Horizontal draft, soil disturbance and specific draft under different conservation tillage implements in UK

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Abstract

Field-based research has been supported by the use of Cranfield University's soil bin facility in order to examine the effect of conservation tillage implements on horizontal draft requirements, degree of soil disturbance, specific draft, and predicted fuel consumption. The soil bin and field study are being undertaken to allow an integrated assessment of the agronomic, environmental and economic performance of five conservation tillage systems in a wheat-oilseed rape rotation. The implements tested were winged tines manufactured by Sumo and Mzuri, tines manufactured by Claydon and Vaderstad; and a disc by Vaderstad. The horizontal draft force required to pull a single tine, ranged from 0.15 kN for the Vaderstad tine (working at 25 mm depth) to 1.85 kN for the Sumo Trio winged tine (operated at 200 mm depth). Implements with different geometry resulted in different energy requirements. The use of winged tines reduced the specific draft. Between implements at the same working depth, tines with lower rake angle resulted in less draft. Thus the horizontal draft (1.32 kN) and the specific draft (62.5 kN m^{-2}) of the winged tine with a rake angle of 45^{o} was less than the draft (1.59 kN) and the draft per area disturbed (95.5 kN m^{-2}) of the non-winged tine with a rake angle of 70^{o}. During the first two years of this research, in the absence of a significant effect of the different cultivation systems on crop yield or on blackgrass (*Alopecurus myosuroides*) weed infestation at a field-scale, the most profitable system is likely to be the one which combines low equipment cost, with the lowest energy and labour costs.

Keywords: Energy, tillage systems, cultivation, soil disturbance, tillage implement geometry

1. Introduction

Soil tillage, especially ploughing, is one of the most energy consuming processes in crop production (Tayel et al. 2015). In general terms, cultivation systems can range from ploughing (inversion tillage) to conservation tillage systems (non-inversion tillage) where: i) the soil is not inverted, ii) soil disturbance is minimized, iii) the surface residue is at least 30% and iv) tillage and seed placement usually occurs in a single pass. Inversion tillage usually degrades soil as it breaks down soil structure, can create a plough pan, and decreases certain populations of soil organisms. In many cases, farmers till the soil more than is necessary and excessive tillage can degrade the capacity of a soil to support high crop yields (Gimenez et al. 2010).

Crop response to different tillage systems is variable because of many factors. Crop germination, emergence and growth are largely regulated by the soil's structural condition in terms of soil's pore size distribution. Pore size distribution determines soil aeration, moisture content, and mechanical impedance to root growth. Tillage operations can loosen, granulate, crush or compact soil structure, changing soil properties such as bulk density, pore size distribution and the composition of the soil atmosphere that all affect plant growth (Fuentes et al., 2009; Aikins & Afuakwa 2012). The intensity of a conservation tillage system depends on the number of operations, the type of equipment employed, whether the implement is driven actively by PTO or passively by drawbar power, the implement geometry and the depth of operation (Loibl 2006; Godwin 2007). The fuel required to carry out the tillage operation is correlated to its intensity (Moitzi et al. 2013).

The energy requirement of tillage is related to the horizontal force needed to pull the implement and associated fuel costs which vary, depending on the tillage operation. Both energy requirement and crop responses can be related to the tillage intensity, working depth, implement geometry and the number of passes carried out in the field (Arvidsson 2010). Mahdi & Hanna (2008) assume that one of the anticipated benefits of conservation tillage is that it will maximize net farm income and reduce costs. This is because of the reduced number of machinery passes, whereby two or more activities are combined into one, and the use of machines with high work rates and low draft requirements.

The reduced soil disturbance associated with conservation tillage, compared to conventional systems, can enhance soil biological activities and soil air and water movement. The soil structure can also improve over the long term through increased soil organic matter, an increased proportion of larger soil aggregates, and reduced soil bulk density (Daraghmeh et al. 2009). According to Spoor & Godwin (1978), there is a critical working depth for all rigid tines below which unwanted soil compaction occurs rather than effective soil loosening. The critical depth is dependent upon the width, inclination and lift height of the tine foot and on the moisture and density status of the soil. Soil loosening efficiency can be quantified by specific draft or specific resistance (kN m^{-2}), which is the draught force divided by the cross- sectional area of disturbed soil. Godwin & Spoor (1977) reported that very narrow tines have working depths far greater than their widths, with aspect ratios (working depth/width) greater than 6.0, while wide tines have working widths far greater than their depth, with aspect ratios of less than 0.5.

The present study focused on field experiments in Northamptonshire in the UK, where the overall research question was: how do commercially-available conservation tillage systems affect: 1) the growth and yield of arable crops; 2) the soil condition; and 3) the profitability of winter wheat and oilseed rape when grown in rotation? One component of the research used the soil bin facilities at Cranfield University to: a) measure the draught requirements of five different tillage implements under uniform soil conditions; b) measure and evaluate the resulting soil disturbance; c) estimate the associated fuel consumption; and d) demonstrate and quantify any effect on soil compaction. Thus for clarification, the term “Treatment” will indicate the equipment as a whole used in the field experiment and the term “Implement” will refer to the main working part (tine or disc) of each treatment tested in the soil bin.

2. Materials and Methods

2.1. Soil bin facility

The experimental work allows a more detailed examination of the commercially available, conservation tillage treatments used in a parallel field study, running from 2013 to 2016, based at the Lamport Hall Estate (52°35'85"N 0.87°25'63"W) in Northamptonshire in the UK. The soil bin and processor is a specially designed experimental facility which is located in the Hudson Building at Cranfield University. This 20 m long, 1.7 m wide and 0.75 m deep soil dynamics facility can be prepared in a series of incremental 50 mm horizontal layers to create a number of highly controlled and repeatable test profile conditions, with realistic field bulk densities with moisture contents of up to 20%. This allows the creation of customised soil profiles. The soil texture in the bin is a sandy loam. The soil bin processor has instrumented mounting points (Figure 1, right) on an extended octagonal ring transducer for the testing of tillage implements. The work evaluated a number of working tillage implements which have been donated by the manufacturers.

Figure 1. Soil bin processor at Cranfield University (left)
and the use of a “test tine” prior to the start of the experiment (right)

The facility was used to determine horizontal draft force requirements, soil disturbance and specific draft. The soil bin processor runs on tracks on either side of the bin (Figure 1).

2.2. Implements tested

The implements included winged tines manufactured by Sumo UK Ltd and Mzuri Ltd, non-winged tines manufactured by Claydon Drills and Vaderstad Ltd, and a disc manufactured by Vaderstad Ltd. The tested implements and their geometry are presented in Figure 2. In particular the implements included:

i) Sumo Trio and drill tine: a winged tine with a 15º rake angle and 215 mm working width

ii) Mzuri Pro Til 3: a winged tine with a 45º rake angle and 150 mm working width

iii) Claydon Hybrid tine: a non-winged tine with a 70º rake angle and 20 mm working width

iv) Vaderstad Seed Hawk: a non-winged tine with a 50º rake angle and 13.5 mm working width

v) Vaderstad Rapid A: a working disc with a 410 mm diameter

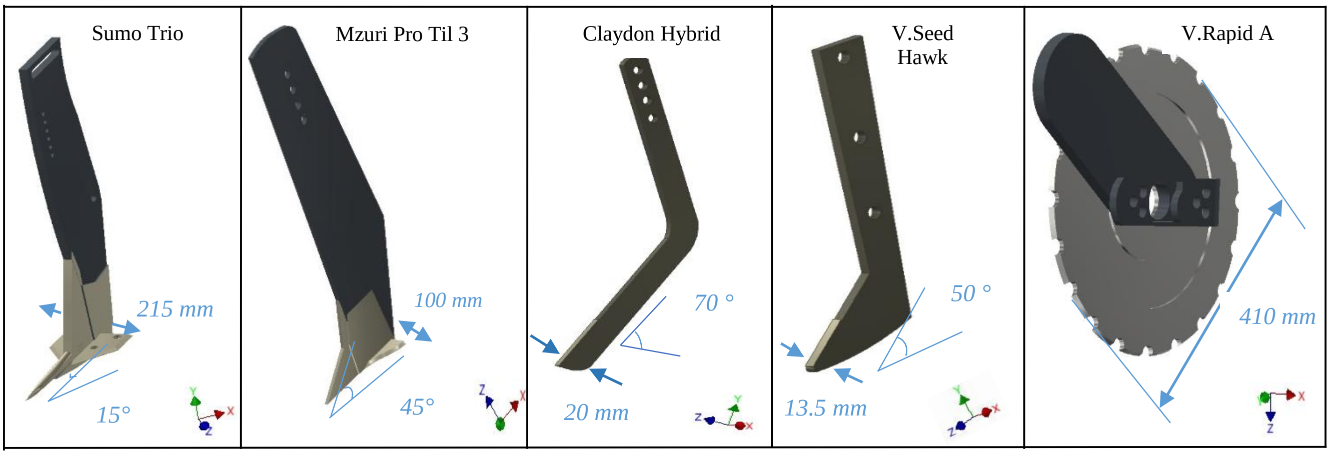

Figure 2. Tillage implements tested in the soil bin facility, showing width and rake angle (not to scale)

2.3. Data collection and analysis

The working depth of each implement was the same as used in the field and the speed for the experimental runs was set to 6 km hr^{-1}. The implements were mounted on the soil processor. After the end of a single run, a Microsoft Excel file was generated by the soil's bin software (Daisy Lab) including the horizontal force at the particular time and point of the experiment. Finally the corresponding diagram was produced which contained the values of the force in relation to time. Bulk density samples and penetration resistance readings were taken prior and after each experimental run to reflect, as closely as possible, the field work protocols in terms of soil compaction properties associated with the different tillage implements. The area of soil disturbance was determined by the extent of the disturbed soil from the surface down to the implements working depth. The soil disturbance was measured with a laser scan device, and the output was used to produce the corresponded diagrams and figures for calculations of the area and volume of soil disturbed. The laser scans were carried out as follows: at three places perpendicular to the soil bin, as indicated by the orange lines in Figure 3. Bulk density rings (50 mm in height and 50 mm in diameter) were used to take soil samples at one depth (0-50 mm) for the shallow implements and at two depths (0-50 mm and 150-200 mm) for the deeper ones. In total, six bulk density samples (two in the front end of the soil bin, two in the middle and two in the back part) were collected prior to the start and after the end of the experimental runs (Figure 3). Penetrometer readings were also carried throughout the soil profile, either between 0 and 100 mm or between 0 and 200 mm depending on the type of tillage implement and its working depth. The Sumo tine worked at 200 mm depth, the Mzuri and Claydon tines at 150 mm depth and Vaderstad Rapid and Seed Hawk implements at 25 mm.

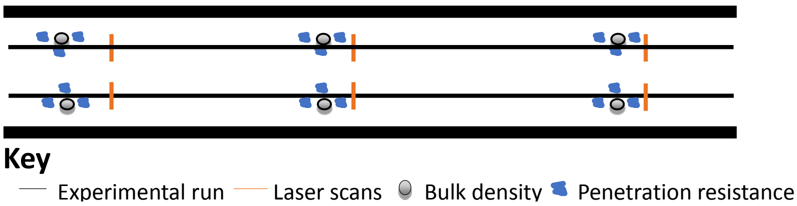

Figure 3. Design of the soil bin experiment, for testing the tillage implements

The experimental runs alongside with their measurements were replicated three times, namely six experimental runs (Figure 3), for each of the 5 types of tillage implements. The overall measurements carried out during the soil bin experiment are presented in Table 1.

Table 1. Measurements carried out during the soil bin experiment

Before the runs	During the runs	After the runs	Estimation
Bulk density (Mg m^{-3}) Penetration resistance (MPa)	Draft (kN)	Bulk density (Mg m^{-3}) Penetration resistance (MPa) Soil disturbance (m^2) Specific draft (kN m^{-2})	Fuel requirements (l s^{-1})

Equation 1 was used to calculate the fuel requirement needed to pull the implements through the soil, based on their horizontal draught (Inns & Kilgour 1978; Serrano et al. 2007). Several assumptions were used in the calculation; a slip efficiency of 0.9, transmission efficiency of 0.8 and a thermal input factor of 3 (personal communication with R. Godwin, 2015) and the specific energy of diesel 38.6 x 106 J l^{-1} (Demirel 2012).

$$\text{Fuel requirement (l s}^{-1}\text{)} = (((F \; x \; S / \eta_s) / \eta_t) \; x \; T_h) / S_e \qquad \text{(Equation 1)}$$

Where F = draught force (N), S = speed (m s^{-1}), η_s = slip efficiency, η_t = transmission efficiency, T_h = Thermal input power factor, Se = specific energy of diesel (J l^{-1}).

3. Results

3.1. Implement horizontal draft and extent of soil disturbance

The Sumo Trio, a subsoiler, was the deepest (200 mm) and widest (215 mm) working implement and resulted in the greatest average horizontal draft of 1.85 kN. The Mzuri and Claydon tines worked at the same depth (150 mm) but because the Mzuri was a winged tine with a rake angle of 45°, this implement resulted in a lower draft (1.32 kN) compared to that of the Claydon (a non-winged tine) (1.59 kN with a 70° rake angle). On the other hand, the shallow working implements, Vaderstad Rapid and Vaderstad Seed Hawk at 25 mm, had 0.09 kN and 0.13 kN draft respectively. Soil disturbance was assessed at the end of the experimental runs in order to understand how the soil failed and how much soil was disturbed when the implement was pulled through it. In general, the winged tines produced greater widths of soil disturbance. They disturbed a greater area of soil, and their horizontal drafts depended on their rake angle and working depth. For the deeper implements, (the Sumo, Mzuri and Claydon), the area of soil disturbance was 5.07 x 10^{-2} m^2, 2.0 x 10^{-2} m^2 and 1.72 x 10^{-2} m^2 respectively, while the shallow working implements (Vaderstad Rapid and Vaderstad Seed Hawk) resulted in 10 to 15 fold lower values (at 8.5 x 10^{-4} m^2 and 1.0x 10^{-3} m^2 respectively). An illustration of the average draft requirements and the resulting area of soil disturbance are depicted in Figure 4.

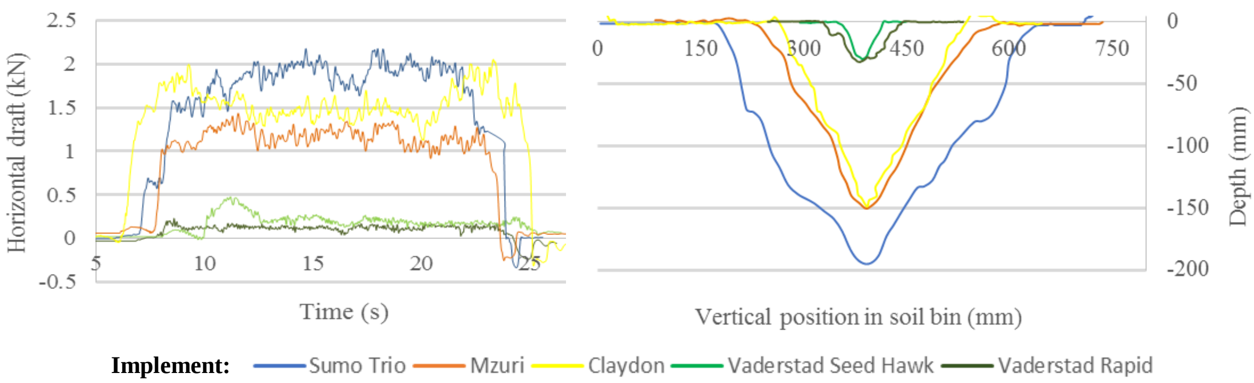

Figure 4. Horizontal draft (kN, left) and soil disturbance to the working depth (right) of the tested implements

Overall the implements resulted in the type of upward and forward failure which tended to loosen the soil in a crescent shape. The aspect ratio (working depth/width) for the implements was below 6, where by definition lateral failure is not apparent. The Claydon's depth to width ratio was slightly over 6, but the analysis showed that the soil failed in a similar manner to the other treatments and there was no effect on sideways compaction or lateral soil failure. The average specific draft (draft per area of soil disturbed) was much higher for the shallow working, rigid tine of the Vaderstad Seed Hawk (150 kN m^{-2}) and the Vaderstad Rapid disc (105 kN m^{-2}). On the contrary, the deep working tines of the Sumo Trio, Mzuri and Claydon resulted in 36.5 kN m^{-2}, 62.5 kN m^{-2}, 95.5 kN m^{-2} respectively. Winged tines increased the efficiency of soil loosening by reducing the specific draft when compared to non-winged tines under the same working depth. Fuel requirements were estimated as a function of the implement draft using Equation 1. For the Sumo Trio for instance, with 1.85 kN = 1850 N horizontal draft, the fuel requirements would be:

Fuel requirement = ((((1850 N *1.7 m s^{-1})/0.9)/0.8)*3)/ 38.6 x 106 J l^{-1} = 3.4 x 10^{-4} l s^{-1}

Similarly the fuel requirements were calculated for the other implements. A summary of the implements characteristics and performance results is presented in Table 2.

Table 2. Implement working depth and summary of performance results

Implement	Working depth (mm)	Width of disturbance (mm)	Area of soil disturbed (m^2)	Horizontal draught (kN)	Specific resistance (kN m^{-2})	Fuel requirement (l s^{-1})
Sumo Trio tine	200	465	0.05070	1.85	36.5	3.4 x 10^{-4}
Mzuri Pro Til 3 tine	150	300	0.02110	1.32	62.5	2.4 x 10^{-4}
Claydon tine	150	235	0.01660	1.59	95.5	2.9 x 10^{-4}
Vaderstad Seed Hawk tine	25	83	0.00100	0.15	150.0	2.7 x 10^{-5}
Vaderstad Rapid disc	25	87	0.00085	0.09	105.0	1.6 x 10^{-5}

3.2. Implement effects on soil properties

There were no significant differences ($p > 0.05$) in bulk density for the different implements after the experimental runs. A similar response was also seen in the field study, where in the majority of cases the bulk density did not show differences for the different tillage treatments.

In the soil bin, there appeared to be differences in penetration resistance due to the different tillage implements. Using the implements did not result in any significant change in the penetration resistance of the soil at 0-50 mm (Figure 5). The effect of the two Vaderstad treatnents were only measured to a depth of 100 mm. In the 150-200 mm soil layer, the Sumo Trio reduced the resistance by 0.40 MPa and the Claydon was found to increase the penetrometer readings, at the 150-200 mm depth by 0.17 MPa (Table 3). The average penetrometer readings of the soil profile for each implement both prior and after the runs are presented in Figure 5. In Figure 5 the prior to run (left) graph shows the starting conditions of each tested implement while the right part of the graph depicts how the penetrometer readings changed after the run. Thus, Figure 5 focuses on the change of penetration resistance more than the starting conditions being constant. Moisture contents prior to runs were 7.2%, 6.7%, 9.1%, 8.2% and 8.3% for the Sumo Trio, Mzuri, Claydon, Seed Hawk and Rapid respectively which explain the different staring conditions. The implements which did show differences in penetration resistance in the soil bin experiment showed similar behavior in the field experiment with Sumo Trio reducing and Claydon increasing the deeper (150-200 mm) penetrometer readings (data not shown).

Table 3. Mean values for bulk density and penetration resistance (150-200 mm) for Claydon (top table) and Sumo Trio (bottom table) prior and after the runs

Soil Property	Prior to run	After the run
Bulk density (Mg m^{-3})	1.54 a	1.54 a
Penetration (MPa)	1.75 a	1.92 b

Soil Property	Prior to run	After the run
Bulk density (Mg m^{-3})	1.47 a	1.48 a
Penetration (MPa)	2.58 a	2.18 b

* Means with the same letter are not significantly different ($p>0.05$) and apply to rows

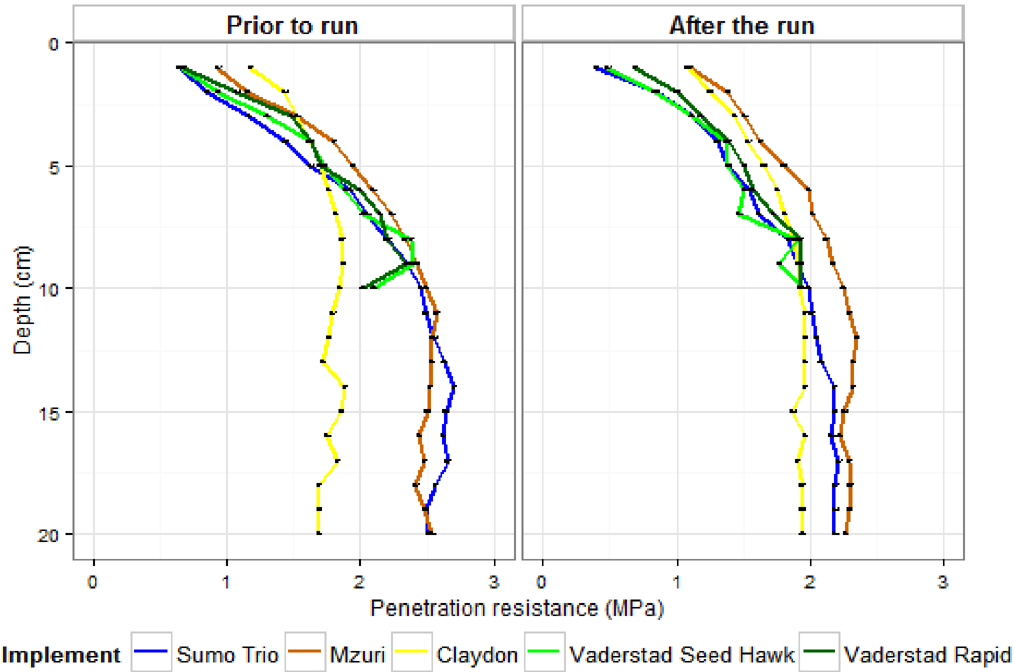

Figure 5. Penetrometer readings with standard error of the means, prior and after the experimental runs in the soil bin

4. Discussion

The soil bin experiment can help us understand tillage energy requirements and the effect of implements on soil condition. The different tillage implements led to significant differences in draft requirements, and hence the results show the importance of tillage implement selection and adjustment to achieve the desired tillage outcome in terms of soil loosening, soil fragmentation and soil compaction. Winged tines increased the loosing effectiveness by reducing the aspect ratio. In a similar way, low rake angles reduced the draft requirements when implements worked at the same depth. There are numerous studies supporting the fact that minimizing the draft force is not the main issue: reducing the magnitude of the specific draft (draft force / cross sectional area of disturbance) is much more significant, as it is a better indicator of overall soil loosing efficiency while cultivating. It is encouraging that the effects of different tillage implements on soil condition were similar between field and soil bin experiments.

In the field experiment, the tillage treatment work rate, it's implement geometry, and working depth had effects on the predicted cost of fuel requirements and labour. The initial field results (not reported here) suggest that the Mzuri and the two Vaderstad implements used less fuel per hectare. This is supported by the draft measurements for the individual implements in the soil bin study. The soil bin experiment highlighted that among the deeper working implements (Sumo Trio, Mzuri and Claydon), the least demanding one in terms of energy was the Mzuri. In the absence of crop yield differences, energy requirements together with cost are assumed to play a role in a farmer's decision when choosing tillage equipment. As shown here, implement geometry namely width and rake angle can affect soil properties and change draft requirements.

As mentioned in the introduction, the experiments in the field in Northamptonshire tried to identify: how do commercially-available conservation tillage systems in the UK affect: 1) the growth and yield, 2) the soil condition and 3) the profitability of winter wheat and oilseed rape grown in rotation. The overall research indicated that the tillage treatments had no significant ($p > 0.05$) effect on wheat and oilseed rape yields for 2013-14 and 2014-15 (data not shown). An important factor that confounded the yield was the blackgrass infestation which occurred when the wheat was planted in the clay field, but was highly variable and did not show a consistent difference between treatments (data not shown).

5. Conclusions

In general, draft force increased as the density of the soil and the working depth increased. Very shallow tillage systems were associated with the lowest width, area and volume of soil disturbance and the lowest fuel requirements. The Mzuri tine gave lower values for the horizontal draft and for the fuel requirements for the same working depth, when compared to the Claydon tine. The soil disturbance differences between Mzuri and Claydon were related to the different geometry of the implements. Mzuri used a winged tine of 100 mm width with a 45° rake angle, while Claydon used a non-winged tine of 20 mm width and 70° rake angle. The winged tine increases the effectiveness of the tillage operation, by reducing the specific draft compared to the other systems. The Sumo Trio had the lowest specific draft of all the implements even though it was working deeper (200 mm). This is again attributed to the widest winged tine (215 mm) and to the lower rake angle of 15° causing soil to fail in a crescent like failure (upwards and forwards). All the tested implements resulted in a crescent failure and none of them caused sideways compaction. In addition, the fuel requirement went up for the Sumo Trio (3.4×10^{-4} for 200 mm depth) but still it performed quite well when compared for example to Claydon's fuel requirement (2.9×10^{-4} for 150 mm depth) which was lower by 5×10^{-5} ls^{-1}. No implement effect on soil bulk density was apparent both in the soil bin and field experiment. The penetrometer readings in the soil bin experiment followed similar patterns with those observed in the field experiment, with the Claydon increasing and Sumo Trio decreasing the deeper (150-200 mm) penetrometer resistance values. Fuel requirement was a function of the horizontal draught of the different implements, which was in agreement with the field experiment, resulting in lower predicted costs for some treatments. Although the literature suggests that crop yields from shallow tillage systems can be lower than with deeper cultivations, the first two years of the field study showed no significant effect on crop yields. As a consequence (and in the absence of yield differences), tillage energy requirements and costs reduction are considered crucial factors when comparing similar tillage systems. Possible future research and more detailed tests using Cranfield University's unique soil bin facility will shed light into the performance of different combinations of tines (with and without wings) and their widths, rake angles and working depths for sustainable soil management.

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