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Evaluation of Traditional and Conservation Tillage Methods for Cereal Cultivation in Central Italy

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In Central Italy, traditional soil tillage for winter cereal cultivation is based on medium depth ploughing followed by soil surface harrowing. Such method may cause undesired effects on soil fertility, surface erosion and energy costs. These negative effects can be reduced by shifting to conservation tillage methods, such as reduced tillage, minimum tillage and no-tillage. We performed tests aimed at evaluating the energy demands of eight implements used for tillage and sowing. We measured: working speed, time and working capacity, P.T.O. speed and torque, tractor wheel slip, traction force, fuel consumption and energy demands. The study was conducted at the CREA-IT experimental farm (Monterotondo, Rome), on soil classified as silty-clay according to USDA textural classification, common in Central Italy. Starting from the data of each tested implement, we evaluated four traditional tillage methods (CT1: four-furrow plough, rotary harrow, seeder; CT2: four-furrow plough, disk harrow, seeder; CT3: four-furrow plough, combined seeder; CT4: subsoiler, combined seeder) and four conservation methods (RT1: subsoiler, disk harrow, seeder; RT2: combined cultivator, seeder; MT: disk harrow, seeder; NT: pneumatic drill for direct seeding). All tests were performed using a 205 kW instrumented tractor. The results showed that total energy required by traditional methods was 725, 704, 670 and 537 MJ ha^{-1} for CT1, CT2, CT3 and CT4, respectively. The conservation methods needed lower energy inputs: 440, 307, 286 and 77 MJ ha^{-1} for RT1, RT2, MT and NT, respectively. As expected, the no-tillage method (NT) gave the best results in terms of energy savings. Finally, we suggested and discussed an integrated tillage system aimed at optimizing tillage for winter cereals in silty-clay soils.

1. Introduction

Traditional tillage systems, which include intensive and continuous soil tillage, may create undesirable effects, such as excessive energy requirements (Perfect et al., 1997; Fanigliulo et al., 2016) and costs (Fedrizzi et al., 2015), deterioration of soil structure, loss of nutrients in the deeper layers and of organic matter in the upper depths, thus increasing soil erosion (De Laune and Sij, 2012). Such negative effects can be avoided by replacing traditional tillage with suitable soil conservation tillage operations (El Titi, 2003) that reduce fuel consumption (Kichler et al., 2011) by decreasing the number of passes and the working depth. This is possible by utilizing one pass implements consisting of tools with right geometry and optimum working width (Godwin, 2007). Soil management practices, including regular crop rotations and maintenance of permanent soil cover (leaving at least 30% of the soil surface covered by plant residues), aim to reduce erosion, soil surface disturbance and compaction, preserving its native fertility (Tebrügge and Düring, 1999). In Central Italy, the most common tillage method applied to silty-clay soils for preparing the seedbed for winter cereals, is based on chopping (or rarely burning) the residues from the previous crop, followed by ploughing (0.30-0.40 m) to bury or incorporate the residues (Valzano et al., 1997; Pezzi, 2005). The operations were followed by harrowing, generally using either a rotary harrow or a disk harrow. Sometimes, as an alternative, ploughing is directly followed by sowing with a combined seeder (a machine with work tools operated by the tractor's P.T.O. and a pneumatic seed drill), which simultaneously provides surface tillage. The Agricultural Machinery Test Center at CREA-IT, performed tests on implements commonly used in traditional and conservation soil tillage and sowing methods. The implements included a four-furrow reversible plough, a rotary harrow and a combined seeder (considered traditional tillage implements) and an offset disk harrow, a subsoiler, a

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combined cultivator (conservation implements). Two pneumatic seed drills were employed in sowing operations in untilled and tilled soil. For each implement, a comprehensive picture of its dynamic-energetic performances was obtained (Pochi et al., 2013). The data for different implements were combined to represent eight cultivation methods (four traditional and four conservation), for sowing winter cereals. The objective of this paper was to compare each one of the studied tillage methods to the traditional method (CT1), and to obtain the knowledge of the related energy requirements.

2. Materials and Methods

2.1 Test site

The tests were carried out at the experimental farm of CREA-IT in Monterotondo (Rome, Italy; 42°5'51.26"N; 12°37'3.52"E; 24 m a.s.l.), on a flat (< 1% slope), untilled soil. This is classified as silty-clay (clay 543 g kg^{-1}, silt 434 g kg^{-1}, sand 23 g kg^{-1}) in the USDA soil classification system (USDA, 2014). Before each test, the following characteristics and parameters were defined to a depth of 0.40 m: water content, dry bulk density and resistance to penetration (Cone Index). The first two parameters were determined on ten soil samples of 100 cm^3 randomly extracted in the test field, by means of a manual soil coring tube, and dried in an oven at 105°C until constant mass. The Cone Index was determined, according to the ASAE standard S313.3 (ASAE, 2004), by means of a hand-operated penetrologger.

2.2 Implements tested and tractor used

The data of the tested implements are shown in Table 1. The implements (Figure 1) were operated by a 4WD tractor with a nominal power of 205 kW and total mass of 11000 kg. The power take off (P.T.O.) speed was 104.7 rad s^{-1} corresponding to an engine speed of 206.7 rad s^{-1}. Before the tests, the engine performance was verified in tests at the dynamometric brake that provided the updated characteristic curves of the engine.

Table 1: Specifications and technical data of the tested implements.

Implement type	m.u.	Plough	Rotary harrow	Pneumatic seed drill	Combined seeder	Combined cultivator	Subsoiler	Disk harrow	Direct seeding
Working tools	-	knife ploughshare, mouldboard	vertical blades, roller	vertical hoe opener	vertical blades	straight shanks, notched disks	straight shanks	notched/plain concave disks	single disk openers
Tools number	-	2x4	40	40	24+24	5+10 (Ø 610)	7	18+18	33
Tools spacing	mm	1150	245	125	245/125	950 shanks 480 disks	430	230	180
Total mass	kg	2560	2910	1930	2680	1730	1670	3465	6380

Figure 1: Tested implements. (1) four-furrow reversible plough, (2) rotary harrow, (3) pneumatic seed drill, (4) combined seeder, (5) subsoiler, (6) combined cultivator, (7) offset disk harrow, (8) pneumatic seed drill.

2.3 Operating parameters

The main quality and operative parameters of each tractor-implement coupling were determined in tests performed in accordance with the protocol for the investigation of performance of soil tillage machines, proposed by ENAMA (National Farm Mechanisation Body). According to these protocol, we measured the following parameters: width and depth of tillage; working speed, time and capacity; P.T.O. torque, speed and

power; traction force and power required for tillage; tractor wheel slip and corresponding power losses; fuel consumption and energy requirements per surface unit and per volume unit of moved soil (ENAMA, 2003).
After field tests, the tractor was connected to the dynamometric brake. Here, with the aim of reproducing the work conditions, the engine speed was adjusted on the same values adopted at the start of each test. Then, by means of the brake, the load at the engine was increased until the corresponding speed reduction reached the average values calculated during the work in field. Such a simulation aimed at evaluating the total torque and power provided by the engine and the corresponding fuel consumption (Pochi and Fanigliulo, 2010). Multiplying the total engine power (W_t, kW) by the actual working time (T_o, h ha^{-1}), allows calculation of the energy required per surface unit (Eq(1)), expressed in MJ ha^{-1}.

$$E_{ha} = 3.6 \cdot W_t \cdot T_o \tag{1}$$

Dividing E_{ha} by the working depth (P, m), gives (Eq(2)) the energy per unit of volume of tilled soil (E_{vol}), expressed in MJ 10^{-3} m^{-3}.

$$E_{vol} = \frac{E_{ha}}{10} \cdot P \tag{2}$$

The power losses for slip (W_s, kW) was estimated on the basis of the tractor self-dislocation power (W_{sd}, kW), by means of the relation presented in Eq(3).

$$W_s = s \cdot (W_{tr} + W_{pto} + W_{sd}) \tag{3}$$

where s is the tractor wheel slip, W_{tr} is the traction power and W_{pto} is the P.T.O. power.
In addition to power loss due to wheel slip, we also considered the power lost in the transmission of motion between engine and wheels (W_{trs}, kW), that differently affects the final energy balance depending on the machines used. They were not directly measured, but estimated adopting a transmission efficiency coefficient equal to 0.87, as indicated in literature for 4WD tractors (Biondi, 1999), with reference to the total engine power (W_t, kW).

2.4 Measurement equipment and data acquisition system

The instrumental system used for no active implements consisted of the following sensors: (1) a digital encoder, mounted on the axis of one of the tractor's rear drive wheel, allowing slip calculation during work; (2) two mono-axial load cells, having a full-scale of 98 kN (plough, subsoiler and combined cultivator tests) and 49 kN (rotary harrow, disk harrow, seed drills and combined seeder tests), respectively, for the measurement of traction force. The load cell is lodged in a drawbar connecting the tractor-implement system to a traction vehicle. The tractor-implement system is pulled, with gear in "neutral", by the traction vehicle at the same working speed recorded during the actual operation. Each traction test is made both with the implement working and raised, to calculate the net traction force as the difference between the two observed values. In addition, two torque meters were applied at the tractor's P.T.O. for the tests with rotary harrow and combined seeder (full scale: 3 kNm) and with the pneumatic seed drills (full scale: 500 Nm). These sensors measure the P.T.O. torque and speed during the work, required for P.T.O. power calculation. The signals from the sensors were recorded at a scan rate of 10 Hz and collected by an integrated data acquisition system based on two units, a field unit and a support unit (Fanigliulo et al., 2004), fully assembled at CREA-IT. The field unit is represented by the tractor (equipped with the above sensors, a computer with a PCI card for real time data acquisition and a LCD control monitor) and a photocell system, placed in the test field, indicating the length of the test basis and the start and stop of the data acquisition. The support unit is represented by a van equipped as a mobile laboratory. The PC of the support unit communicates with the field unit's PC by means of a radio-modem system, exchanging data and allowing to monitor, in real time, the behaviour of critical parameters and the efficiency of the transducers and of the data acquisition system. Preliminary tests were conducted to find the most correct adjustment of each tractor-implement system considering soil characteristics and workability. Working speed and depth were set according to the values commonly adopted in central Italy for each implement type. The plough was set in the in-furrow configuration. Three replications were made for every test. All measurements were referred to a 100 m reference distance.

2.5 Tillage treatments

The energy requirements data of each implement were collected for eight tillage methods. Four traditional methods were considered. The first method (CT1) consisted of a main tillage at medium depth, performed by a four-furrow reversible plough, followed by a soil refinement with a single pass of a rotary harrow. In the second method, CT2, the refinement after the ploughing was obtained by double pass of the offset disk harrow. The third method (CT3) consisted of a single pass of the combined seeder after ploughing. In the fourth traditional method (CT4), the plough was replaced by the subsoiler, followed by a single pass of the combined seeder. As to conservation methods, two were based on reduced tillage: the first method (RT1) consisted of a main tillage at medium depth with subsoiler, followed by refinement with a single pass of the offset disk harrow; the second (RT2) consisted of a single pass with the combined cultivator. The third conservation method was minimum tillage (MT) and which was two passes of the offset disk harrow. The last was a no-tillage method (NT) with cereal direct sowing by means of a pneumatic seed drill. The above mentioned dynamic and energetic variables can be referenced to a surface unit area (hectare), providing information on both each single implement and on the combination of implements forming each tillage method. The values of actual and operative working time, fuel consumption per hectare, energy requirement per hectare and energy losses for slip and transmission, used for each tillage method resulted as the sum of values measured for each of the implements employed. As to the slip, for each implement, the average values of each replication were used to calculate power and energy losses.

2.6 Statistical analysis

The probability of statistically significant differences among tillage methods in terms of dynamic and energetic parameters was assessed by one-way analysis of variance (ANOVA) and subsequent multiple pair-wise comparisons, performed by the HSD-Tukey's test. The significance of comparisons (α = 0.05) among treatments was determined after the Bonferroni correction. The statistical procedure was computed with the software R (R Core Team, 2013).

3. Results and discussion

Soil characteristics were similar in all tests, with the following mean values: moisture content equal to 19.5 % (± 0.5 Standard Deviation); dry bulk density equal to 1445 kg m^{-3} (± 172 SD); Cone Index equal to 1.74 MPa (± 0.12 SD). The tests provided data that accurately describe the performance of each machine and, properly combined, of the eight tillage methods. Table 2 shows the mean values resulting from the measurements of the main dynamic and energetic parameters referred to each tractor-implement coupling. Considering the single operations, Table 2 shows that the highest requirement of energy per surface unit area (MJ ha^{-1}) was observed for the plough and the rotary harrow (mostly due to low working speed).

Table 2: Average and standard deviation values of the dynamic and energetic parameters referred to the tested machines.

Implement State of the soil	m.u.	A untilled	B ploughed	C ploughed	D ploughed	E tilled	F untilled	G untilled	H untilled	I untilled
Actual work. speed	km h^{-1}	4.31	3.36	6.33	5.03	7.94	5.12	5.40	7.46	7.21
SD		*0.06*	*0.03*	*0.04*	*0.05*	*0.04*	*0.07*	*0.07*	*0.01*	*0.01*
Working width	m	2.50	5.03	3.92	3.00	5.00	2.45	3.00	3.92	5.94
SD		*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.01*	*0.02*
Working depth	m	0.41	0.15	0.19	0.10	0.04	0.37	0.35	0.16	0.04
SD		*0.02*	*0.01*	*0.02*	*0.01*	*0.01*	*0.01*	*0.02*	*0.01*	*0.01*
Actual working time	h ha^{-1}	0.94	0.60	0.42	0.67	0.25	0.81	0.65	0.36	0.24
SD		*0.01*	*0.01*	*0.002*	*0.01*	*0.001*	*0.01*	*0.01*	*0.001*	*0.003*
Operative work. time	h ha^{-1}	1.44	0.69	0.69	0.89	0.38	1.10	0.81	0.63	0.37
SD		*0.01*	*0.01*	*0.002*	*0.01*	*0.001*	*0.01*	*0.01*	*0.001*	*0.003*
Fuel consumption	kg ha^{-1}	29.4	20.2	10.3	20.2	3.3	21.7	20.2	9.6	5.3
SD		*1.57*	*0.38*	*0.31*	*1.04*	*0.11*	*0.05*	*0.53*	*0.15*	*0.36*
Traction force	kN	60.5	11.9	19.0	19.1	9.7	43.5	52.7	30.0	16.5
SD		*6.94*	*2.00*	*1.96*	*3.48*	*1.50*	*4.40*	*4.79*	*1.21*	*2.26*
Traction power	kW	73.4	11.1	33.4	26.7	21.4	61.8	78.9	62.1	33.1
SD		*8.08*	*2.47*	*4.30*	*5.00*	*3.56*	*6.53*	*7.32*	*3.05*	*2.87*
P.T.O. speed	rad s^{-1}	-	107.2	-	108.1	97.2	-	-	-	104.4
SD		-	*0.60*	-	*1.12*	*0.42*	-	-	-	*0.27*
Torque at the P.T.O.	Nm	-	860	-	659	36	-	-	-	70
SD		-	*51.40*	-	*33.79*	*0.47*	-	-	-	*1.0*
Power at the P.T.O.	kW	-	92.2	-	71.3	3.6	-	-	-	7.3
SD		-	*5.36*	-	*4.92*	*0.79*	-	-	-	*0.80*
Energy/surface unit	MJ ha^{-1}	403	284	131	267	39	267	270	124	77
SD		*3.30*	*1.00*	*4.52*	*3.44*	*1.20*	*3.15*	*5.88*	*2.34*	*1.43*
Energy/volume unit	MJ10^{-3}m^{-3}	99	191	68	268	-	73	76	77	-
SD		*4.94*	*2.89*	*3.01*	*3.82*	-	*2.47*	*4.02*	*3.66*	-
Tractor wheel slip	%	28.9	3.6	7.7	5.9	3.1	14.8	11.0	8.8	1.4
SD		*1.43*	*0.29*	*0.48*	*0.55*	*0.29*	*1.03*	*0.99*	*0.19*	*0.19*
Energy losses	MJ ha^{-1}	125	38	21	39	*6*	*62*	*55*	*23*	*10*
SD		*5.81*	*0.22*	*0.62*	*0.36*	*0.08*	*0.97*	*2.70*	*0.42*	*0.34*

Legend: Implement: A: reversible plough; B: rotary harrow; C: offset disk harrow; D: combined seeder; E: pneumatic seed drill; F: combined cultivator; G: subsoiler; H: offset disk harrow; I: pneumatic seed drill for direct seeding.

The energy required per volume unit of moved soil (MJ 10^{-3} m^{-3}) was higher for the combined seeder and the rotary harrow (due to the higher power required by the tractor P.T.O.). The highest values of fuel consumption per surface unit area (kg ha^{-1}) were observed for the plough, due to high operative working time, and subsoiler. The average traction force required for tillage ranged from a minimum of 11.9 kN for the rotary harrow, to a maximum of 60.5 kN for the four-furrow plough, depending on the high variability of working width and depth. The width varied from 2.45 to 5.03 m as the depth varied from 0.10 to 0.41 m. The highest values of tractor wheel slip were obtained by the plough and the combined cultivator, due to the high working depth. All described parameters play a role in the energy balance of the system and can be managed with the aim of reducing power requirements and losses, also for optimizing the coupling between tractor and implement (McLaughlin et al., 2008). Based on the values reported in Table 2, it has been possible to quantify the overall values resulting for each of the traditional and conservation tillage methods described above. Statistical analysis showed significant effects in each of the examined parameters. Consequently, it was possible to perform, for each parameter, the Tukey-HSD post-hoc test and to separate the averages. These results are shown in Table 3.

Table 3: Comparison of the total amount of the main dynamic and energetic parameters for each method. The averages followed by the same letter do not differ significantly according to HSD-Tukey's test.

Parameters	m.u.	CT1	CT2	CT3	CT4	RT1	RT2	MT	NT
Actual working time	h ha^{-1}	1.79 b	2.05 a	1.61 c	1.32 d	1.33 d	1.07 e	0.97 f	0.24 g
Operative working time	h ha^{-1}	2.51 b	3.20 a	2.33 c	1.69 e	1.88 d	1.49 g	1.63 f	0.37 h
Fuel consumption	kg ha^{-1}	52.9 a	53.4 a	49.6 a	40.4 b	33.9 c	25.0 d	22.5 d	5.3 e
Energy requirement	MJ ha^{-1}	725 a	704 a	670 b	537 c	440 d	307 e	286 e	77 f
Average tractor slip	%	11.9 b	11.8 b	17.4 a	8.5 cd	7.3 cd	9.0 c	6.9 d	1.4 e
Energy losses	MJ ha^{-1}	168 a	172 a	163 a	94 b	82 bc	67 c	52 d	10 e

Figure 2 shows the percent variations in energy requirements, referred to the values reported in Table 3, obtainable moving towards to less intensive methods, compared to CT1, assumed as the reference traditional tillage method. Figure 2 shows also that NT requires about 90% less energy than CT1. Moreover, MT and RT2 allow the highest savings of working time and energy. CT2 shows an energy requirement lower than CT1, despite the fact that this method requires three operations. This is explained by the lower energy demand for disc harrow compared to other implements. The CT4 method has a high slip value as it combines the work of two high-slip implements.

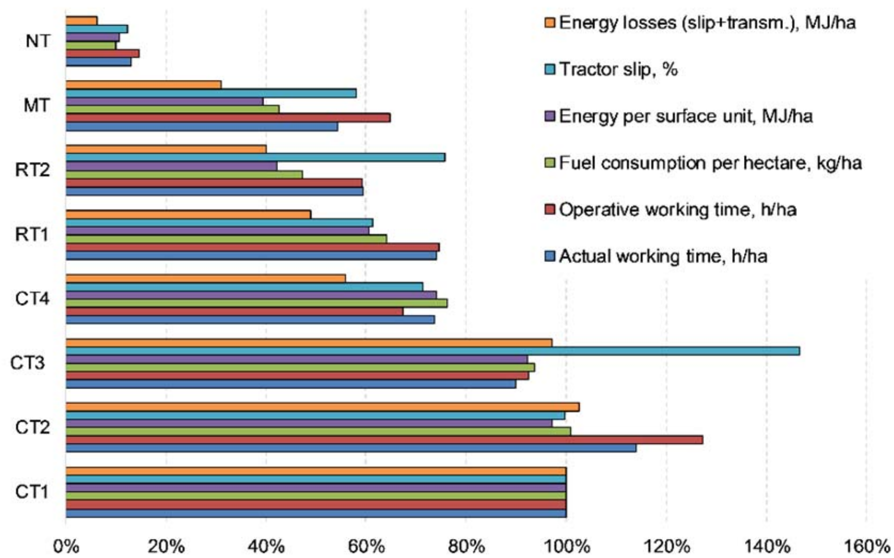

Figure 2: Percent reduction of the main dynamic and energetic parameters from traditional to conservation tillage methods (the method "CT1 = plough + rotary harrow + seed drill" was assumed as the reference method).

4. Conclusions

The spreading of conservation tillage methods can contribute to reduce the energy requirements on farming activities, keeping productivity at satisfactory levels. The correct application of each tillage method depends on soil characteristics, which determine the choice of the most suitable implements and, therefore, the effects on energy and labour savings. The study, carried out on compact soils, which are commonly found in Central Italy, showed that three methods, NT, MT and RT2, allow to achieve significant energy savings. Medium and long-term observations are needed to achieve comprehensive information on the effects of long application of conservation methods on compact soils. Potential problems linked to cereal cultivation, such as difficult weed management and reduced deep-water infiltration, could be prevented by alternating different conservation methods over the years. In the hypothesis of a three-years period, the application of the RT2 method during the first year would allow, in a single pass of the combined cultivator, to disrupt compacted subsurface layers and to incorporate crop residues and biomass into the soil. In the second year, a no-tillage method could be applied, improving energy savings. Finally, in the third year, the minimum tillage (MT) would contribute to bury excessive biomass and residues left after the no-tillage method, and to reduce the application of agrochemicals. In conclusion, according to the needs and the characteristics of each farm, the choice of the most suitable cultivation method has the potential to significantly reduce the level of the interventions on soil and, consequently, the incidence of the related costs.

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