Effects of six primary tillage implements on energy inputs and residue cover in Central Italy

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Abstract

The use of agricultural machinery represents the main aspect contributing to the total energy input in the agricultural system. The study evaluated the energy requirements and the work quality of two conventional (three-furrow plough and spading machine) and of four conservation implements (rotary harrow, subsoiler, disk harrow, combined cultivator) for medium-deep primary tillage in a silty-clay soil, widespread in Central Italy. The tests were carried out with the aim of selecting the most energy-efficient implement. Working speed, force of traction, fuel consumption and energy demands were measured, using a 205 kW instrumented tractor. Cloddiness and roughness of the tilled soil, biomass coverage index and burying degree were evaluated. The conservation tillage implements gave the best results in fuel consumption and energy requirements respect to the conventional implements, with energy savings up to 86% in the case of disk harrow. The rotary harrow showed intermediate values and the best soil refinement. Among the conservation implements, the disk harrow showed the best performance on biomass coverage index (43.8%), while the combined cultivator showed the highest value of biomass burying (87.8%) and the best performance on fuel consumption per hour (25.8 kg h^{-1}).

Introduction

Primary tillage represents the major soil manipulation and the required implements can be utilised both in conventional and conservation tillage systems. Conventional tillage systems may produce undesirable effects, such as worsening of soil structure due to compaction, loss of nutrients in deeper layers and of organic matter in upper depths (Lal, 2004), increasing soil erosion caused by wind or by surface runoff (De Laune and Sij, 2012), excessive energy requirements and costs (Perfect *et al.*, 1997). These effects can be reduced, especially in compact clay soil, by replacing conventional implements with soil conservation tillage equipment, to reduce the number of passes, the working depth, the fuel consumption and the energy input (Raper and Bergtold, 2007; Fanigliulo and Pochi, 2011), by using one pass implements with wider working width and equipped with suitable geometry working tools (Godwin, 2007).

The availability of data on energy requirement, fuel consumption and force of traction of tillage implements is the main factor to determine the power class of the required tractor (Moitzi *et al.*, 2013; Pochi *et al.*, 2013) and to estimate the effects of different implements in relation to the quality of the tillage in specific soil types, in terms of depth of tillage, soil cloddiness and crop residue or biomass cover (Raper *et al.*, 2000; Chen *et al.*, 2004; Sahu and Raheman, 2006).

Studies on conventional and reduced tillage in scientific literature have provided a large amount of information on methods, labour and energy in different soil conditions (Al Suhaibani and Al-Janobi, 1997; Arvidsson *et al.*, 2004; Wandkar *et al.*, 2013), but only a few gave a comprehensive picture of the energy request and of the quality of tillage for the most common methods performing primary tillage in compact soils. McLaughlin *et al.* (2008) studied energy inputs and draft for eight different primary tillage implements in a clay loam soil, but no data on tillage quality parameters were provided.

Pezzi (2005) evaluated the performance of a mouldboard plough and two power take-off (PTO)-driven implements (spading machine and rotary chisel) along with two soil depths and two forward speeds, on a silty-clay soil. The PTO-driven implements gave lower fuel consumption, higher hourly capacity and energy efficiency of the tractor-tillage implement linkage.

We performed tests to compare the energy demand and the work quality of two conventional and of four conservation implements for medium-deep primary tillage in a silty-clay, untilled soil, widespread in Central Italy.

The objective of this paper was to provide, for each tested implement, a complete picture of its dynamic-energetic data with the aim of choosing the best coupling tractor-implement and the energy-efficient implement, in relation to its capacity to maintain adequate biomass coverage on the soil surface.

Materials and methods

In Table 1 are summarised the main technical data of the six tested implements. The tests were carried out on a flat soil, classified as a silty-clay (clay 54.3, silt 43.4, sand 2.3%) according to the United States Department of Agriculture (USDA) soil classification system (USDA, 2014), at the experimental farm of *Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria, Unità di ricerca per l'ingegneria agraria* (CREA-ING) in Monterotondo (Rome, 42°5'51.26" N, 12°37'3.52" E; 24 m a.s.l.). Before the tests, in ten random points for each test plot, the following parameters were defined in the layer corresponding to the working depth: moisture content and dry bulk density, cone index (CI) (ASAE, 2004), soil coverage index by crop residues. The first two parameters were calculated from soil samples of 100 cm³ extracted by means of a soil coring tube. The CI was measured by means of a digital penetrometer. The coverage index was determined by detecting and quantifying the percentage of soil covered by residues by means of image analysis.

The implements were operated by a 4WD tractor with nominal power of 205 kW and total mass of 11,000 kg. Before the tests, the engine performance was verified at the dynamometric brake.

According to the protocol proposed by *Ente Nazionale per la Meccanizzazione Agricola* (ENAMA, 2003), we reported the following dynamic-energetic parameters: width and depth of tillage; working speed, time and capacity; force of traction required by the tillage; fuel consumption; energy requirements; tractor's slip.

After the field tests, the average working conditions of fuel delivery and measured engine speed during the tillage, were reproduced by means of the dynamometric brake. This simulation aimed at evaluating the total power provided by the engine (Pochi and Fanigliulo, 2010).

The quality of tillage was evaluated through the determination of the following parameters, measured in five random points on each test plot. Soil refinement index (by means of hand-operated sieving), soil surface roughness index and soil raising (by means of a laser profilemeter); then we calculated the biomass burying degree (Römkens and Wang, 1986; Sandri *et al.*, 1998; Peruzzi *et al.*, 1999).

The instrumental system consisted of the following sensors. A digital encoder mounted on the axis of a rear wheel of the tractor for the measurements of speed and slip. Two mono-axial load cell, with full scale of 98 kN (plough, subsoiler and combined cultivator tests) and 49 kN (rotary and disk harrow tests), lodged in a suitable drawbar. The load cells directly measure the force of traction generated when the tractor-implement system, with gearbox in neutral, is pulled by a dynamometric vehicle.

The transducers' signals were collected (scan rate: 10 Hz) and recorded by an integrated data acquisition system, fully assembled at CREA-ING (Fanigliulo *et al.*, 2004).

Preliminary tests were conducted with the aim of finding the most correct adjustment of each tractor-implement system. Each test was replicated three times. The experiment was arranged according to a completely randomised block design, based on the random selection of 100 m long plots in the experimental field.

A Shapiro-Wilk normality test was performed on the data, revealing that they did not follow normal distribution. Therefore, the likelihood of statistically significant differences among implements, in terms of dynamic-energetic parameters and working quality indices, was assessed by a non-parametric test, the Kruskal-Wallis test for multiple comparisons corrected with the Bonferroni factor. A P-value of less than 0.05 was considered significant in the tests. The statistical procedures were computed with the software R (R Core Team, 2013).

Results and discussion

Soil characteristics before tillage

The soil characteristics were similar in all tests, showing the following mean values: moisture content equal to 20.5% [±0.6 standard deviation (SD)]; dry bulk density equal to 1401 kg m⁻³ (±159 SD); CI equal to 1.94 MPa (±0.17 SD); soil coverage index equal to 90.2% (±3.8 SD).

Dynamic-energetic parameters

The results of the Kruskal-Wallis test, reported in Table 2, indicate statistically significant differences in each of the examined variables. Table 2 shows that the highest demand of energy (MJ ha⁻¹) and fuel consumption (kg ha⁻¹) were observed for the plough and the spading machine, due to the higher tillage depth and to the consequent greater power required by the tractor. The differences among these parameters were significant for all the studied implements.

The energy required per soil volume unit (kJ m⁻³) and the fuel consumption per hour (kg h⁻¹) resulted higher for conventional implements. Rotary harrow showed values statistically similar to those of the spading machine for the energy required per soil volume unit. As to fuel consumption per hour (kg h⁻¹), the combined cultivator, the disk harrow and the subsoiler belonged to the same group and showed reduced fuel consumption. The slip values were proportional to the traction force values and were statistically different for each implement.

Table 1. Main characteristics of the tested implements and operating data.

Implement type	Three-furrow plough	Spading machine	Rotary harrow	Combined cultivator	Subsoiler	Offset disk harrow
Manufacturer	Nardi	Selvatici	Sicma	Nardi	Maschio	Nardi
Working tools	Knife ploughshare, mouldboard	Straight spades	Vertical blades, packer roller	Straight shanks, notched disks, roller	Straight shanks	Notched and plain concave disks
Tools number	3×2	12	40	5+10 (Ø 610 mm)	7	18+18
Tools spacing, mm	1200	250	245	950 shanks 480 disks	450	230
Total mass, kg	1971	1900	2910	1730	2355	3465
Working width, m	1.70	2.80	5.03	2.45	3.04	3.92
Tillage depth, m	0.36	0.25	0.12	0.34	0.27	0.11
Working speed, m s⁻¹	1.22	0.73	0.96	1.29	1.79	2.10

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The conservation tillage implements gave the best results in fuel consumption and energy requirements respect to the conventional implements, with energy savings up to 86% in the case of disk harrow. The wide ranges of values observed in force of traction, energy requirements and fuel consumption indicate that energy savings can be obtained by selecting energy-efficient tillage implements, capable to satisfy specific agronomic requirements in terms of cloddiness and biomass coverage, in conservation systems, or in terms of biomass complete burying, typical of conventional tillage methods.

Working quality parameters

Table 2 also shows the indices describing the interaction between soil and implements. The spading machine produced the highest soil raising (0.21 m), which makes difficult and expensive the subsequent soil surface refinement for seedbed preparation. The combined cultivator showed the lowest value (0.05 m) that does not differ significantly from the two harrows and the subsoiler. The conservation implements, however, left a fairly levelled soil (with values ranging from 0.05 m to 0.09 m) due to the levelling action of the rear rollers.

All implements showed significant differences in soil surface roughness. The best performance was obtained by the rotary harrow (1.86 cm), thanks to the soil compacting action of the rear packer roller. The soil surface refinement index reached similar high values with the rotary harrow (0.86, thanks to the counter-rotating action of the working tools) and with the disk harrow (0.80, due to the high total mass and working speed) compared to all implements. Combined cultivator and subsoiler did not differ significantly.

As regards the biomass soil coverage index after the tillage, the best performance (*i.e.*, high presence) was obtained by the disk harrow (43.8%), though in tilling with high working speed and maximum angle of inclination of the disks (22.5°). Even the spading machine (30.7%) and the subsoiler (27.6%) reached similar percentage, while the combined cultivator showed very low values (10.5%), as a consequence of soil reversing and mixing action with biomass operated by the two gangs of disk. This trend was confirmed by the evaluation of the biomass burying degree, which was obviously higher for the three-furrow plough and the combined cultivator (100 and 87.8% respectively), due to the high working depth, while for the disk harrow was equal to 56.2%.

Conclusions

Field tests were conducted to compare the main dynamic-energetic parameters and soil tillage quality indices of six conventional and conservation implements for primary soil tillage. The tests gave detailed evaluations of the performances of the tested machinery, useful for comparing them.

The conservation implements showed positive performances, in terms of reduced demand of labour and fuel consumption, lower energy requirements and best soil surface levelling and refinement.

It is appropriate to differentiate the use of the tested implements in relation to the soil texture and workability, and to the agronomic benefits provided by the different working tools. For shallow tillage in light soils is commonly preferred to use a disk harrow, compared to the rotary harrow, because it allows high labour, fuel and energy savings, and a good soil surface refinement. Moreover, in conservation systems, the disk harrow left an adequate biomass cover on the soil surface. In the studied conditions on compact soil, where it is requested a medium-deep tillage, it seems appropriate to use the combined cultivator, which can reduce the labour, fuel and energy demand. This machine, when compared with the subsoiler and the disk harrow, provides, in a single pass, significant agronomic benefits (*i.e.*, deep vertical shatter, light superficial soil reversing and mixing with biomass, soil refining and levelling, greater biomass burying degree and a good soil refinement index).

Table 2. Means values of main dynamic-energetic parameters and quality tillage indices, and group of statistical differences. Means followed by at least one common letter does not differ significantly according to the Kruskal-Wallis test for multiple comparisons corrected with the Bonferroni factor (P<0.05).

	Three-furrow plough			Spading machine			Rotary harrow			Combined cultivator			Subsoiler			Offset disk harrow		
	Means	SD	Group	Means	SD	Group	Means	SD	Group	Means	SD	Group	Means	SD	Group	Means	SD	Group
Operative working time, h ha^{-1}	2.06	0.01	a	1.52	0.01	b	0.68	0.0	e	1.29	0.02	c	0.73	0.01	d	0.62	0.0	f
Traction force, kN	67.7	0.2	a	−13.7	1.1	e	6.4	0.5	de	42.5	0.7	ab	33.9	2.0	bc	31.9	0.4	cd
Fuel consumption per hour, kg h^{-1}	44.9	0.3	a	34.7	0.7	ab	32.3	1.0	bc	25.8	0.6	d	28.5	2.3	cd	28.1	0.3	d
Fuel consumption per hectare, kg ha^{-1}	61.0	0.2	a	47.7	1.1	b	18.8	0.7	d	23.1	0.9	c	15.3	1.5	e	10.0	0.1	f
Energy per surface unit, MJ ha^{-1}	940.1	1.0	a	595.1	12.4	b	260.6	4.1	d	295.9	12.1	c	199.7	22.9	e	130.4	1.6	f
Energy per soil volume unit, kJ m^{-3}	262.5	7.5	a	239.2	14.9	ab	218.1	18.6	bc	86.5	8.5	de	74.6	10.1	e	118.3	18.1	cd
Tractor slip, %	21.9	1.1	a	−9.5	0.8	f	1.0	0.1	e	12.1	1.1	b	6.4	0.6	d	7.8	0.6	c
Soil raising after the tillage, m	0.12	0.03	ab	0.21	0.04	a	0.07	0.02	bc	0.05	0.01	c	0.09	0.03	abc	0.06	0.01	bc
Surface roughness index, cm	7.39	0.12	a	5.84	0.14	b	1.86	0.10	f	4.66	0.10	d	4.98	0.14	c	4.08	0.07	e
Soil refinement index	0.17	0.02	e	0.55	0.03	de	0.86	0.03	a	0.69	0.03	bc	0.63	0.03	cd	0.80	0.03	ab
Biomass burying degree, %	100	0	a	68.5	2.4	c	77.0	7.1	b	87.8	2.2	a	70.2	3.2	bc	56.2	2.8	d

SD, standard deviation.

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