AN ANALYSIS OF EIGHT TILLAGE METHODS IN A SILTY-CLAY SOIL: PROPOSAL FOR FLEXIBLE TILLAGE CYCLES
/
ANALISI DI OTTO METODI DI LAVORAZIONE DI TERRENI LIMO-ARGILLOSI: PROPOSTA DI CICLI FLESSIBILI DI LAVORAZIONE

Fanigliulo R., Biocca M., Pochi D.
Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria (CREA), Centro di ricerca Ingegneria e Trasformazioni agroalimentari (Research Centre for Engineering and Agro-Food Processing), Monterotondo (Rome), Italy
Tel: +39 0690675215; E-mail: marcello.biocca@crea.gov.it

Keywords: *conventional tillage, conservation tillage, energy requirements, multivariate statistics, soil quality indexes.*

ABSTRACT

Soil preparation based on ploughing is a conventional method commonly adopted for cereal cultivation in silty-clay soil. Replacing this method with conservation tillage was the subject of this study based on the evaluation of eight implements used in conventional and conservative tillage. By differently combining the implements, we hypothesized eight methods and assessed the overall energy balance and quality of work for each method. Basing on test results, we proposed an approach to the choice of proper tillage methods, aiming at integrating the benefits of conventional and conservative tillage methods.

RIASSUNTO

La preparazione del terreno basata sull'aratura è un metodo convenzionale comunemente adottato per la coltivazione di cereali in terreni limoso-argillosi. La sostituzione di questo metodo con le lavorazioni conservative è stato l'oggetto di questo studio basato sulla valutazione di otto attrezzature usate nelle lavorazioni convenzionali e conservative dei terreni. Combinando tali attrezzi, abbiamo ipotizzato otto metodi e valutato il bilancio energetico e la qualità del lavoro per ciascun metodo. Sulla base dei risultati dei test, abbiamo proposto un approccio alla scelta corretta dei metodi di lavorazione, con l'obiettivo di integrare i vantaggi dei metodi di lavorazione tradizionali con quelli conservativi.

INTRODUCTION

The meanings of the definitions "conventional tillage" and "conservation tillage" imply that such categories cannot be uniquely defined. In other words, each type of intervention on the soil should be assigned to one category or the other depending on the specific type of soil and environmental conditions. On the other hand, the soil tillage methods considered conventional for a given environment are dictated by the experience gained over the centuries and, therefore, can be identified as the most suitable to preserve the characteristics of the soil. From this point of view, there should be a virtual identification between conventional and conservation techniques. Such identification is often interrupted within intensive farming that progressively eliminated practices such as crop rotation and organic fertilization, maintaining traditional (conventional) soil tillage methods and causing, during the years, the occurrence of several problems involving both the aspects of energy requirements and soil fertility.

For instance, the most common conventional method adopted in silty-clay soils of Central Italy to prepare the seedbed for winter cereals, is based on the chopping (rarely the burning) of the residues from previous crop, on a medium depth ploughing (0.20 - 0.30 m aimed at burying the residues, and on the harrowing of the upper layer, by means of a rotary harrow, a disk harrow or a combined seeder (a machine with working tools operated by the tractor's P.T.O. (Power Take-Off) and a pneumatic seed drill).

Unwanted effects of such technique can be: excessive energy requirements (*Fanigliulo et al., 2016*) and related costs (*Fedrizzi et al., 2015*), worsening of soil structure due to compaction, loss of nutrients in deeper layers, mineralization of organic matter in upper layers, increasing soil erosion caused by wind and runoff (*De Laune and Sij, 2012*). Such effects can be limited, in some cases, by adopting conservation methods (*Lal et al., 2007; Fanigliulo et al., 2017*) that contribute to energy savings and to preserving soil fertility through the reduction of number of passes and of working depth, by using one pass combined machines characterized by wide working width (5-7 m) and working tools with geometry (*Godwin, 2007*). Combining these points with the maintenance of a surface coverage of at least 30% and with crop rotation allows reducing soil erosion, surface disturbance and compaction, preserving natural fertility.

Among conservation methods, we can find interventions with different intensity in terms of working depth. The main approaches are (*ASABE Standard, 2005*): reduced tillage, aimed at soil lifting and shattering, reducing the compaction of both shallow and deep layers, without inversion (e.g. by means of subsoilers or combined cultivators) leaving 15-30% residue cover on soil surface (*Townsend et al., 2016*); minimum tillage, in which the level of soil manipulation is reduced to the least compatible with crop production (e.g. with use of disk harrows); no tillage, that entails direct sowing into the previous crop stubble with no prior tillage. The comparison among conservation methods was the subject of many studies, especially focused on grain yield, greenhouse gas emissions and economic profitability, as few data were provided on tillage quality parameters. Other studies regarded the measurements of fuel consumption, force of traction and power required by tillage implements (*Pochi et al., 2013*) under various soil conditions. *McLaughlin et al.* (2008) measured the force of traction and energy inputs of eight tillage implements in a clay loam soil. The results showed that significant energy savings can be realized through the selection of proper tillage methods and tractor-implement coupling.

CREA carried out tests with a series of implements, commonly used for tillage and sowing, collecting, for each of them, the data of energy requirements and tillage quality. Combining the implements and relative data, allowed to hypothesize four conventional (CONT) and four conservation (CT) methods and to assess their relative energy balances and quality of work with the purpose of their comparison, assuming CONT1 as a reference. Lastly, the data of measurements have been used to develop a proposal for an integrated tillage system capable to adapt, time by time, to the actual needs dictated by the conditions of the soil.

MATERIALS AND METHODS

The tests were carried out in the farm of CREA in Monterotondo (Rome, Italy; 42°5'51.26"N; 12°37'3.52"E; 24 m a.s.l.), on flat surface plots (< 1% slope) and on untilled soil classified as silty-clay (clay 543 g kg^{-1}, silt 434 g kg^{-1}, sand 23 g kg^{-1}) according to the USDA soil classification system (USDA, 2014). Before the tests, in ten random points for each plot, the following parameters were measured at a depth of 0.40 m (Table 1): water content, dry bulk density, penetration resistance (cone index) and soil biomass coverage index (SCI). The first two parameters were determined on soil samples of 100 cm^3 extracted by means of a manual soil coring tube (Eijkelkamp) and dried in oven at 105°C up to constant mass. Cone index (c.i.) was determined according to the ASAE Standard S313.3 (ASABE Standards, 2004), by means of a hand-operated Penetrologger (Eijkelkamp), measuring the force needed for the penetration in the untilled soil. It provides a detailed vertical profile of soil strength compaction. Then, the SCI was determined by analysing digital pictures of square sections of the ground surface with an area of 1 m^2. A graphic editor programme (Adobe Photoshop), was used to quantify the percentage of soil areas covered by residues.

Table 1

Average values of the physical-mechanical characteristics of the soil

Implement type	M.U.	Four furrow plough	Rotary harrow	Pneumatic seed drill	Combined seeder	Combined cultivator	Subsoiler	Disk harrow	Seed drill for direct seeding
Water content	%	19.4	18.8	22.7	17.3	16.7	22.5	19.5	15.0
Dry bulk density	kg m^{-3}	1460	1490	1410	1260	1600	1400	1470	1200
Average cone index	MPa	1.90	-	-	-	2.10	1.70	2.25	-

The main technical data of the tested implements are reported in Table 2. The selected implements are commonly used in soil tillage aimed at cereals cultivation. The tests with the seed drills were conducted with filled hoppers (seeding rate: 190 kg ha^{-1}). All implements were operated by a 4WD tractor (Case IH MX 270) with a nominal power of 205 kW and total mass of 11,000 kg. The P.T.O. speed was 104.7 rad s^{-1} corresponding to an engine speed of 206.7 rad s^{-1}. All tests were performed with diesel fuel in compliance with the EN 590 (*EC Standard, 2013*). It was always provided by the same supplier. Consequently, its quality was assumed to be constant, with a Low Heating Value of 42.7 MJ kg^{-1}.

The following parameters were measured: width and depth of tillage; speed, time and capacity of work; P.T.O. torque, speed and resulting power; force of traction and resulting power; tractor's slip and corresponding power losses; fuel consumption and energy required per surface unit and per volume unit of tilled soil.

Table 2

Main technical data of the tested implements

Implement type	Four furrow plough	Rotary harrow	Pneumatic seed drill	Combined seeder	Combined cultivator	Subsoiler	Disk harrow	Seed drill for direct seeding
Working tools	skim coulter, knife ploughshare, mouldboard	vertical blades, packer roller	vertical hoe opener	vertical blades, hoe opener	straight shanks, notched disks, roller	straight shanks	notched and plain concave disks	single disk openers, depth band
Tools number	2x4	40	40	24+24	5 + 10 (Ø 610 mm)	7	18+18	33
Lateral 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

Before field tests, the tractor's engine performances were verified at the dynamometric brake that provided the updated characteristic curves of the engine. After field tests, the tractor was newly connected to the dynamometric brake used to reproduce the working conditions: the engine speed was set on the same values adopted at the start of each test. Then, the engine load was increased in such a way that the resulting engine speed reductions were equal to the average speeds measured during the field test. This method provided the average values of total torque and power required to the engine and the corresponding fuel consumption (*Pochi and Fanigliulo, 2010*). Multiplying the total power (W_t, kW) by the actual working time (T_o, h ha^{-1}), will provide the energy required per surface unit area:

$$E_{ha} = 3.6\ W_t\ T_o \quad [\text{MJ ha}^{-1}] \tag{1}$$

Dividing E_{ha} by the working depth (P, m), will give the energy per unit of volume of tilled soil (E_{vol}), expressed in:

$$E_{vol} = \frac{E_{ha}}{10 \cdot P} \quad [\text{MJ } 10^{-3}\text{ m}^{-3}] \tag{2}$$

Knowing the power required by tractor self-dislocation (W_{sd}, kW), it is possible to assess the power losses for slip (W_s, kW), by means of the relation (3):

$$W_s = s\ (W_{tr} + W_{pto} + W_{sd}) \quad [\text{kW}] \tag{3}$$

where s is the tractor slip, W_{tr} is the traction power and W_{pto} is the P.T.O. power.

In addition to the aforementioned components or power, the total engine power also includes the power dissipated in the transmission of motion to the wheels (W_{trs}, kW) and to the power take-off. It was assumed the transmission efficiency equal to 0.87.

As to the quality of tillage, the evaluation was based on the determination of: crop residues/biomass burying degree (*BBD*), soil surface roughness index (*SRI*), roughness reduction degree (*RRD*), clod-breaking index (*CBI*), cloddiness reduction degree (*CRD*) and seedbed quality index (*SQI*). They were measured in ten random points in each test.

The *BBD* is calculated from the values of the SCI determined before and after the implement tillage by means of the equation 4.

$$BBD = 100\frac{SCI_{us} - SCI_{ts}}{SCI_{us}} \quad [\%] \tag{4}$$

where SCI_{us} is the soil coverage index of untilled soil and SCI_{ts} is the index of tilled soil.

The SRI and the working depth were determined immediately after the passage of the implement, by means of a profile-meter. The sensor was a laser (Leica Geosystem Disto, Switzerland) moving on a horizontal rail placed perpendicularly to the tilled strip. Running along the rail, every 10 mm the sensor measures its distance from the ground, drawing the surface profile of the ground. A personal computer collects and processes the data. The surface profile is detected in the same point before and after the passage of each implement, obtaining the roughness indexes σ_{r1} and σ_{r2} (standard deviations of the detected heights series). In addition, were also calculated the average levels of surface before and after the tillage, and of the bottom of the tilled layer (after manually removing all the ground).

The RRD resulting from the secondary tillage is calculated as follows:

$$RRD = 100\ \frac{\sigma_{r1} - \sigma_{r2}}{\sigma_{r1}} \quad [\%] \tag{5}$$

The cloddiness was measured digging a 0.5 m side square trench to the working depth. The soil aggregates were removed from the trench avoiding any manipulation and left to dry for at least 20 min. Then they were divided into six size classes by means of hand-operated standard sieves and weighed. An index (I_{ai}), ranging from 0 for the biggest class to 1 for the smallest class, was attributed to each class. The cloddiness results as the percent of each size class mass referred to total mass of the sample. From the cloddiness, the CBI (I_a) is calculated as follows:

$$I_a = \sum_{i=1}^{6} \frac{M_i \cdot I_{ai}}{M_t} \quad [\%] \tag{6}$$

where: $M_i \cdot I_{ai}$ is the product of the index assigned to a clod size class and the mass (kg) of ground belonging to the same class; M_t is the total mass of the sample (kg).

Comparing the CBI values observed before (I_{a1}) and after (I_{a2}) the secondary tillage, will provide the CRD by means of the equation 7.

$$CRD = 100 \frac{I_{a2} - I_{a1}}{I_{a2}} \quad [\%] \tag{7}$$

The quality of the seedbed is assessed basing on the cloddiness values observed after the passage of the implements. It is described by the SQI, by means of the Eq. (8):

$$SQI = \frac{M_{\emptyset \leq 10}}{M_{\emptyset \geq 10}} \tag{8}$$

where: $M_{\emptyset \leq 10}$ is the mass of the clods with diameter less or equal to 10 mm and $M_{\emptyset > 10}$ is the mass of the clods with a diameter over 10 mm (kg).

An instrumental system was used in the tests. A digital encoder, mounted on a rear wheel of the tractor measured wheel revolutions on a given distance, allowing calculation of travel speed under tractor self-displacement, working conditions and slip. Two mono-axial load cells, with full-scale respectively of 98 kN (tests with plough, subsoiler and combined cultivator) and 49 kN (tests with rotary harrow, disk harrow, seed drill and combined seeder), measuring the force of traction as follows. In traction tests, the load cell is lodged in a drawbar properly designed to protect it from transversal stresses and connecting a traction vehicle to the tractor-implement system. This is pulled, with gear in “neutral”, at the same working speed set in the actual tillage with the same implement: this test executed with implement working will provide the gross traction force. Repeating the test with implement raised will provide the force required by the self-displacement of the tractor-implement system. The net fraction force will result as the difference between said values. Two torque meters were alternatively applied at the tractor’s P.T.O. (full scale 3 kNm and 500 Nm respectively) depending on the characteristics of tested implements. Torque meters 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 on the tractor (field unit). By means of a radio-modem, the data collected during the tests are transmitted to a support unit (a van equipped as a mobile laboratory) where real time test monitoring and data processing are made.

Working speeds and depths were set considering soil physical-mechanical characteristics and tillage possibility (according to water content). The plough was set in the in-furrow configuration. Three replications were made for each tractor-implement coupling. The experiment was carried out following a randomized distribution of the plots treated with each tillage method. The plots were 100 m long and 20 m wide.

Eight tillage methods (Table 3) were considered in this study, including: four conventional tillage (CONT), two reduced tillage (RT), a minimum tillage one (MT) and a no-tillage one (NT). The parameters of field performances were measured for each implement and referred to the surface unit area (hectare). Consequently, the values of actual and operative working time, fuel consumption, energy requirement and energy losses for slip for each tillage method, resulted as the sum of the values measured for each of the implements used in it. As to the slip, for each implement, the average values of each replication were used to calculate power and energy losses. Regarding the tillage quality indexes (SCI, BBD, SRI, CBI and SQI), for each tillage method were considered the values observed after the intervention of the last implement. In the case of no-tillage, the quality indexes were assumed to be identical to those resulting from disk harrowing on untilled soil, given the similarity between the two operations.

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

A Principal Component Analysis (PCA) was conducted using the software PAST (*Hammer et al., 2001*), to observe the ordering of treatments and to indirectly analyse which variable best contributes to differentiate treatments. Before the PCA, all variables were standardized (i.e., normalized to mean 0 and variance 1) to avoid problems caused by different units of measurement.

Table 3

Description of the eight tillage methods hypothesized

Type	Method	Operations	Implements
Conventional	CONT1	main tillage + seedbed preparation in a single pass	four-furrow reversible plough + rotary harrow + pneumatic seed drill
	CONT2	main tillage + seedbed preparation in a double pass	four-furrow reversible plough + offset disk harrow + pneumatic seed drill
	CONT3	main tillage + sowing with contemporary seedbed preparation	four-furrow reversible plough + combined seeder
	CONT4	main tillage + sowing with contemporary seedbed preparation	subsoiler + combined seeder
Conservation	RT1	main tillage + seedbed preparation in a single pass	subsoiler + offset disk harrow + pneumatic seed drill
	RT2	combined tillage in a single pass	combined cultivator + pneumatic seed drill
	MT	minimum tillage in two passes	offset disk harrow + pneumatic seed drill
	NT	no-tillage and direct sowing on untilled soil	pneumatic seed drill for direct seeding

RESULTS

Table 4 shows the average values of the parameter measured for each tractor-implement coupling. The highest requirements of energy per surface unit (MJ ha^{-1}) were observed for plough and rotary harrow, implements using considerable power at rather low speed. 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.).

Table 4

Average values of the parameters describing the technical performances of the tested machines

Implement	M.U.	A	B	C	D	E	F	G	H	I
Soil conditions		untilled	ploughed	ploughed	ploughed	refined	untilled	untilled	untilled	untilled
Actual working speed	km h^{-1}	4.31	3.36	6.33	5.03	7.94	5.12	5.40	7.46	7.21
Working width	m	2.50	5.03	3.92	3.00	5.00	2.45	3.00	3.92	5.94
Working depth	m	0.41	0.15	0.19	0.10	0.04	0.37	0.35	0.16	0.04
Actual working time	h ha^{-1}	0.94	0.60	0.42	0.67	0.25	0.81	0.65	0.36	0.24
Operative working time	h ha^{-1}	1.44	0.69	0.69	0.89	0.38	1.10	0.81	0.63	0.37
Operative working capacity	ha h^{-1}	0.69	1.44	1.45	1.13	2.63	0.91	1.24	1.60	2.72
Fuel consumption per hour	kg h^{-1}	31.2	33.8	24.4	30.1	13.1	26.7	31.0	26.6	22.3
Fuel consumption per hectare	kg ha^{-1}	29.4	20.2	10.3	20.2	3.3	21.7	20.2	9.6	5.3
Force of traction	kN	60.5	11.9	19.0	19.1	9.7	43.5	52.7	30.0	16.5
Traction power	kW	73.4	11.1	33.4	26.7	21.4	61.8	78.9	62.1	33.1
P.T.O. speed	rad s^{-1}	-	107.2	-	108.2	97.0	-	-	-	104.4
Torque at the P.T.O.	Nm	-	860	-	635	38	-	-	-	70
Power at the P.T.O.	kW	-	92.2	-	68.5	3.7	-	-	-	7.3
Total engine power	kW	119	132.0	85.9	110.6	43.1	91.3	115.0	95.3	91.3
Energy per surface unit	MJ ha^{-1}	403	284	131	267	39	267	270	124	77
Energy per volume unit	MJ 10^{-3}m^{-3}	99	191	68	268	-	73	76	77	-
Tractor slip	%	28.9	3.6	7.7	5.9	3.1	14.8	11.0	8.8	1.4
Energy losses	MJ ha^{-1}	125	38	21	39	6	62	55	23	10

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 sowing.

The plough showed the highest fuel consumption for surface unit (kg ha^{-1}), due to high operative working time. The higher values of fuel consumption per hour were obtained for the rotary harrow (33.8 kg h^{-1}), the plough (31.2 kg h^{-1}) and subsoiler (31.0 kg h^{-1}). The average force of traction 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. Such parameters can vary depending on the conditions of use of each tractor-implement coupling, which, within certain limits, can be managed with the aim of reducing power requirements and losses.

As to the quality of tillage, Table 5 shows the values of the parameters describing the effects of the implements on the soil. The best BBD was provided by the plough (96.6%). Good performance was also provided by the combined cultivator (86.6%), with two ranks of disks with opposite angles, which determine effective reversing of the soil and its mixing with surface biomass residues. The best SRI was produced by the combined seeder, the rotary harrow and the combined cultivator, due to the compacting action of the rear rollers. The best performances on CBI were provided by combined seeder and rotary harrow. Even for this parameter, the result of the combined cultivator is worth mentioning, considering that it operates a deep vertical soil crushing and a good soil breaking in a single pass. As for the SCI, a value higher than 15% was observed only with the offset disk harrow on untilled soil. Thus, the observed surface cover cannot be considered fully adequate for preventing soil erosion. Statistical analysis showed significant variations of soil quality values caused by the implements. Consequently, it was possible to perform, for each parameter, the Tukey's HSD post-hoc test and to separate the averages (i.e. the averages with the same letter are not significantly different) (Table 5).

Table 5

Average values of work quality parameters for each implement and results the Tukey's HSD test (the values followed by the same letter are not significantly different)

Implement type	**u.m.**	**Reversible plough**	**Rotary harrow**	**Disk harrow**	**Combined seeder**	**Combined cultivator**	**Subsoiler**	**Disk harrow**
Soil condition		untilled	ploughed	ploughed	ploughed	untilled	untilled	untilled
Coverage index	%	3.31 c	0.28 d	2.07 cd	0.55 d	11.57 b	10.74 b	17.08 a
Biomass burying degree	%	96.59 a	91.67 a	33.03 b	79.14 a	86.56 a	75.93 a	82.92 a
Surface roughness index	-	6.70 a	2.41 e	4.86 b	1.70 f	3.60 d	3.90 c	3.80 c
Roughness reduction degree	%	-	63.7 b	32.8 c	81.1 a	-	-	-
Clod-breaking index	-	0.35 d	0.81 a	0.60 c	0.84 a	0.66 b	0.61 c	0.64 bc
Cloddiness reduction degree	%	-	56.3 a	55.0 a	37.0 b	-	-	-
Seedbed quality index	-	0.20 g	0.87 c	0.43 f	1.08 b	0.82 d	0.75 e	1.47 a

Basing on the values reported in Table 4, we obtained the overall values of the parameter that describe the energy requirements for the eight composed tillage methods. Also in this case the results underwent ANOVA and subsequent Tukey's HSD test to separate the significant differences (Table 6).

Table 6

Technical performances of the eight tillage methods and results of Tukey's HSD test. The averages followed by the same letter do not differ significantly

Parameters	**u.m.**	**CONT1**	**CONT2**	**CONT3**	**CONT4**	**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 1 shows the percent variations in energy requirements obtainable moving towards more CT, compared with CONT1. NT requires about 90% less energy. Moreover, MT and RT2 allow the highest savings of working time.

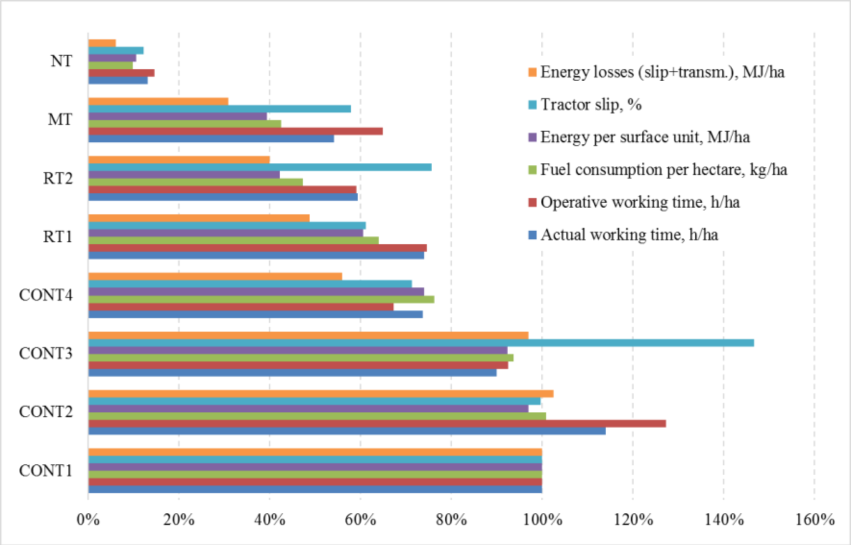

Fig. 1 - Percent reduction of the main technical performance from traditional to more conservation tillage methods compared with CONT1 (CONT2, CONT3, CONT4, RT1, RT2, MT, NT = tillage methods)

The PCA regarded both the energy parameters of Table 6 and the tillage quality indexes of Table 5 assuming, for each tillage method, the same indexes observed for the implements involved. A bi-plot graph (Figure 2) shows the results of the PCA, providing a comprehensive picture of the relationship among parameters and tillage methods.

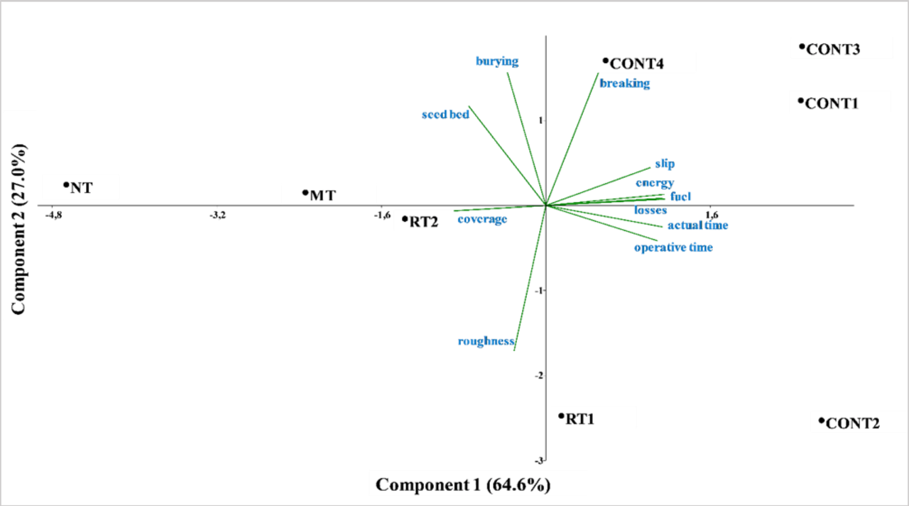

Fig. 2 - Biplot graph with the results provided by PCA

Energy = energy requirement (MJ ha^{-1}); fuel = fuel consumption (kg ha^{-1}); actual time = actual working time (h ha^{-1}); operative time = operative working time (h ha^{-1}); losses = energy losses for slip and transmission (MJ ha^{-1}); burying = BBD (%); roughness = SRI; seedbed = SQI; coverage = SCI (%); breaking = CBI.
CONT1, CONT2, CONT3, CONT4, RT1, RT2, MT, NT = tillage methods

The first two principal components (PC) explained 91.6% of the total variance (64.6% for PC 1 and 27.0% for PC 2). PC 1 was responsible for the separation between conventional and RT methods: this was especially evident for CONT1, CONT2 and CONT3 versus MT and NT, while CONT4, RT1 and RT2 were intermediate. NT was the most distant from all other methods. As to PC 2, the visible separation between CONT2 and RT1, compared to CONT1, CONT3 and CONT4 can be related to tillage quality aspects.

The Table 7 shows the PCA loading values, which define the discriminatory power of each variable in the principal component 1 and 2 and its position on the diagram. For instance, the PCA indicates that NT is characterized by low working times, fuel consumption, energy requirement and energy losses. These parameters are highly related to the conventional methods, especially CONT1, CONT2 and CONT3 (i.e. the methods entailing the use of the plough), characterized by the highest energy and fuel requirements and operative and actual working times. RT1, RT2 and CONT4 seem more similar in terms of operative parameters, as they clearly differ for the quality of tillage: CONT4 provides a better seedbed than RT1 (especially in terms of roughness index); the position of RT2 in the diagram is intermediate, (evident with respect to PC2). The methods NT, MT and RT2, different in terms of operative parameters (see position with respect to PC1), are more similar in terms of tillage quality, providing a medium quality of seedbed, with energy saving compared to conventional methods. In this context, the combined cultivator (RT2) seems to be an efficient implement, offering reduced energy requirements and good agronomic performance.

Considering what is conventional or conservation and the environmental conditions of the tests subject of this work, the question is if an indefinite adoption of conservation tillage method is sustainable or not in order to preserve soil fertility. In a medium or long-term perspective, it seems probable that the indiscriminate application of RT, MT or NT methods in a silty-clay soil could negatively affect its fertility. The natural ground settling and the traffic of machines, would determine progressive loosing of structure and increasing soil compaction, accelerated by the lack of organic matter (confined, when present, in the surface layer). Consequently, the soil could gradually lose its nutrients and the capability to store water in depth, becoming asphyxiated and inhospitable to plants' roots. Such a process can have different duration depending on the type of tillage, resulting longer in the case of more energetic techniques (RT1 and RT2) involving deeper interventions that, anyway, beyond relatively limited energy savings, would not allow the organic matter to be incorporated into the soil and to express its beneficial action towards soil structure.

The occurrence of this process could be prevented through a less rigid approach to soil preparation, based on the alternation of different tillage methods. This would lead to the definition of flexible tillage cycles whose duration and constitution (the whole of the interventions on the ground) will depend on the specific environments (e.g.: pedological and climatic characteristics, slope), on the needs of the types of crop to be carried out, on the possibility/willingness to apply crop rotation, on the available types of machines. The criteria that will guide the decision through such factors should be as simple as possible: for example, they could be represented by a few, easily measurable parameters, capable to provide wide and useful information. Soil resistance to penetration and moisture are probably the most comprehensive parameters, requiring simple measurements. The moisture provides the first indications on soil practicability and the risk of damaging its structure. Consequently, the value of field capacity can be assumed as the reference moisture value (30 - 35% for silty-clay soils). In general, with moisture above the field capacity, any soil manipulation should be avoided, but in case of urgency, such as a delayed sowing following a rainy period, MT of NT techniques could represent solutions for seedbed preparation with low impact on the soil. Below the field capacity, the possibility of choosing the tillage method will certainly be wider, but still depend on other soil actual conditions (mostly the structure and the organic matter). The cone index (c.i.) could be a useful parameter to describe the status of the soil. The availability of the trend of the c.i. along the layer explored by the roots, rather than its average value, will increase the quality of information. The diagram of Figure 3 shows the trend of the c.i. at increasing depth (0 cm up to 40 cm), in a silty-clay soil used for the tests described above.

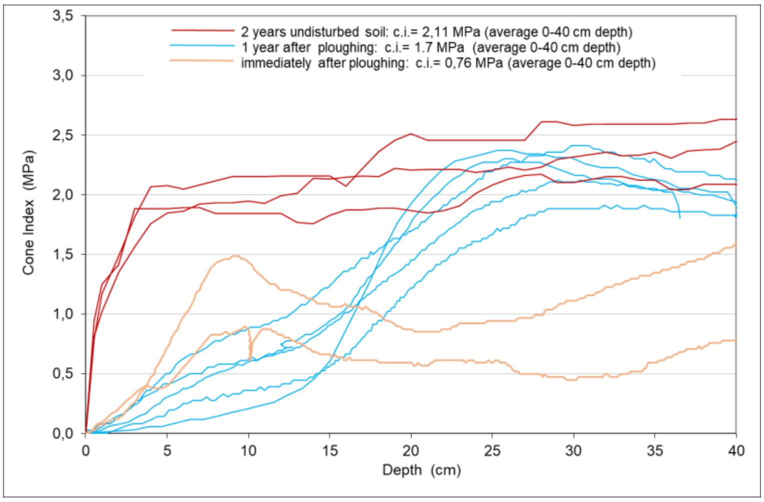

Fig. 3 - Different trend of the c.i. in the same silty-clay soil of the tests, depending on different types of intervention, in the 0 - 40 cm depth layer. All measurements were made with soil moisture between 22 and 24%

The measurements were made during prior CREA's test activities, by means of the described penetrologger. The curves of c.i. are grouped by colour and their shapes clearly differ by each other depending on the three operations to which they refer. After two years of spontaneous soil settling, without transit of machines, but characterized by rainy weather, the c.i. increases up to over 2 MPa in the first 5 cm of depth. Increasing the depth, the c.i. increases very slowly. The resulting average value is 2.2 MPa. This means a high level of compaction interests the whole layer involved in crop growth. One year after medium depth ploughing, the general shape of the related curves changes showing the maximum (2.0 - 2.3 MPa) at 25 - 30 cm of depth, in correspondence of the bottom of ploughing. In this case the c.i. increases, and in the 0 - 25 cm layer, the soil conditions remain good for the plants. The resulting average c.i. value is 1.7 MPa.

The measurements made immediately after the ploughing, show general lower c.i. values although the presence of big clods affects its trend that increase in the first 10 cm, then decreases and increases again, keeping however distant from the values of the previous cases. The average value is 0.76 MPa. The evolution of moisture and c.i. in the layer explored by the crop roots will suggest the most proper methods to be adopted with the purpose of maintaining the soil characteristics within a range of sustainability for the plants. At the same time, the resulting alternation of methods will allow reducing the overall energy requirements, compared to the continuous use of conventional tillage methods. The test results reported above can be a basis for formulating hypotheses of an integrated tillage system (based on annual cycles) for cereal cultivation and estimating the relative energy demands and the energy savings.

Table 8 shows an example of such an approach, showing the evolution of “cycle 1” followed by the beginning of “cycle 2”. The cycles have not predefined duration and alternation of methods, but evolve, adapting to the actual soil conditions described by c.i. and moisture. In the example, each cycle starts with a conventional technique (CONV1) and ends when the deterioration of soil conditions requires the conventional technique anew. The necessary information is provided by the average values of c.i., by the shape assumed by the curves of the c.i. vs. increasing depth, by the moisture, considering the reference values proposed for these parameters in Figure 3.

Table 8

Example of application of the integrated tillage system with reference to the silty-clay soil of the tests

Cycle	Year	Average cone index* (MPa)	Shape of cone index curves**	Moisture*** (%)	Tillage method adopted	Energy requirements (MJ ha^{-1})	Energy losses (MJ ha^{-1})
1	1	2.2	1	21	CONT	725	168
1	2	1.8	2	25	RT1	440	82
1	3	2.0	2	35	MT	286	52
1	4	2.2	2	34	MT	286	52
2	1	2.4	1	22	CONT	725	168

** the values reported must be compared with those reported in Figure 3 for that soil. ** The shapes of c.i. curves refer to the diagram of Figure 3, i.e.: “1”: long period of untilled soil, showing high c.i. values already from the first few centimetres, as described by the red curves; “2”: cone index gradually increasing to a maximum in correspondence of the tillage bottom at 25-30 cm, as described by the blue curves. “…n”: c.i. curves with different shapes can be observed depending on actual soil specific manipulations. *** The reference moisture value is the “field capacity”, around 35%*

“Cycle 1” starts with CONV1, based on the ploughing, needed because of the high soil compaction level in the surface layer (average cone index: 2.2 MPa; shape of c.i. curve: 1) and lasts 4 years during which the tillage methods vary depending on the evolution of soil moisture and compaction. The moisture does not represent an obstacle to the ploughing. This operation allows the burial of the surface residues, which contribute to restore the organic matter and the structure of the soil. In the 2nd year, the c.i. (average: 1.8; shape: 2) and moisture testify of still good conditions in the first 25 - 30 cm of soil, with probable presence of tillage bottom. RT1 seemed suitable to break it, limiting the risk of water stagnation. In the 3rd and 4th years, the compaction progressively increased, but the high humidity did not allow significant interventions on the soil. Its preparation for the sowing could be done by MT. At the end of the 4th year, the compaction reached the initial level, requiring starting a new cycle, “Cycle 2”, with CONV1, to restore conditions favourable to plants’ growth. The overall energy requirement and losses of the “cycle 1” over 4 years can be estimated by means of the data of Table 6 for each implement. The sum of the annual energy requirements reported in Table 8 is equal to 1,737 MJ ha^{-1}. Adopting CONV1 over 4 years would result in 2,900 MJ ha^{-1} energy requirements. The about 40% energy saving deriving from the comparison of these values is the consequence of lower overall energy requirements and of lower energy losses. The latter, calculated similarly to the requests, are equal to about 47% compared to CONV1 repeated over 4 years. The lower relative weight of the losses on the global energy balance testifies a progress toward the optimization of the energy use. The results of such calculations probably overestimate the actual achievable benefits, because indefinitely repeating CONV1 would keep the soil in such conditions that the requirements and losses of energy are lower than those used as reference for the comparison just above.

CONCLUSIONS

This study evaluated the effects of the adoption of eight tillage methods (four conventional, CONT, and four conservative CT methods) on energy requirements and tillage quality in a silty-clay soil. The results showed that CT (specially NT, MT and RT2) allow to achieve significant energy savings (up to 89%), working time reduction (up to 85%) and a satisfactory quality of tillage, compared to CONV1, thus widening the range of possible options for the farmers. Aiming at preserving the soil fertility, the commonly spread distinction between the meanings of CONT and CT gets less rigid, in relation to the characteristics and needs of the soil in question, as in the case of the silty-clay soil of this study. In general, conservation and conventional tillage methods (according to their common definition) should not be considered antithetical and adopting the former or the latter should not be the consequence of ideological, definitive choices, but should derive from the continuous evaluation of actual soil conditions, defining, each time, the more proper type of intervention. This results in the alternation of different tillage methods, according to flexible integrated tillage system, with variable duration, in which the benefits of both conventional and conservation methods are integrated in a compromise solution that should allow achieving an overall reduction of energy requirements compared to conventional methods and maintaining soil fertility at a satisfactory level during time.

REFERENCES

[1] De Laune P.B., Sij J.W., (2012), Impact of tillage on runoff in long term no-till wheat systems, *Soil & Tillage Research*, vol.124, pp.32-35;

[2] Fanigliulo R., Biocca M., Pochi, D. (2017), Evaluation of traditional and conservation tillage methods for cereal cultivation in central Italy, *Chemical Engineering Transactions*, vol.58, pp.211-216;

[3] Fanigliulo R., Biocca M., Pochi, D. (2016), Effects of six primary tillage implements on energy inputs and residue cover in Central Italy, *Journal of Agricultural Engineering*, vol.47 (3), pp.177-180;

[4] Fedrizzi M., Sperandio G., Guerrieri M., Pagano M., Costa C., Puri D., Fanigliulo R., Bazzoffi P., (2015), Economic competitiveness gap related to the application of the GAEC standards of cross-compliance on farms: Evaluation methodology, *Italian Journal of Agronomy*, vol.10(s1): 696p.;

[5] Godwin R.J., (2007), A review of the effect of implement geometry on soil failure and implement forces, *Soil & Tillage Research*, vol.97, pp.331-340;

[6] Hammer O., Harper D.A.T., Ryan P.D., (2001), PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica*, vol.4 (1), pp.1-9;

[7] Lal R., Reicosky D.C., Hanson J.D., (2007), Evolution of the plough over 10.000 years and the rationale for no-tillage farming, *Soil & Tillage Research*, vol.93, pp.1-12;

[8] McLaughlin N.B., Drury C.F., Reynolds W.D., Yang X.M., Li Y.X., Welacky T.W., Stewart G., (2008), Energy inputs for conservation and conventional primary tillage implements in a clay loam soil, *Transactions of the ASABE*, vol.51 (4), pp.1153-1163;

[9] Pochi D., Fanigliulo R., Pagano M., Grilli R., Fedrizzi M., Fornaciari L., (2013), Dynamic-energetic balance of agricultural tractors: active systems for the measurement of the power requirements in static tests and under field conditions, *Journal of Agricultural Engineering*, vol.44, pp.415-420;

[10] Pochi D., Fanigliulo R., (2010), Testing of soil tillage machinery, In: *Soil Engineering*, Vol. 20, “Soil Biology” Book Series. Springer, Berlin, Germany, pp.147-168, ISBN: 978-3-642-03680-4;

[11] R Core Team, (2013), R*: A language and environment for statistical computing. R Foundation for Statistical Computing*, Vienna, Austria. Available at: http://www.R-project.org/; accessed 10/6/2016;

[12] Townsend T.J., Ramsden S.J., Wilson P., (2016), How do we cultivate in England? Tillage practices in crop production system, *Soil Use and Management*, vol.32, pp.106-117;

[13] ***ASABE Standards, (2004), *S313.3: Soil Cone Penetrometer*, St. Joseph, Michigan, USA;

[14] ***ASABE Standards, (2005), EP291.3: *Terminology and Definition for Soil Tillage and Soil-Tool Relationships*, St. Joseph, Michigan, USA;

[15] ***EC Standard, (2013), EN 590: *Automotive Fuels-Diesel-Requirements and Test Methods*, Brussels.