the minimum number of repetitions. The results have shown that Rotary Paraplow generated a well-prepared subsurface cultivation furrow. The evaluation of the operational tests for the dimensionless graphs has determined that the best setting is that in which the tool works with forward speed of 0.36 m.s^{-1}, rotation of 514 min^{-1} and depth of 150 mm. The action of this new tool can be considered as conservation tillage because all parameters are within limits imposed by the literature on the subject in order to consider soil tillage as conservational.

Key words: Soil dynamics, dimensional analysis, paraplow.

INTRODUCTION

Many studies have been carried out seeking to propose new tools for soil preparation, and great efforts have been made in order to experimentally prove their real advantages and operating configurations. The preparation of agricultural soil is a mechanical process that may lead to the cutting, overturning and inversion of the layer of soil, through the actions of the active organs of the implements, seeking to provide minimum conditions for developing crops (ASAE, 1997).

Conservational soil tillage reduces the intensity level of soil preparation, retaining wastes and forming a surface vegetation cover, which may lead to an accumulation of organic matter on the surface, producing a layer from 10 to 15 cm, from which the greatest benefits are an improvement in the stability of soil's structure, while the improved physical qualities of the soil (Carter, 2004) may also increase the association of minerals and organic particles, resulting in the formation of organo-mineral

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micro-structures, and in certain situations an increase in the biological activity of soil (Temesgen et al., 2012). Furthermore, the macro-fauna complements some levels of soil preparation under the ground, and although many studies into the effects of tillage systems on the soil organisms make comparisons between the two extremes (without tillage and conventional cultivation), it is known that intermediate forms of soil tillage produce intermediate effects (Kladivko, 2001).

Chang (2010) developed a rotary type, which is a fusion of a vertical milling cutter and a conventional Paraplow. The vertical cutter allows having a better mobility in the subsurface and thus greater penetration of water, while the Paraplow only affects the soil in the horizontal position without inverting it, keeping waste on the surface of cultivation soil and forming a cover.

The rotary paraplow is a new tool for soil preparation that performs a good sub-surface preparation of the planting strip, while hardly affecting the surface (Albiero et al., 2011a). According to the SSSA (2005), the paraplow is a type of non-inversive implement for subsoiling (conservational) designed to increase the force of structural breaking of the soil sideways using wide subsoiling surfaces crosswise to the movement and angled laterally so as to raise the soil. The soil cultivated with the paraplow is fractured into zones of weakness, in other words, the soil is moved around and not inverted (Erbach et al., 1992).

The rotary paraplow consists of 3 paraplow tines separated by 120°, and they have the same characteristics as paraplow. These blades are welded onto a circular upper support, drilled specifically for cutter supports, seeking to increase the rigidity of the tool's structure, while the lower side blades have been extended to a central supporting tube with a diameter between 20 and 60 mm. This tube also has the function of carrying fertilizer to the planting strip being tilled.

In the strips cultivation the habitat of the soil's flora and fauna is only partially destroyed (Geissen et al., 2003; Trevini et al., 2013). Cultivation in strips influences the total porosity of the soil, the apparent density, and particularly the rate of infiltration in relation to direct planting; this is noticeably higher (Geissen et al., 2003).

Maciel and Albiero, (2007) tested several models of rotary paraplows, a vertical rotary hoe and a conventional paraplow, in a soil bin and in the field. In the soil bins tests it was found that the rotary paraplow has a considerable vertical force, allowing automatic penetration due to their geometry, which acts on soil like a thread, thus doing away with the need for external force for their penetration.

In this context, the methodology of dimensional analysis is ideal since Maciel (1993), in his doctorate thesis, proved that dimensional analysis:

"Establishes qualitatively the identification of the parameters that influence the phenomenon of soil preparation, while also determining quantitatively the occurrence of inter-relationship of the parameters set for this phenomenon."

Albiero et al. (2011b) asserts that dimensional analysis captures the differences between treatment with great accuracy and less work. The dimensionless graphs make the differences visible and fit for calculation through the differentiation of the angular coefficients of the straight lines that represent the specific behaviours, while the method in itself optimizes the necessary quantity of data for obtaining perceptible responses, generating graphs with the minimum number of points and no requirements of normality. The collected data are treated through Pi-terms that are invariable non-dimensional factors, that is to say, they show constant behaviour as a function of the specific characteristics of the phenomenon, which represents inter-related behaviours among parameters that are linearly independent, allowing the proportional quantification of the variations as a function of their properties, which generates different straight lines (different angular coefficients), considerably easing the interpretation of the results.

The aim of this paper is to evaluate and describe the new conservational tillage tool – the rotary paraplow – in order to discover by experiment its best operational configuration and to carry out studies addressing the changes in structure and in mechanical properties of soil after the operation of the tool.

MATERIALS AND METHODS

Rotary paraplow

The rotary paraplow used in this experiment, Figure 1, consists of three paraplow tines separated by 120°. The technical recommendations of the soil dynamics science described in the literature were followed to improve the conservational performance: The optimized rotary paraplow has a set of three blades, each one with two mounted blades, with the lower blade welded at an oblique angle in relation to the upper one, and attached to the support. The lower blade has two inclination angles, one on the vertical plane (leading angle) and the other one on the horizontal plane (cutting angle).

The upper blade, attached to the support, has a 30° cutting angle, following Tupper et al. (1998) suggestion, while the lower blade is welded onto the upper and to the central tube, and has three different angles: one on the horizontal plane and the other one on the vertical (angle of advance and leading angle, respectively), both at 45° (Gill and Vanden Berg, 1968; Upadhyaya et al., 2009); the third angle derives from the blade's inclination in relation to the oblique plane where it is placed (due to the angles of the horizontal and vertical planes) and measures 15° (Koolen and Kuipers, 1983). This configuration has the purpose of shearing the soil through a stress composition that raises it, causing the rupture of the body of soil at the natural rupture angle, thus reducing resistance to stress. These blades are welded onto an upper circular support with an appropriate hole, like those of mechanical scythes. To increase the tool's rigidity, the lower side blades were extended to a central supporting tube with a 25 mm diameter (Figures 1 and 2).

The rotary paraplow was pulled by a Bertolini 318 mini-tractor, loaned by the company Argos Tech, which runs on a single-cylinder

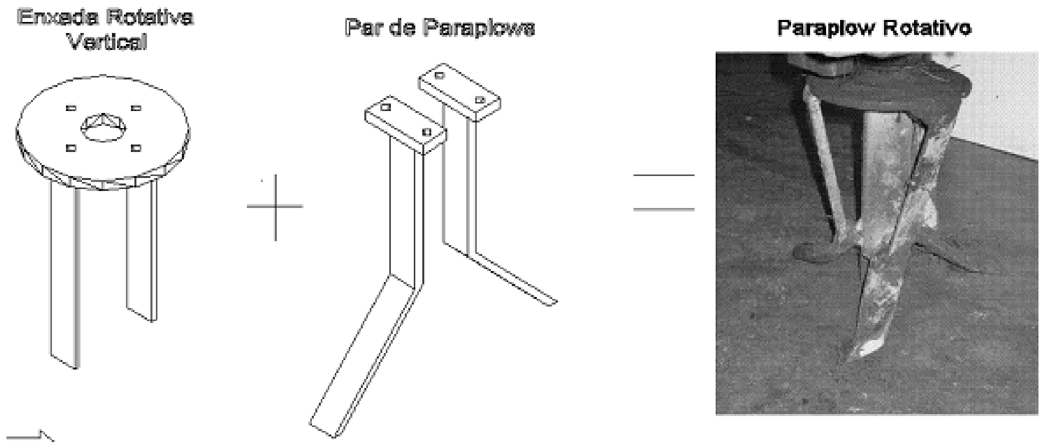


Figure 1. Conceptual idea of rotary paraplow.

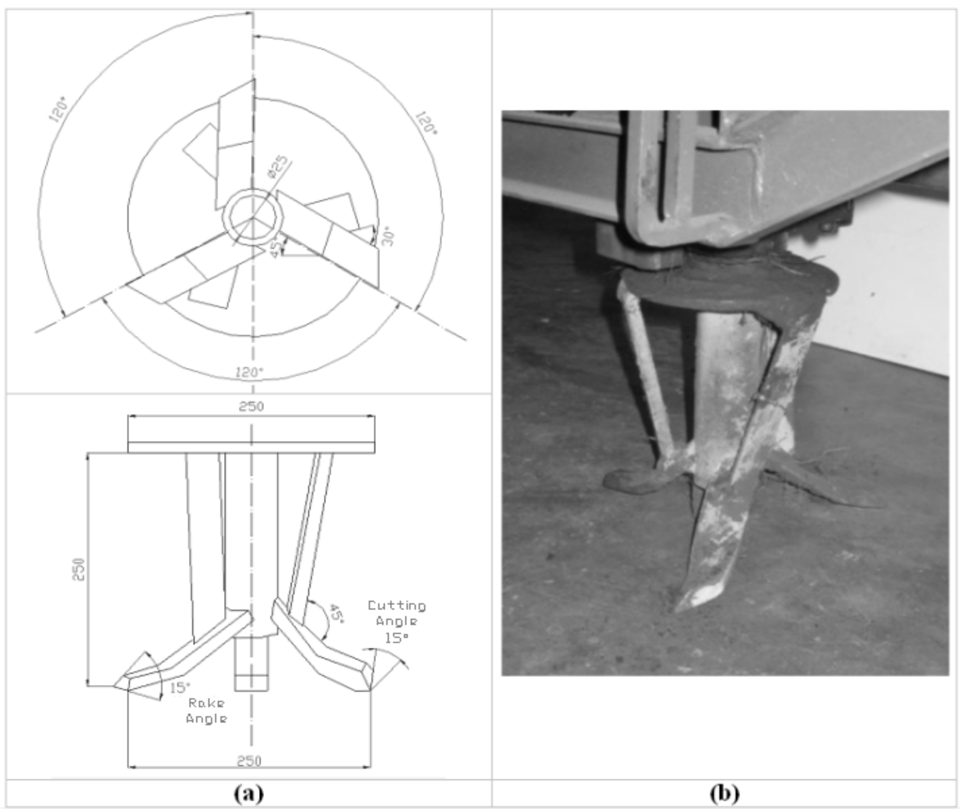


Figure 2. (a) Technical drawing of the rotary paraplow; (b) Rotatory paraplow used in the experiment (Albiero et al., 2011a).

diesel engine that develops 12 HP (8.95 kW) rated power at 3000 min^{-1}, with two speeds for the PTO (power take off) (V1 = 600 min^{-1} V2 = 900 min^{-1}), coupled to a tool-carrying chassis fitted with a conical reduction gear, with reduction of 1.75: 1.

In this experiment, it was used as the 1st and 2nd gears, which develop a speed of 0.36 and 0.7 m.s^{-1} on a concrete track. Rotations 1 (600 min^{-1}) and 2 (900 min^{-1}) were used, considering that the reduction ratio of the transmission of the rotary paraplow has the following rotations on the tool: 1 (342 min^{-1}) and 2 (514 min^{-1}).

Characteristics of the test area

This research has been developed in the Experimental Field of the Agricultural Engineering Faculty / University of Campinas, which has the following geographical coordinates: Latitude: 22°48'57" South, Longitude 47°03'33" West, and an average elevation of 640 m. The soil where the experiment was conducted is typical of the region of Campinas, São Paulo State, Brazil; in the Oxisol ortose case (Freire, 2006). Its granulometry is: 60% clay, 19% silt , 18%

Table 1. Combination of the dependent variable of the experiment.

Treatment	Vm	Rot	Pr
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

Obs: Vm1= 0.3; Vm2= 0.7; Rot1= 342 rpm; Rot2= 514 rpm; Pr1= 150 mm; Pr2= 200 mm.

sand and 3% organic matter. The last planting took place 7 years prior to the experiment, with corn (*Zea mays*). The area proved to be compacted, with a cone index above 1500 kPa, and is the upper part of a slope with a 3% gradient, infested with guinea grass (*Panicum maximum* Jacq.) and *Brachiaria decumbens* Stapf. (Kissmann, 2000).

In order to choose the most relevant parameters, determination of the experimental procedures, and to prioritize planning elements, it was used the dimensional analysis methodology, which starts with a judicious choice of dependent and independent dimensional variables of the studied phenomenon, followed by a method of algebraic calculation to determine the essential components and combinations among the parameters, finalizing with the determination of the minimum number of repetitions.

In this context, and based on studies carried out under the light of the existing theories and literature concerning a conservational appraisal of soil-tilling machines, the following variables were selected: Cohesion (c) and internal friction angle (ϕ) of the soil seeking to obtain knowledge of the dynamic properties of the soil and the alterations sustained; original cone index (CI0) and cone index after the operation in the crack areas (CIF) of the area prior to the operation for inference of resistance to root penetration and level of de-compacting; weighted mean diameter of wet aggregates (WMD) to evaluate the degree of stability of the aggregates faced with erosion; apparent density (γ) of the soil to evaluate the changes in soil compaction. Lower width (LW) of the planting strip (planting strip well prepared; width fissures of the region (WF) of the planting strip (planting strip turned); width of raising (WR) of the planting strip (planting strip turned); raised area (AR) (plaintiff strip turned); water content (U). All these parameters (considered as independent variables for dimensional analysis) varied freely and had their data gathered in experiments.

Experimental outline

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 de-compacting of the soil it performs. Therefore, a totally random experimental project was followed, 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. This is suited to small-scale experiments (with few dependent factors), where the increase of accuracy of experimental projects in randomized blocks does not yield great advantages due to the loss of degrees of freedom.

Considering the independent parameters of this experiment (theoretical forward speed (Vm) (0.36 and 0.7 m s^{-1}); regulation depth of the work (Pr) (150 and 200 mm) and rotation speed (Rot) (342 and 514 min^{-1}), along with the characteristics of the Bertolini 318 mini-tractor, we have two variations of these parameters, which amount to a total of 8 operational combinations. Each combination will hereinafter be referred to as treatment, and each treatment had two repetitions, making up a total of 16 experimental lines. Each experimental line had 5 data-collection points, making a total of 80 sampling points for all the parameters deemed independent for the dimensional analysis. From now on each combination will be referred to as a treatment (Exxx), being that each treatment had ten repetitions, totaling 80 sampling points of all the parameters (Table 1). From this point onwards, the terminology will be as follows: Theoretical working speed, V1 = 0.36 m s^{-1}, V2 = 0.7 m s^{-1}; Rotation speed of the rotary paraplow, R1 = 342 min^{-1}, R2 = 514 min^{-1}; Regulation of the work depth, Pr1 = 150 mm, Pr2 = 200 mm.

The denomination of the treatment will follow this rule: Exyz, where x represents the theoretical speed; y represents the rotation of the tool and z represents the regulation depth. Considering that the test area was divided into 16 experimental lines, and that each one had 10 m useful length of evaluation, plus 2 m of buffer space and 2 more meters to enter the regime, while each line had five data-collection points spread randomly and staked along the experimental line, we have a totally random experimental project.

According to Albiero, (2006), dimensional analysis has two technical requirements that must always be respected: all the variables must have dimensions; all the variables must be in the same system of measurements. The upshot of the first requirement is the need to make manipulations of parameters that are non-dimensional, so as to transform them into dimensional parameters; while the second leads to a homogenization of all the units into only one system of units.

Dimensional analysis

The calculation methodology used in dimensional analysis was predicted by Murphy (1980) and Taylor (1974), described by Langhaar (1951) and Szucs (1980), and applied by Maciel (1993) and Albiero, (2006) to soil tillage machinery.

In this paper, due to the great variety of parameters, referring to various phenomena, quantifications and standards, it was necessary to adapt these parameters 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 GCS system (gramme (g), centimetre (c) and second (s)). Thus, the parameters pertinent to the experiment were converted into generic variables broken down into their basic characteristic dimensions (Table 2).

The first step is to convert the parameters relevant to the experiment on generic variables decomposed only in its dimensions basic features. The second step is to mount the dimensional matrix

Table 2. Table of dimensional conversion of the evaluated parameters.

Name	Parameter symbol	Dimension obtained	CGS dimension	Basic dimension
Soil cohesion	c	kPa	kgf/cm^2	[M].[L]$^{-1}$.[T]$^{-2}$
Internal attrition angle	ϕ	rad	cm	[L]
Original cone index	CI0	kPa	kgf/cm^2	[M].[L]$^{-1}$.[T]$^{-2}$
Weighted mean diameter	WMD	mm	cm	[L]
Apparent density	γ	g/cm^3	g/cm^3	[M]. [L]$^{-3}$
Lower width of furrow	LW	cm	cm	[L]
Width of fissures	WF	cm	cm	[L]
Raised area	AR	cm^2	cm^2	[L]
Water dimensional	Du	g	g	[M]

composed of the exponents of the basic dimensions. The third step is to check that the matrix is a sub - dimensional vector space of the phenomenon. This means that this must be three dimensional subspace (M, G, T). For such verification is essential to draw the rank of the matrix. So we chose an appropriate subspace and proved that the phenomenon can be represented by a three-dimensional subspace. In this experiment the determinant of this subspace is equal to -2, so the rank of general subspace.

The fourth step is to assemble the system of homogeneous linear equations, through the lines of the dimensional matrix, which represent the dimensions algebraically independent vector subspace. These equations must be equated to zero, because according to Langhaar (1951), considering a homogeneous linear system, the solution of this system are the dimensionless Pi-terms. The fifth step is to assemble the matrix solution, whereas all the parameters are arranged and represented by three main parameters chosen to describe the phenomenon (γ, WMD, c) .

According to Maciel (1993), the number of Pi-terms is determined by the number of variables minus the dimension of the subspace of the phenomenon, thus bringing the Pi-terms responsible for explaining the phenomenon studied, which are assembled in a matrix solution matrix. The rows of the matrix solution are the exponents of the components of the Pi-terms, also called invariants. The sixth step is to determine the correlation between the Pi-terms to find which has the dimensionless graphs behavior better correlated. This determination is made by the correlation matrix. According to Snedecor and Cochran (1989), the correlation coefficient is closely connected with the bivariate normal distribution. The seventh and final step is considering the Pi-terms that have the highest correlation coefficients dimensionless build graphs for the desired parameters.

The basic dimensions considered were mass [M], given in grammes (g), length [L] given in centimeters (cm) and time [T], given in seconds. All the dimensions of the parameters will be converted into these 3 basic forms, and the dimensions that have components of force will be converted into [M]*[L]*[T]$^{-2}$ due to Newton's second law.

With these parameters the dimensional matrix was set up, which represented a vectorial sub-space of the experiment. Thus, we defined a system of linear and homogeneous equations, from which was defined the solution matrix for the experiment, hence the Pi-terms were obtained according to Upadhyaya et al. (2009). With Pi-terms defined, and with a view to easing interpretation of the data, it was necessary to determine the correlation among them so as to find which dimensionless graphs have the best-correlated behaviours. For choosing the best correlated Pi-terms for constructing dimensionless graphs of the sets of treatments, it was considered the greatest correlation coefficients of each treatment for each pair of Pi-terms after operation of the rotary paraplow, and the considered correlation coefficient was the product of Pearson R^2. It should be pointed out that the correlation coefficient of the product of Pearson is a coefficient that addresses the variances of the correlated values (Table 3).

In order to make an assessment of the structural changes and mechanical properties of soil, every variable considered in dimensional analysis were treated by classical descriptive statistics: mean value, variance, standard deviation, minimum value, maximum value and amplitude. As a normality test of the distributions of the measurements of the parameters in the treatments, the tests of Kurtosis and symmetry will be considered, taking as values for rejection of normality: Kurtosis (k >2 or k < 2); symmetry (g > 2 or g < 2) like affirm Snedecor and Cochran (1989) and Montgomery (2004).

RESULTS AND DISCUSSION

The results obtained support the conclusions concerning the conservational characteristics of the rotary paraplow (Table 4). Particularly from the groups of graphs presented, which determined the optimum conservational configurations as a function of parameters for evaluation of soil tilling machines. In Figures 4, 5, 6 and 7, we have a better overall analysis of the tool, through the clear demonstration found experimentally from the variation in behaviour of the soil as a function of the different operational configurations chosen (theoretical speed, rotation of the tool and regulation depth of the work), enabling a determination of the best combination of these operating parameters for the soil studied, so as to respect the requirements of conservation. To determine the best configurations, it should be noted that all the determinations and choices are restricted only to the texture of the studied soil, in the Oxisol ortose case (Freire, 2006), since all the experimental variables have their trends tied to the physical, chemical and dynamic characteristics of this specific texture due to the extremely high clay content in its constitution. All presented data can be considered to pertain to a normal distribution due to tests of kurtosis and symmetry; therefore, the standard deviation is a good measure of dispersion.

In general, the strip prepared by the rotary paraplow have the following main characteristics: furrow upper width (UW), between 12 and 13 cm with standard deviation (SD) of 0.57 cm; furrow lower width (LW), between 21 and 23 cm with SD 1,36 cm; width of lift ups (WR), between 30 and 28 cm with SD 2.8 cm; width of

Table 3. Specified form of the selected Pi-terms.

Pi-terms	Description
$\Pi_2 = \phi$ / WMD	Its physical meaning behaviour of the internal attrition angle of the soil, which indicates the growth of chiseling tension necessary to generate the fault by chiseling and consequent breakdown of the soil, due to the reduction of stability of the soil also related to the breakdown caused by erosive processes
Π_3 = CI0 / c	Its physical meaning the inversely proportional behaviour of the soil, which defines the chiseling tension on the plane of the fault that subsists after the operation, indicating the de-compacting of the soil as a function of the original cone of the soil.
Π_5 = LW / WMD	The relationship between the lower width of the prepared strip and the weighted mean diameter provides a geometric relationship of the strip, relating it to the level of stability of the soil related to aggregation of the soil.
Π_8 = WR / WMD	Provides a geometrical relationship of the strip, relating it to the level of de-compacting due to a change of density and mobilization of the soil considered as subsequent modification of the stability of the aggregates of the soil, de-structuring it.
Π_{10} = WF / WMD	The relationship between the width of the fissures of the prepared strip and the weighted mean diameter provides a geometric relationship of the strip, relating it to the level of de-compacting and extent of the dynamic effects on the soil considered as a subsequent change to the stability of the aggregates of the soil.
Π_{13} =Du / (γ*(WMD)^3)	The relationship between the quantity of water in the soil, its density and the weighted mean diameter permits considerations of the effects of the quantity of water in the soil in relation to its apparent density and the level of its stability, resulting in a dimensionless figure characteristic of the soil in relation to its physical properties.

Table 4. Average tables of all treatments of the characteristics of prepared furrow and soil properties before and after the operation of rotary paraplow.

Before operation									
Treatment	**Samples**	**Mean**	**Variance**	**Standard deviation**	**Minimum**	**Maximum**	**Amplitude**	**Symmetry**	**Kurtosis**
c (Pa)	80	25556	20604801	4189.42	19195	30947	11752	-0.397	-0.618
ϕ (rad)	80	0.41	0.014	0.10	0.29	0.546	0.25	0.003	-0.966
CI0 (kPa)	80	1715	11619	91	1587	1830	243	-0.38	-0.880
WDM (mm)	80	2.40	0.350	0.52	1.85	2.98	1.13	0.075	-1.423
γ (g/cm^3)	80	1.79	0.065	0.24	1.43	2.16	0.73	0.138	-0.386
After operation									
Treatment	**Samples**	**Mean**	**Variance**	**Standard deviation**	**Minimum**	**Maximum**	**Amplitude**	**Symmetry**	**Kurtosis**
c (Pa)	80	19220	14035279	3331.62	14771	23962	9191	-0.137	-0.800
ϕ (rad)	80	0.96	0.151	0.28	0.632	173.137	0.67	0.003	-1.137
CI0 (kPa)	80	201	2224	43	138	259	120	-0.038	-0.776
WDM (mm)	80	2.06	0.270	0.45	1.60	2.55	0.95	0.080	-1.49
γ (g/cm^3)	80	1.21	0.0287	0.15	0.99	1.46	0.47	0.311	-0.103
HR (cm)	80	4.46	1.78	1.31	2.50	6.50	4.00	0.230	-0.10
RA (cm^2)	80	88	2210	32	49	137	88	0.392	-0.715
U (%)	80	22	15.12	3.62	16.6	28.25	11.37	0.268	-0.202
LW (cm)	80	21.66	2.0	1.36	20.1	23.6	3.5	0.305	-0.665
UW (cm)	80	12.75	0.35	0.57	12	13.6	1.6	0.436	0.858
WF (cm)	80	42.48	13.21	3.23	37.7	48.6	10.8	0.411	0.413
WR (cm)	80	30.45	9.36	2.80	26.6	35.1	8.5	0.318	-0.255

cracks (WF), between 40 and 45 cm with SD 3.23 cm; height of lift ups (RA), between 3 and 9 cm with SD 3 cm; depth between 12 and 20 cm with SD of 1.65 cm.

The average WMD of wet soil aggregates before the operation was from 2.54 and 2 mm with SD 0.52 mm; the apparent density before the operation was between 1.73 and 2.0 g/cm^3 with SD 0.15 g/cm^3; the water content before the operation was around 20%; the original cone index was around 1700 kPa with SD 91 kPa and the soil cohesion before the operation was between 22.8 and 30 kPa with SD 4.1 kPa and the internal friction angle before the operation was between 0.3 and 0.46 radians with SD 0.1 radians.

After the operation, the average WMD of wet soil aggregates was between 2.2 and 2 mm with SD 0.45 mm, the cone index in the center of the furrow was

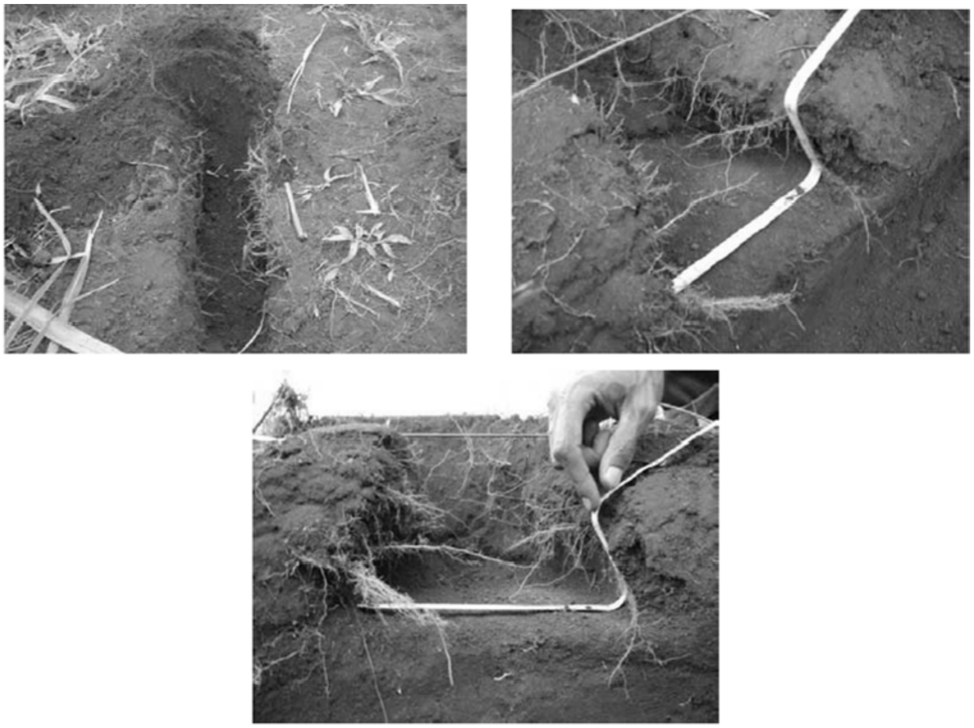


Figure 3. Conformation of the tilled strip prepared for the "Rotary Paraplow".

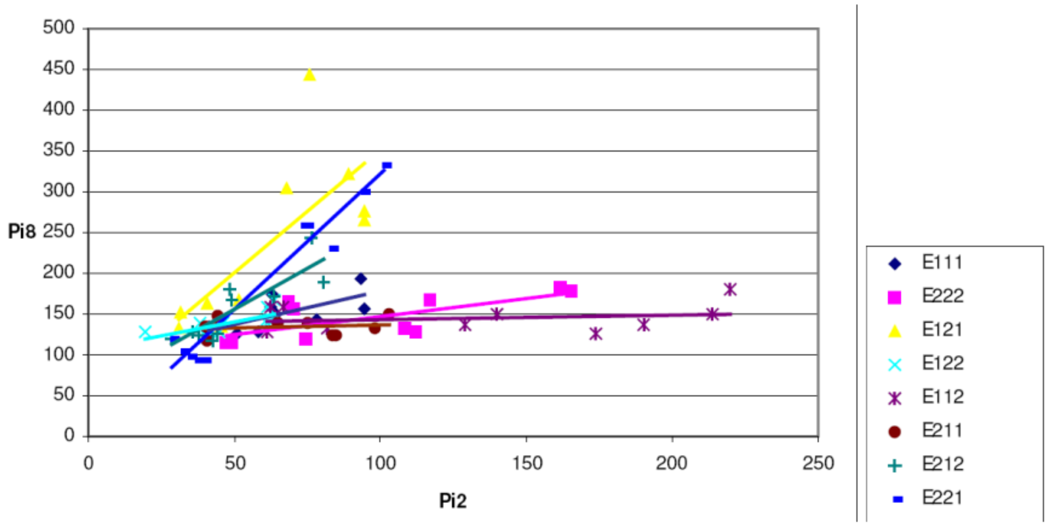
around 2 and 10 kPa with SD 0.43 kPa, the Cone index of the fissures region was around 150 and 250 kPa with SD 34 kPa, the apparent density between 1.3 and 1.0 g/cm^3 with SD 0.15 g/cm^3; the water content after the operation was around 20%, the soil cohesion after the operation was between 13.7 and 23 kPa with SD 3.3 kPa, the internal friction angle after the operation was between 0.6 and 1.8 radians with SD 0.28 radians. According to Upadhyaya et al. (2009) and Mandal et al. (2012), all these parameters are within limits imposed by the literature on the subject in order to consider soil tillage as conservational. The rotary paraplow generated a planting strip with a narrow upper surface and a well-prepared wide lower surface with the formation due to the volumetric subsoil of lateral fissures that improve the infiltration of water (Figure 3). From the data presented in Table 4, one may infer that rotatory paraplow generates a moderate disruption on the soil (decrease of 50% in the soil cohesion and an increase of 50% in the angle of internal friction) without pulverizing it (WDM of 2.0 mm after the operation); therefore, acting in favor of soil conservation. One may observe the decrease of cohesion values, cone index and apparent density of soil, while the internal friction angle increases.

Coulouma et al. (2005) states that different values for soil cohesion lead to different intensities of its fragmentation with a direct influence on its structure, while Maciel (1993) and Bravo et al. (2012) states that in consolidated soils, the cohesion of the soil has greater values, larger values of apparent density, and therefore a behaviour directly proportional to the level of fragmentation of the soil in relation to the resulting reduction of apparent density. Albiero et al. (2011b) states that in consolidated soils the internal friction angle suffers after the soil has been worked by a tool in inverse proportion in relation to the resulting apparent density; thus the greater the internal friction angle the lower the density.

The combined effects of these interdependent parameters generate a great reduction of cone index (8.5 times lower than the original), what in fact is good for soil and plants once it prevents erosion caused by compact and improves soil conditions for water infiltration and root penetration.

The rotary paraplow has these effects mainly due to its volumetric action on subsoil. The rotary paraplow blades, due to its specific geometry, generate a phenomenon of breakdown of the soil in its natural angle of cracks; this crack naturally occurs in the region of soil body which has less resistance, so the disruption of the soil is made in a more efficient manner since it is needed less energy in order to generate larger cracks, in addition to being formed in very specific regions of soil body, known as regions of natural cracks of soil, which depend on the conformation of aggregates, of the amount of organic matter, of the internal variation of textures, and of internal variations in the size of aggregates.

Due to the rotation of the rotary paraplow, vibrations



E111	E222	E121	E122	E112	E211	E212	E221
y = 3,34x - 10,80	y = 0,45x + 102,31	y = 3,03x + 48,23	y = 0,64x + 108,32	y = 0,08x + 129,91	y = -0,21x + 146,37	y = 2,01x + 55,18	y = 3,33x - 10,80
R^2 = 0,9439	R^2 = 0,5087	R^2 = 0,5533	R^2 = 0,4659	R^2 = 0,4439	R^2 = 0,286	R^2 = 0,7367	R^2 = 0,9439

Figure 4. Dimensionless graph π_2 x π_8 containing all treatments.

with lots of frequency components are caused, which correspond to the variation of resistance to soil cut due to “preferred” regions where there are occurrences of cracks; hence, cracks and ripples are produced on the surface of clods of soil. The description of the formation of these cracks is very complex and needs fractal analysis tools (Kataoka et al., 2002; Nussenzveig, 2008). So these cracks occur in oscillations related to the rotative tool and they work in a cylindrical volume around rotary paraplow proved by cracks formed after the use of the tool; these cracks have an expressive width (WF), as shown in Table 4, reaching their size four times more than the furrow upper width (UW).

Thus, when rotary paraplow hits the soil, there is a breakdown in regions naturally established with no disruption “not natural”, in other words, there is a breakdown of soil aggregates by mechanic action; therefore, there is no excessive reduction of WDM of aggregates, becoming possible the reduction of the compact of the soil with no reduction of WDM.

This fact is proved by WDM values, which Lucarelli (1997) and Pinheiro et al. (2004) assert that in conservational systems of soil preparation the WMD value in general falls between 2 to 2.5 mm on surface horizons, which means little turnover of the soil. This is a huge advantage since Osunbitan et al. (2005) asserts that in direct planting systems, the main conservational system, the apparent density is significantly greater in relation to conventional treatments, considering oxisols; thus rotatory paraplow enables the reduction of apparent density and of the soil compaction maintaining the advantages of no-till system.

From the values obtained in Table 4, we have a surface raised in height ranging (HR) between 2.5 and 6.5 cm, which demonstrates movement of the soil without turning over and inversion, besides the effect of elevating the soil due to geometric form of the rotary paraplow. The dimensionless graph Π_2 x Π_8, Figure 4, represents the behaviour of soil breakdown (ϕ/WMD), (π_2) as a function of its movement and de-compacting (RW/WMD), (Π_8). In general, this graph can be considered as an interrelationship between the internal friction angle of the soil (ϕ) and the height of volumetric expansion (RW), as both pi-terms have WMD as denominator. This dimensionless graph demonstrates an intimate link between physical characteristic of soil (ϕ) with its structure (RW), therefore, this graph can also be considered intrinsically physical-structural (Figure 4).

The higher the internal friction angle, the lower the density, and consequently the greater the breakdown of the soil indicated by the width of the raised section, which demonstrates movement of the soil without turning and inversion, besides the effect of raising the soil due to the geometric shape of the rotary paraplow, confirming the soil disturbance below the surface, which according to Rosa (1997) refers to the expansion of the soil in digging operations due to a change in the density of the soil.

The best operational configuration is that in which there is lesser breakdowns (relatively lower values of Π_2) and great mobilization (relatively higher values of Π_8). This focus is seen in Figure 4, where the best behaviours were with treatments E221 and E121, which mobilized the largest areas and concerning relative terms it de-structured less the soil. One may note that both

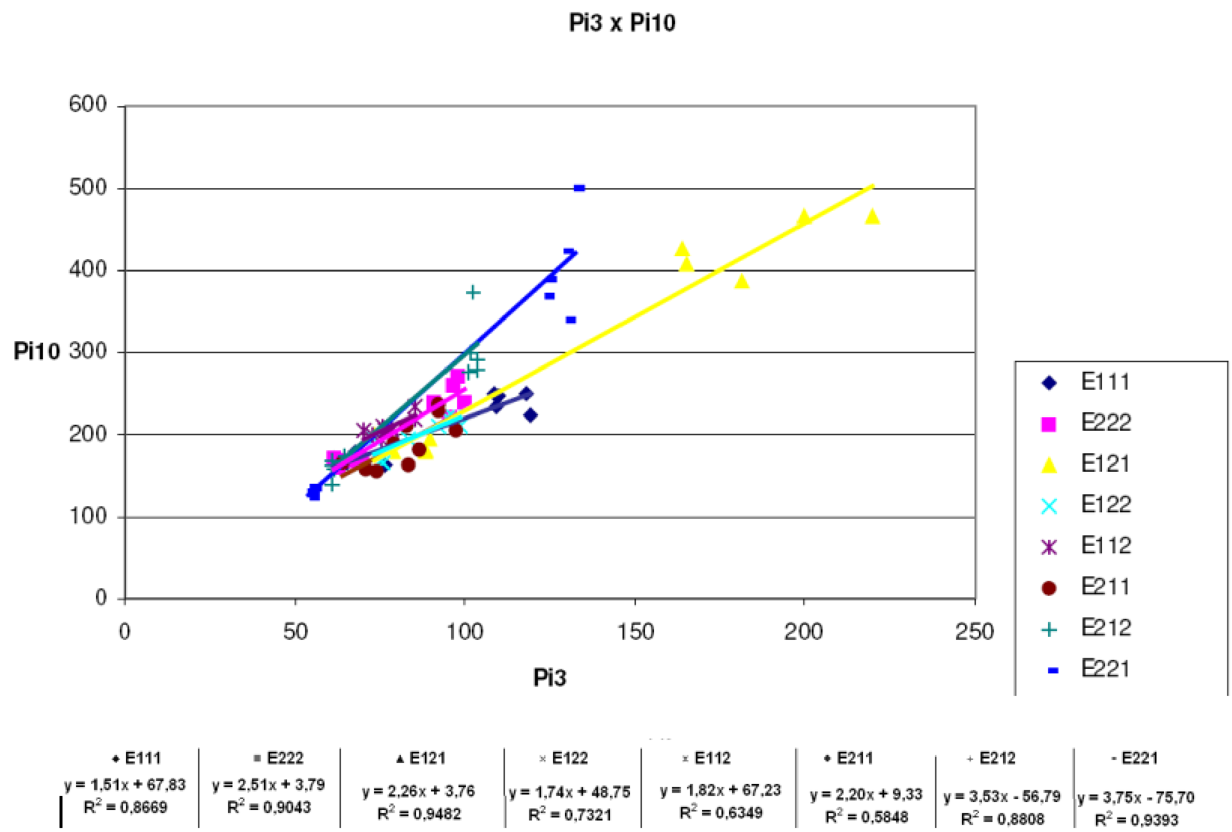


Figure 5. Dimensionless graph π_3 x π_{10} containing all treatments.

treatments have the same combination of operating depth and tool rotation, with only the speed varying, indicating that in terms of breakdown and mobilization of the soil, configuration X21 has excellent characteristics for conservation. An opposed situation is represented by E112 treatment, which presented a high de-structuring demonstrated by high values of internal friction angle, but lower volumetric expansion of the soil, which leads one to understand that the soil volume has not increased because the aggregates were too small, in other words, there was a pulverization of soil aggregates. Another interesting note it that there was a high variation of angular coefficient due to a number of combinations of independent parameters, which indicates that there is a tendency of differentiation of soil de-structuring due to many possible operational configuration.

The dimensionless graph Π_3 x Π_{10} (Figure 5) represents the behaviour of soil de-compacting generated by its de-structuring ((CI0/cohesion)), (Π_3) as a function of the lateral fissures related to the reduction of stability of the aggregates generated in the soil (WF/WMD), (π_{10}). In this dimensionless graphic, it must be considered the information I n Table 3, especially the ones related to WMD and to CI0.

As data is in accordance with a normal distribution, the standard deviation is an acceptable measure of dispersion; thus, when evaluating CI0 standard deviation, a coefficient of variation of 21% is given, so one may consider the value of the cone index as frequent around its average, and the same can be applied to WMD, which has a variation coefficient of 22%; thereby, this graph demonstrates a clear link between the subsoil action of rotary paraplow through the width of fissures (WF) and soil de-structuring due to the reduction of cohesion of the same operation. The turning of the paraplows amplifies such actions due to the consequent periodical vibrations that the soil receives with each rotary cut, since according to Kataoka et al. (2002), the soil is cuted periodically and may have the direction changed due to rotation of the blade. These phenomena cause vibrations which cause sideways chiselling, generating fissures in the soil around the line of action since the rupture of the soil in scarification with a paraplow takes place through lines of fissures that move around the zones where the soil is turned, apparently forming patterns of extensive lateral rupture (Hamilton et al., 2002; Amiotti et al., 2012).

Kataoka et al. (2002) asserts that the forces distributed by the tilling blades generate fissures in the soil that are dependent on the speed of the operation, while the dynamics of these blades and the behaviour of the soil have a highly-complex primary behaviour. The best operational configuration is that in which there is greater

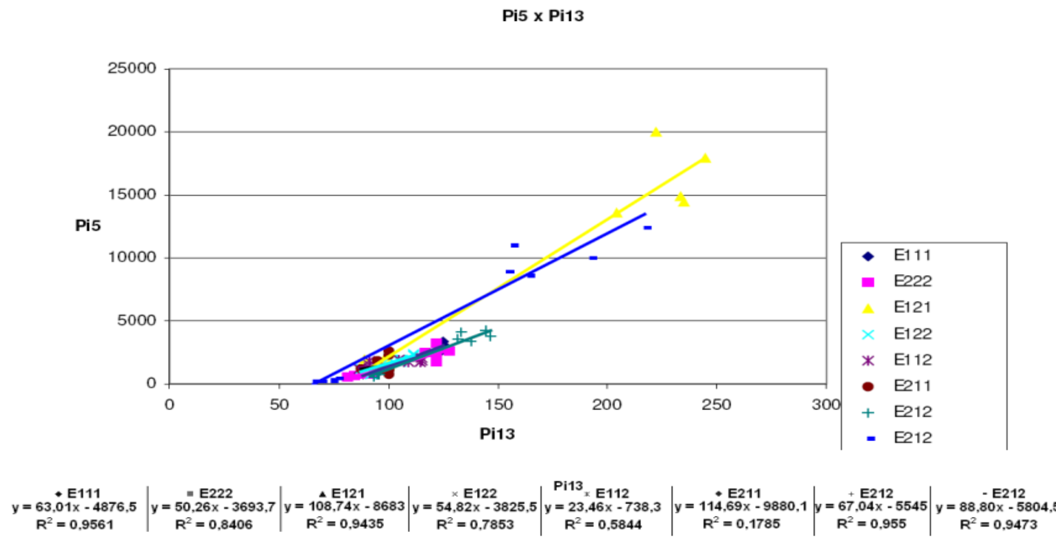


Figure 6. Dimensionless graph π_5 x π_{13} containing all treatments.

de-compacting related to reduction of the coefficient of cohesion (relatively higher values of Π_3) and great lateral fissuration of the soil (relatively higher values of Π_{10}). From this standpoint, one may note in Figure 5 that the best behaviours were from treatments E111, E212, E221 and E121, as they had large bands of de-compacting generated by the de-structuring captured by the variation of cohesion after use of the tool along with high values for width of fissuration of the soil after the operation, due to the action of volumetric scarification produced by the action of the paraplow turning, as the original concept of the paraplow is subsoiling the soil through dynamic actions produced by the design of its geometry, where. The dimensionless graph Π_5 x Π_{13}, Figure 6, represents the behaviour of the lower width of the prepared strip (LW/WMD) (Π_5) as a function of physical and structural properties of the soil (Du / (γ*(WMD)^3);), (Π_{13}).

The immediate effect in the use of a tilling implement is greater or lesser turning-over caused by the active organ, resulting in a change of the size and distribution of lumps, an increase in the volume of porosity with the consequent reduction of apparent density, and change of thermal, chemical and biological behaviour of the soil. The best operational configuration is that in which for a given value of these properties the values for lower width are greater (higher values of Π_5 in relation to the values of Π_{13}). Thus, for the same range of values of physical properties, the treatments with larger lower widths have an action of soil preparation in trapezoidal form without inversion. From this standpoint, Figure 6 reveals that the treatments with the best behaviours were E212 and E121. It is noticed that both treatments with better results in terms of lower width are opposite in all independent treatment, and that all the other combinations have approximately the same variation rate, either in Π_5 or in Π_{13}. The large lower width is related to operational combinations: low speed, high rotation and little depth; and high speed, low rotations and great depth. These operational combination cause a higher volumetric disruptive action in the region of soil body which is closer to the end of rotary paraplow. This volumetric action refers to the action of oscillatory cut of the soil due to the rotation of the tool; and the greatest effect occurs at the end of the tool due to the turning. This oscillations causes a vibration in the soil that increases the scope of the effect of disruption. When this volumetric action occurs with lower speed and little depth, but with high rotation (E121), the conformation of soil body which receives such vibrations (high rotation) have the maximum effect due to the exposure time (low speed, more time to advance) and the minimum soil resistance (little depth, soil more easily mobilised). Concerning the situation in which it is operated the high speed and very depth, but with less rotation (E212), we have similar effects as soil body receives less vibrations (lower rotation), but in less time (higher speed); therefore, it can be considered with higher frequency acting at greater depths (greater soil resistance) generating the same effect. The dimensionless graph Π_8 x Π_{10}, Figure 7, represents the degree of de-structuring and de-compacting of the soil (RW/WMD), (Π_8) as a function of the lateral width of the fissures generated (WF/WMD), (Π_{10}). In general, this graph can be considered as an interrelationship between the high volumetric expansion of the soil (RW) and the widht of fissures (WF), as both pi-terms has a WMD denominator. This dimensionless graph demonstrates the relation between subsoiling generated by rotatory paraplow (WF) and the generated de-structuring (RW).

These complex characteristics of soil movement of generation of superficial cracks/fissures and the

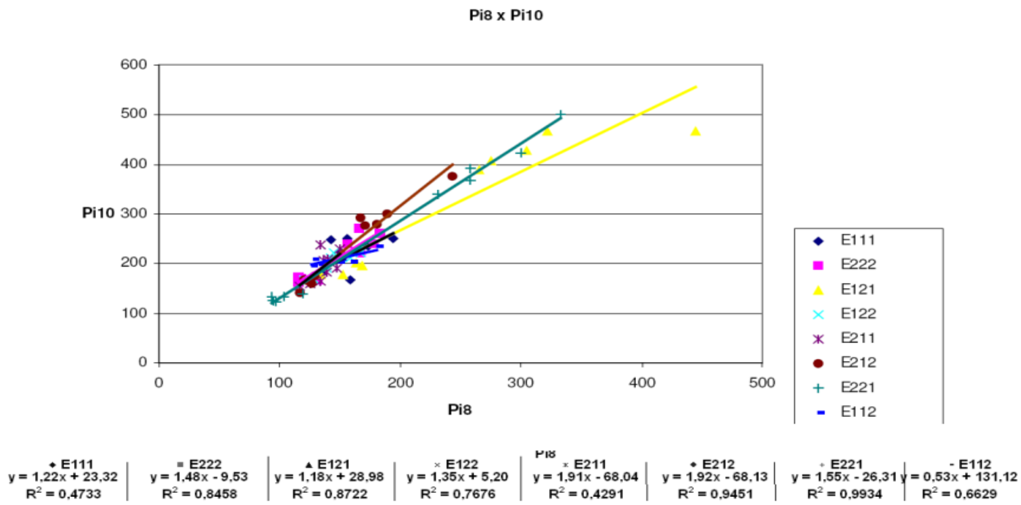


Figure 7. Dimensionless graph π_8 x π_{10} containing all treatments.

volumetric expansion of the soil are interrelated, as can be seen in Figure 7. The angular coefficients of the regression lines present different values for each treatment, which means that the operational combinations influence in subsoiling actions and blistering. The rotary paraplow when generating de-compacting of soil due to it lateral volumetric action (caused by the geometry of blades) has a lift action of the soil due to a vectorial component of cutting force towards to the surface. This force acts especially as an amplifier of cracks and fissures formed by a vibration of volumetric action of tool over soil body. The best operational configuration is that in which great de-compacting has large width of fissures (greater value of Π_8 for large values of Π_{10}).

It is possible to observe that greater widths of fissures occur in treatments E212, E121 and E221, which are also the treatments with greater de-compacting. Another interesting characteristic is that all the treatments have proportional relationships making straight lines with declivities of around 45°, which demonstrates the strict interrelationship between the degree of de-structuring (RW) and de-compacting (WF) of the soil with the width of the fissures.

According Albiero et al. (2011a) the rotary paraplow generated a 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.

Conclusion

The rotary paraplow generated a well-prepared subsurface cultivation furrow with a small upper width and a large lower width, characterizing a trapezoidal profile, besides creating lateral cracks as a result from the subsoil volumetric action. The configurations that achieved the best operational and conservational results for each dimensionless graph are listed in decreasing order of success as follows: 1st - E121; 2nd - E221; 3rd - E111; 4th - E212; 5th - E222; 6th E112 and E211; 7th - E122. After operation of the rotary paraplow important changes in structure and in mechanical properties of soil were done. It was generates a moderate disruption on the soil with decrease of 50% in the soil cohesion and an increase of 50% in the angle of internal friction without to decrease the weight diameter mean below of the conservational limit, the cone index decreased 90% and the apparent density decreased 30%, these results show a conservational tillage tool.

Conflict of Interests

The author(s) have not declared any conflict of interests.

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