Vertical tillage parameters to optimize energy consumption

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Abstract: Proper selection and correct use of machinery in agriculture must be understood as a component of a process which aims to optimize crop yield and to make a more efficient use of resources. The objective of this study was the assessment of different chisel plow body arrangements using different settings of the most important operating parameters for tillage work in order to optimize energy consumption for vertical tillage. The influence of different operating parameters of tillage tools on the performance in cultivation practice must be considered before applying deep plowing for a more efficient use of energy. The parameters considered in this study were: 1) working depth based in the critical depth theory 2) position and spacing of chisels 3) number of bodies and 4) usage of wings or sweeps. The field work was divided into five different groups of chisel arrangements and a control group. The field experiment was performed using an articulated chisel plow prototype allowing the setting of those operation parameters, an integral force transducer with three extended octagonal rings to measure the draft forces (kN) and a perfilometer to determine the cross-sectional area of soil disturbed (m2) in terms of specific resistance of the soil (kN/m2) were used. The total energy consumption for disturbed soil area (MJ ha-1) was determined assessing the area under the curve generated by draft force using Matlab R2012b V software.

The results shown that the best arrangement for vertical deep tillage was the one integrated by four shallow chisels working at 0.20 m and two deep winged chisel at 0.30 m when compared with the integral arrangements of seven chisels working at the same depth of 0.30 m. A significant savings up to 23.9% in the total energy consumed, 40% in power demand and 38.7% in the specific soil resistance was obtained with an increase of 7.35% in disturbed soil area.

Keywords: depth plowing, tillage, chisel plow, energy consumption, critical depth

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1 Introduction

The food demand, fuel and energy resources continue increase worldwide, the achievements in crop yields are not sufficient when compared with the high cost of energy applied to crop production therefore, it is necessary to optimize the resources used in activities that require higher costs in agricultural production, such as soil tillage, which is considered one of the most costly agriculture operations (Adewoyin and Ajav, 2013). Soil tillage operations requires a large amount energy consumption; this may limit agricultural activities reducing the cost effectiveness of the production system (Kichler et al., 2007); however, if technological changes are implemented in appropriate systems of food production including conservation agriculture, an estimated 50% of fossil energy could be saved (Pimentel et al., 2008).

Reduced or non-tillage not only saves time and energy, but also reduces the cost of cultivation, improves soil environment for better crop yield and increases water availability for plant growth (Shrivastava and Satyendra, 2011; Dutzi, 2008; Brunotte and Sommer, 2009). To

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this respect, vertical tillage could be a better alternative as a conservation system even when it may result in a small crop yield reduction. On the other hand, energy saving is considerable (Cavalaris and Gemptos, 2002).

Energy savings using vertical tillage compared to conventional system have been documented in several studies (Hoogmoed and Derpsh, 1985; Cadena et al., 2004; Camacho and Rodriguez, 2007). The draft force required for the implements and work quality depends on the specific soil resistance, working depth, soil density and moisture at the time of the operation; spacing between chisels in combination with critical depth work could result in different force requirements even for the same soil condition (Arvidson et al., 2004; Raper and Bergtold, 2007; Manuwa, 2009).

For the above-mentioned statement is important to analyze different parameters of tillage work and their effect on tillage quality (Camacho and Rodriguez, 2007). The draft force requirements for a given tillage work will also be affected by the soil conditions and the geometry of the implement (Taniguchi et al., 1999; Naderloo et al., 2009; Olatunji et al., 2009). Most of the research on draft force demand concerns narrow tines performance (Arvidsson et al., 2004).

Tine geometry has a useful working depth, below this depth also called the Critical Depth (**CD**), compaction may occur instead of soil loosening and values of the specific soil resistance may increase (Spoor and Godwin, 1978). Critical depth is dependent upon tine geometry and soil conditions. Mckyes (1985) described that a critical depth exists for chisel performance, in which lateral soil removal occurs, and depends on the implement width, rake angle, as well as on the density and soil moisture content. Thus, plowing depth depends upon the crop to be cultivated, soil characteristics and also on the source of available power (Pandey, 2004). In addition to this, fuel consumption rises proportionally with plowing depth (Moitzi et al., 2006; Kalk and Hülsbergen, 1999). The effect of the rake angle, evaluated by (Payne and Tanner, 1959) and (Spoor and Godwin, 1978), clearly shows how both, horizontal and vertical force, increase when increasing the rake angle. The rake angle for a lowest specific soil resistance was found to be at 25 degrees (Siemens et al., 1965; Wildman et al., 1978; Magalhaes and Souza, 1990; Mathur and Pandey, 1992 and Chaudhuri, 2001). Increasing of soil disturbance, with lower specific soil resistance can be achieved by attaching wings or sweeps to the tines combined with the use of shallow tines working ahead of the deep tines.

In a tool arrangement integrated by shallow tines ahead of deep tine significantly reduced the draft force, indicating that loosening the soil by a separate operation, prior to deep loosening, offers an effective way of reducing draft force demand on the deep tine. This could be particularly useful in circumstances where the traction force available is a limiting factor. The addition of shallow tines positioned ahead of a deep tine may reduce the total draft force by approximately 10%. The influence of wing geometry and position on tillage work performance is discussed together with the influence of tine spacing on deep soil loosening.

After a rigorous review of the most representative scientific papers about vertical tillage, it was determined that, for a more efficient use of energy, four operating parameters must be considered before applying deep plowing. Those parameters are: 1) working depth based in the critical depth theory 2) position and spacing of chisels bodies 3) number of bodies and 4) use of wings or sweeps. Each of these parameters evaluated individually represents a significant savings in energy demand.

The purpose of this work was to optimize the total energy applied to tillage work through out the integrated evaluation of those four operating parameters in the specific soil resistance and to determine the arrangement that requires the least application of draft force per cross sectional area of disturbed soil when applying vertical deep tillage.

2 Materials and methods

2.1 Experimental location

The experiments were carried out from 2012 to 2014 at the facilities of the experimental field station Humberto Treviño Siller, belongs to the Universidad Autónoma Agraria Antonio Narro, located at the state of Nuevo Leon, Mexico at 25°01΄50.88´´ latitude and 100°37΄35.65´´longitude and an altitude of 1884 MOSL. The soil was characterized as a sandy clay loam soil containing 47.5% sand, 45% loam, 6.8% clay with 12% of soil moisture with a specific soil resistance ranging from 1800 up to 3390 kPa at a 0.30-0.40 m depth with penetrometer sampling. The size of the experimental plot considered was three hectares divided into 15 arrangements with three replicates each considering the four mentioned operating parameters.

2.2 Equipment

An articulated chisel plow prototype with a double tool bar attached by a parallelogram system was designed and built to set the vertical tillage parameters. One tool bar fixed in the front for shallow chisels (two or four bodies) and another at the rear allowing movement by a combination of hydraulic proportional valves and two actuators moving upward and downward for deep winged chisels (one or two bodies). The distance between tool bars was set at 0.75 m. A three point hitch dynamometer integrated by three extended octagonal ring transducers (EOR΄s), with a capacity of 80 kN each, was employed as shown in Figure 1 in order to measure draft forces.

Figure 1 Articulated chisel plow prototype with the three point hitch dynamometer

Semi straight chisel of 0.75 m leg length, 0.06 m tip width and 28 degrees rake angle were used in both tool bars. A 0.60 m width wings or sweeps were coupled to rear deep chisels. For data collection, an instrumented tractor (Figure 2) with a portable data acquisition system DaqBook 2000 together with a signal conditioner DBK-43A both of IOTECH were used. To record the information of the draft forces, data was collected at a frequency of 20 Hz. For the draft force a spectral analysis of each of the replicates per array was done, the total data obtained from the EOR΄s were collected for the same period of time per replicate. The tractor speed was set at 1.84 m/s.

Figure 2 Data acquisition systems employed to measure the soil reaction forces

2.3 Vertical deep tillage parameters

The parameters used in field experiments for the application of primary soil tillage were considered as follows:

Regarding **working depth,** the type and degree of soil disturbance is the prime factor when selecting tillage implements but this must be considered together with the draft and penetration force requirements for efficient operation. There are two major variables in the design and selection of the appropriate geometry for given tillage implements as Equation (1) and Equation (2):

(i) Depth /width ratio (d/w) (1)

(ii) Rake angle (α) (2)

Three categories of such blades need to be distinguished depending upon their depth/width (d/w) ratio (Godwin, 2007) as Equation (3), Equation (4) and Equation (5).

1.- Wide of tines (blades) with d/w < 0.5,

2.- Narrow tines with 1 < d/w < 6,

3.- Very narrow tines with d/w > 6.

The **rake angle** is indicated by the angle at which the opener creates a horizontal line in the shift direction. The optimum rake angle is considered to be 25 degrees due to increased mobilization of soil; whereas the increase of the angle increases proportionally draft force (Chaudhuri, 2001).

The **use of shallow chisel tines** reduce significantly the force on the deep chisel indicating that loosening the soil surface by a separate operation before deep loosening offers an effective way to reduce draft force on the deep chisel. To successfully operate this arrangement **position and spacing**, the shallow chisel must be close enough to the deep chisel.

Positions considered as a function of the working depth of the deep tine for the shallow chisels (Godwin, 2007) are given by Equation (6), Equation (7) and Equation (8):

Depth = 2/3 times of the deep tine depth (6)

Lateral spacing = 2.5 times of the deep tine depth (7)

Forward spacing = ≥ 1.5 times of the deep tine depth (8)

Godwin et al., (1984) described how **spacing between tines** can affect the soil disturbance pattern produced by a pair of tines operating at the same depth. The effect of tine spacing on the resulting draft force, area of disturbance and specific soil resistance has been reported by Spoor and Godwin (1978). The spacing for deep and shallow tines recommended for good soil loosening is given by Equation (9) and Equation (10):

(iii) 1.5 times of working depth for simple tines (9)

(iv) 2.0 times of working depth for winged tines. (10)

Wings attached to the foot of a tine will modify the type of soil disturbance, duplicates the disturbed area just only by increasing 30% in draft force. This significantly increases the effectiveness of the operation, by reducing the specific soil resistance (draft force/disturbed area) by almost 30% (Spoor and Godwin, 1978). (3)

The advantage of the use of **wings** (4) is their ability to increase significantly soil disturbance (5) area at deeper layers. The soil failure planes developed from the wing extremities tends to approach to the vertical in direction rather than develop approximately at 45 degrees to the horizontal. This is due to a change in the configuring soil stress situation above the wings, caused by the soil loosening created by the leading subsoiler tip. The wing width selected will, however, depend upon soil strength, impact risk and overall draft force considerations as well as specific soil resistance. Wings width of 0.7-0.8 of the working depth has been used satisfactorily on many low impact risk soils at working depths between 0.3 to 0.45 m.

2.4 Field work test procedure

To perform field evaluation of the effect of the vertical tillage parameters in the specific soil resistance and the total energy consumed, the methodology was divided into five blocks with a total of 15 arrangements. Each setting parameters of the chisels arrangements are described in Table 1.

Table 1 Parameters of vertical tillage operation

Chisel	Working depth(m)	Number of bodies	Wings	Spacing between Chisels (m)
***Shallow**	0.20	2, 4	None	0.60
****Deep**	0.20	1, 2	With out	1.20
	0.20,0.30, 0.40	1, 2	With	1.20

Note:* Shallow: one fixed working depth and spacing between chisel. ** Deep: positioned at the center between shallow chisels.

The individual evaluation refers to the arrangement configured either by one front shallow leading chisels or the rear section with one deep winged chisels of the articulated chisel plow prototype. The integral evaluation refers to the arrangement, with at least three chisel, set at the front and rear section. The check assessment was setup by seven chisel plow used with a uniform 0.30 m working depth.

To determine the specific soil resistance by vertical tillage, a set of 15 different tests were carried out with different chisel plow arrangements with the above mentioned parameters, three replicates for each test were performed, for practical purpose the tests were divided into five groups (I, II, III, IV and V), as shown in Table 2.

Table 2 Field test arrangements at vertical tillage settings parameters

Group	**Treatment**	***Arrangement**	**Description**
I	1	1DC20UNW	One rear un-winged chisel at 0.20 m depth
-	2	1DC20W	One rear winged chisel at 0.20 m depth
-	3	1DC30W	One rear winged chisel at 0.30 m depth
-	4	1DC40W	One rear winged chisel at 0.40 m depth
-	5	2DC30W	Two rear winged chisels at 0.30 m depth
II	6	2SC20	Two front chisels at 0.20 m depth
-	7	4SC20	Four front chisels at 0.20 m depth
III	8	2SC20 + 1DC20UNW	Two front at 0.20 m depth + a rear un-winged chisel at 0.20 m depth
-	9	2SC20 + 1DC20W	Two front chisel at 0.20 m depth + a rear winged at 0.20 m depth
IV	10	2SC20 + 1DC30W	Two front chisel at 0.20 m depth + a rear winged at 0.30 m depth
-	11	2SC20 + 1DC40W	Two front chisel at 0.20 m depth + a rear winged at 0.40 m depth
-	12	4SC20 + 2DC20W	Four front chisel at 0.20 m depth + a rear winged at 0.20 m depth
-	13	4SC20+ 2DC30W	Four front chisel at 0.20 m depth + a rear winged at 0.30 m depth
-	14	4SC20 + 2DC40W	Four front chisel at 0.20 m depth + a rear winged at 0.40 m depth
V	15	7C30UNW	Seven un-winged chisel, four at front and three at the rear at the same working depth 0.30 m

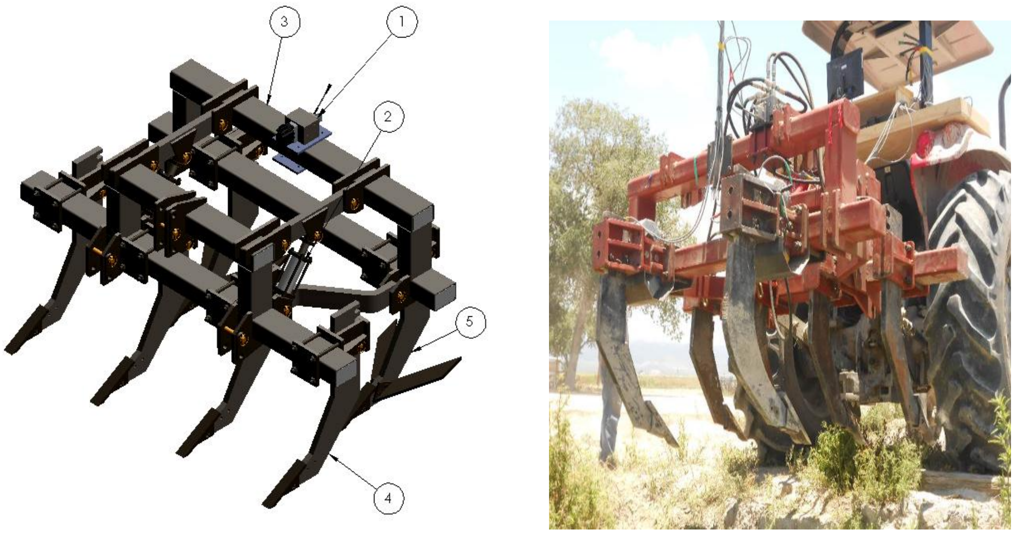
Note: * Arrangement: DC: deep chisel, UNW: unwinged, W: winged, SC: shallow chisel, 20, 30 and 40: working depths.

Group I (individual assessment), arrangements of one rear winged chisel plow were analyzed with three working depths (0.20, 0.30 and 0.40 m). Each one of these arrangements was compared to those with one un winged chisel at 0.30 m depth and to two rear winged chisels at 0.30 m. G**roup II (individual assessment),** arrangements of two and four shallow chisel tines were analyzed; for shallow chisels no wings were used and the depth was maintained constant at 0.20 m. G**roup III (integral assessment),** a combination of the groups I and II, with arrangements of two shallows depths and one deep winged rear chisel with three working depths (0.20, 0.30 and 0.40 m) were compared with the arrangement of two front shallow chisels at 0.20 m and one deep unwinged chisel at working depth of 0.30 m. G**roup IV (integral assessment)** combinations of groups I and II, with arrangements of four shallow tines and two rear winged chisels with three working depths (0.20, 0.30 and 0.40 m) were compared with the arrangement of four shallow chisels and two deep unwinged chisels at a working depth of 0.30 m. G**roup V (reference assessment)** an arrangement of seven chisels (four in the front and three at the rear) was analyzed. No wings were used and the working depth remained constant at 0.30 m. The lateral spacing between chisels was set at 0.75 m. This evaluation was carried out using commercial chisel plow equipment.

For each one of the 15 evaluated arrangements, the magnitude of the total draft force in (N) was determined by using the data obtained with the data logger and analyzed by the spectral analysis method described by Campos and Wills (1995). To determine the cross-sectional disturbed soil area (m^2), a profile meter with a graduate rule was used to measure the depth each 0.10 m of the working width. Afterwards, the specific soil resistance ($Sr= F*dA^{-1}$) in N/m^2 was determined. The total energy consumption for disturbed soil area (MJ/ha) was determined using the method of area under the curve in Matlab program R2012b V described by (Pérez, 2002). A randomized complete block with three replicates experimental design was used. Likewise, concerning the analysis and interpretation of the results, Minitab 15 statistical package was used.

3 Results and discussion

The Figures 3a and 3b show an example of the six chisel prototype arrangement evaluated under field conditions. The tool bars and their components are clearly shown.



1. Proportional valve for automatic depth adjustment 2. Hydraulic actuators for displacement upward and downward of the articulated section. 3. Tool bar of articulated section for the variable depth application of primary tillage. 4. Shallow chisels 5. Deep winged chisels

Figures 3a Designed layout prototype and 3b Built Prototype of articulated chisel plow for vertical tillage

On Table 3 are shown the results for one chisel body comparing (T1 vs T3) and integral assessment (T8 vs T 10). It could be observed that specific soil resistance decreased by 32.0% and 34.8% respectively due to the increased disturbed area by the coupling of wings behind the deep chisel. Similar results on the reduction of the specific soil resistance were obtained by Spoor and Godwin (1978), who compared the use of a chisel plow with two different geometries of wings with a conventional chisel working at the same depth. Kumar and Thakur (2005) concluded that the specific soil resistance could decrease up to 26.9% using straight winged chisels compared to conventional chisels working at a depth of 0.30 m in a clay loam soil.

Table 3 Test results arrangements with vertical tillage parameters for deep plowing

Treatment /group	Arrangement	Chisel tines Draft force (kN)	Soil disturbance area (m^2)	Specific soil resistance (kN/m^2)	Consumed energy (MJ/ha)
1/I	1DC30UNW	14.99abc	0.126d	121.10a	**
2/I	1DC20W	9.88c	Nq	Nq	**
3/I	1DC30W	13.65abc	0.171cd	82.40abc	**
4/I	1DC40W	23.94abc	Nq	Nq	**
5/I	2DC30W	34.91a	0.434abcd	80.67abc	**
6/II	2SC20	13.57abc	0.157d	86.86ab	**
7/II	4SC20	14.03abc	0.410abcd	34.25c	302.5e
8/III	2SC20+1DC30UNW	23.12abc	0.292abcd	70.77abc	Nq
9/III	2SC20+1DC20W	11.96bc	0.191cd	62.35bc	423.9de
10/III	2SC20+1DC30W	15.08abc	0.236abcd	63.76bc	514.8de
11/III	2SC20+1DC40W	18.98abc	0.268abcd	70.79abc	688.8cd
12/IV	4SC20+2DC20W	20.41abc	0.590abc	36.62c	664.5cd
13/IV	4SC20+2DC30W	19.88abc	0.630ab	32.10c	823.1bc
14/IV	4SC20+2DC40W	33.04ab	0.640ab	49.48bc	1121.2a
15/V	4SC30+3DC30UNW	33.12ab	0.680a	52.35bc	1093.2ab

Note: Nq: variable was not quantified, **: energy consumption was quantified only for integral arrangements. In each column the means with different letter have significant difference (Tukey, ≤ 0.05).

Comparing the performance of the arrangements (T2 vs T3 vs T4), it can be observed that for an increase in the working depth, the demand of draft force was greater for T4 with a 48% higher than T3 and T3 58% higher than T2. Sahu y Raheman (2006) mention that the working depth has a greater influence on the specific soil resistance than the increased draft force.

For the arrangements of three chisels for individual treatments (T6 + T3) compared to the integral treatment T10, the results show a reduction of 44% on draft force. The same behavior was found with integral arrays with six chisel for individual treatments (T5 + T7) compared to the integral treatment T13, where the results show a significant reduction of 59.0% in draft force demand, in both cases shallow chisels were used ahead of deep chisel winged tines. The proposed configuration for the evaluation of vertical tillage parameters are described in Table 1. Spoor and Godwin (1978) reported that the addition of wings to the tine foot subsoiler increased the draft force in approximately 30%. This increase is within the range of 15 to 30% found for the same evaluated chisel tine plow under other soil conditions. For this increase in draft force, the total soil disturbance area was doubled giving a significant improvement in the specific soil resistance.

At the Figure 4 are shown the results of draft forces with the proposed integral arrangements equipment with three (T10) and six chisel (T13) compared with the arrangement of seven chisel (T15) commercial equipment used as a reference for the traditional vertical tillage. The increase of draft force between T13 vs T10 is due to the increasing number of chisel and the configuration arrangements. On the other hand, there is a decrease of up to 40% on the draft force between T13 vs T15. This significant force savings is due to the use of six chisel instead of seven, the working depth and spacing of shallow chisels ahead of deep chisels, and for the use of wings. Minimized draft force is not the main issue in soil tillage, reduced magnitude of the specific resistance (draft force/disturbed area) is much more important, because it is a better indicator of the overall tillage performance (Godwin, 2007).

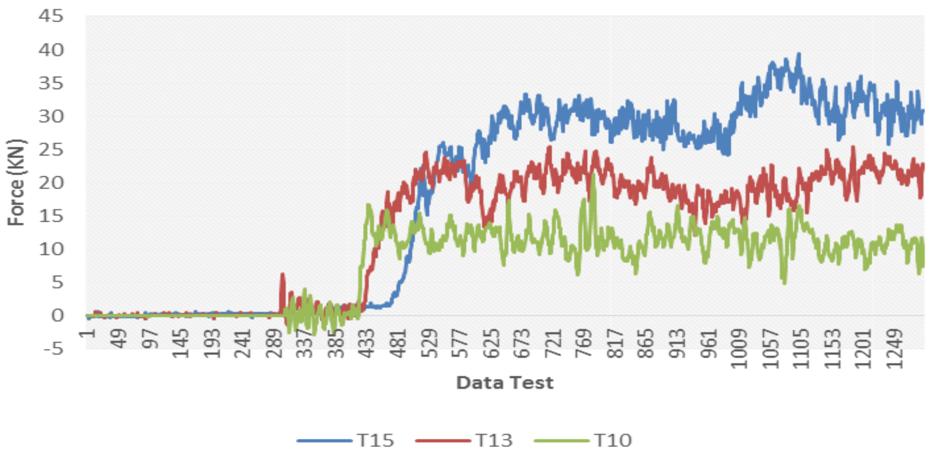


Figure 4 Comparison of draft force behavior with integral arrangements (T15, T13 and T10)

Figure 5 shows the effect on disturbed cross section area with the use of different integral treatments (T10, T13 and T15). There could be appreciated that the best performance was obtained with T13, similar values for T15, however with a lower specific soil resistance of 38.7% using four front shallows chisels bodies working at 0.20 m depth followed by two winged chisel at 0.30 m depth in comparison with the traditional vertical system; similar results were found by Camacho and Magalhaes (2004) on the effect of the use of winged subsoiler, compared to traditional chisel plough, for vertical tillage in the increment of soil disturbed area and reduction of the specific soil resistance. Disturbed area values and corresponding draft force are shown in Table 3.

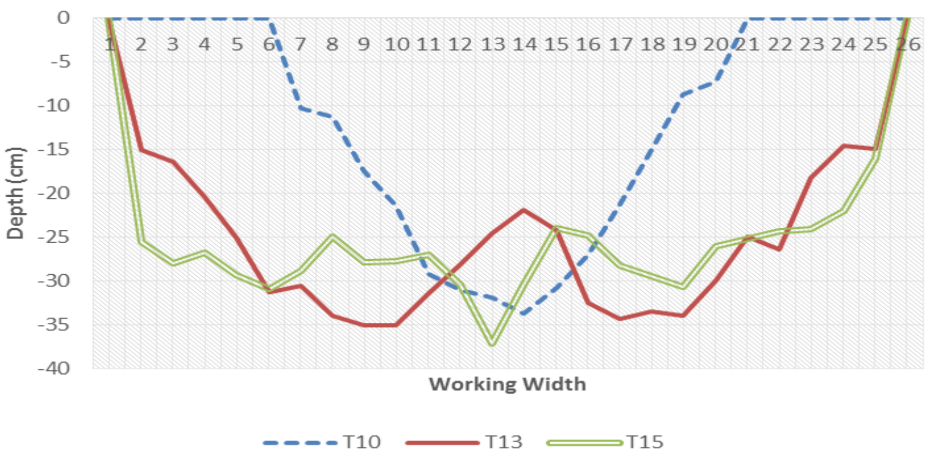


Figure 5 Comparison of soil disturbed area with three integral arrangements

In Figure 6 the draft force demand for the proposed arrangement with six chisel bodies (T13) is shown. It can be observed that the total energy consumed during the test was 823.1 MJ/ha, similar tendency was reported by (Cadena, 2012) and (Hetz and Barrios, 1996) on evaluated chisels arrangements using three bodies with different positions and spacings and with and without wings.

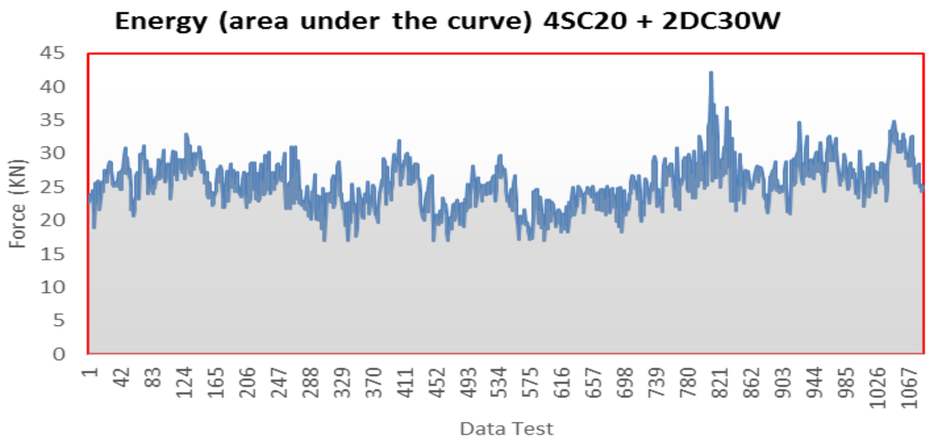


Figure 6 Energy consumption of vertical tillage treatment (T13)

In Figure 7 the draft force applied with the traditional vertical systems arrangement, with seven chisel bodies, (T15) is shown where the total energy applied along the test surface can be observed. For this arrangement the total energy was 1093.2 MJ/ha. It is important to indicate that the total covered area obtained represents an alternative of quantifying applied energy for tillage.

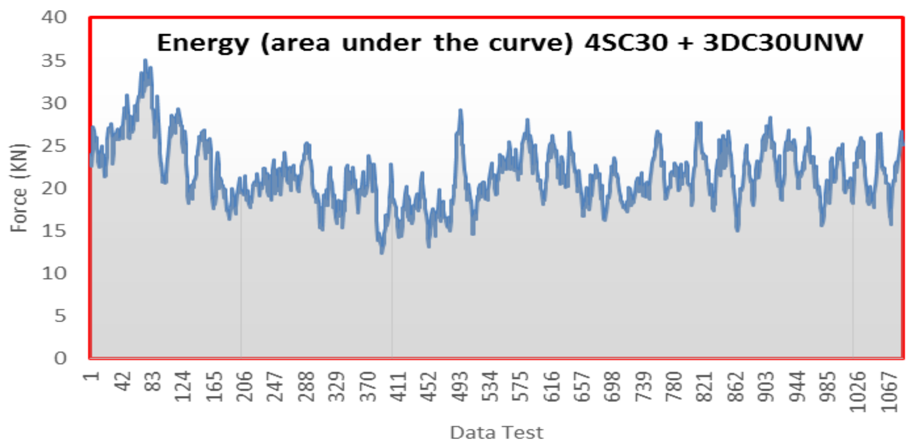


Figure 7 Energy consumption with traditional vertical tillage treatment (T15)

Finally and according to the results given in Table 3 could be observed the behavior of the integral proposed arrangements of six chisels at three different working depths (0.20, 0.30 and 0.40 m) in comparison with the traditional system of seven chisel to a uniform depth of 0.30 m, used as reference in the traditional system of vertical deep tillage. The results shows that for the integral arrangements T12 vs T15, exist a significant savings of 39.2% in energy consumption and 30% reduction on the specific soil resistance.

In the comparison of the integral arrangements T13 vs T15 at the same working depth, it can be appreciated that there are a significant savings of 23.9% in energy consumption, 40.0% in draft force demand and 38.7% in the specific soil resistance, regarding to a non-significant increase in the disturbed soil area of 7.35%. This is due to the adjustment of operating parameters. Therefore, the use of six chisels should be preferred instead of the recommended seven fixed chisel, working at the same depth, currently used in the traditional system.

In the Comparison of the integral arrangements T14 vs T15, it can be observed that the T14 has a significant increase in draft force demand from 19.9 to 33.04 kN, but no significant change in the disturbed area compared to

T13 when goes from 0.20 to 0.30 m deep. Therefore, it is assumed that plowing is applied to critical depth which causes soil compaction instead of soil loosening.

4 Conclusions

The use of combined operating parameters (working depth, position-spacing, number of chisel and use of wings) evaluated using one, three and six chisel compared to the traditional arrangement of seven bodies show a significant reduction in the specific soil resistance of 32.0, 34.8 and 38.7% for both individual and integral arrangements.

Regarding to the total consumed energy, results show a significant reduction in the arrangement of six chisel for the three tested depths as compared to the arrangement of seven chisel used as a reference in the traditional system.

The best arrangement for vertical deep tillage was the treatment T13 (four shallows chisel at 0.20 m and two deep winged at 0.30 m) when compared with the integral arrangements T15 (seven chisel at the same deep to 0.30 m) with highly significant savings of 23.9% in the total energy consumed, 40% in power demand, and 38.7% in the specific soil resistance with a non-significant increase in disturbed soil area of 7.35%, therefore it is recommended the use of six bodies arrangement instead of seven bodies currently used in the traditional system.

Treatment T14 has a significant increase in draft force demand from 19.9 to 33.04 kN, with non-significant change in the disturbed soil area compared to T13 when going from 0.20 to 0.30 m working depth.

The results obtained in this study referring energy savings, could applied in precision agriculture technology in order to optimize the energy requirements by the variable working chisels depth application (VRT) in primary tillage.

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