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Effects of tillage systems on energy and carbon balance in north-eastern Italy

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Abstract

An energy analysis of three cropping systems with different intensities of soil tillage (conventional tillage, CT; ridge tillage, RT; no tillage, NT) was done in a loamy-silt soil (fulvi-calcaric Cambisol) at Legnaro, NE Italy (45°21′N, 11°58′E, 8 m above sea-level (a.s.l.), average rainfall 822 mm, average temperature 11.7°C). This and measurements of the evolution of the organic matter content in the soil also allowed the consequences to be evaluated in terms of CO_2 emissions.

The weighted average energy input per hectare was directly proportional to tillage intensity ($CT > RT > NT$). Compared with CT, total energy savings per hectare were 10% with RT and 32% with NT. Average energy costs per unit production were fairly similar (between 4.5 and $5\,MJ\,kg^{-1}$), with differences of 11%. The energy outputs per unit area were highest in CT for all crops, and lowest in NT. The RT outputs were on average more similar to CT (−12%). The output/input ratio tended to increase when soil tillage operations were reduced, and was 4.09, 4.18 and 4.57 for CT, RT and NT, respectively. As a consequence of fewer mechanical operations and a greater working capacity of the machines, there was lower fuel consumption and a consistently higher organic matter content in the soil with the conservation tillage methods.

These two effects result in less CO_2 emission into the atmosphere (at 0°C and pressure of 101.3–103 kPa) with respect to CT, of $1190\,m^3\,ha^{-1}\,year^{-1}$ in RT and $1553\,m^3\,ha^{-1}\,year^{-1}$ in NT. However, the effect owing to carbon sequestration as organic matter will decline to zero over a period of years.

Keywords: Plough tillage; Ridge tillage; No-tillage; Energy analysis; CO_2 emission

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1. Introduction

Energy use in agriculture can be divided into two components: (1) indirect consumption, necessary for production and delivery of farm inputs (fertilisers, pesticides, non-farm feedstuffs, etc.), machinery and equipment, etc.; (2) direct consumption of fuels and electrical energy in the various cropping operations. Energy consumption in Italian agriculture amounts to around 0.42×10^9 GJ year^{-1} (4–5% of national consumption), of which 55% relates to arable crops, 27% to the stock rearing sector and 16% to tree crops. The direct energy used is around 30–40% of total consumption (Biondi et al., 1989). Within each agricultural sector, direct energy costs are a small percentage of the Gross Saleable Production, varying from 1–3% for cereal farms practising monoculture to 4–6% for stock farms (the highest values implying the use of crop drying processes) (Pellizzi and Castelli, 1984; Pellizzi, 1992). The energy costs rise to 7–10% when indirect consumption is included (Biondi et al., 1989).

This analysis suggests that the problem of energy saving in agriculture is marginal in comparison with the more complex topic of the national energy balance. However, Italy imports more than 90% of its energy needs and a rational use of energy in the primary sector contributes towards reducing this dependence and also helps limit production costs. In addition, there are environmental implications. The sources of energy currently used for manufacturing farm inputs and running machinery are mainly of fossil origin. Their use causes a one-way transfer of carbon from the geosphere to the atmosphere in the form of CO_2, CH_4 and other greenhouse gases, contributing to the 'greenhouse effect' in the atmosphere.

It therefore important to analyse cropping systems in energy terms and to evaluate alternative solutions, especially for arable crops, which account for more than half of the primary sector energy consumption. From this point of view, it is worth while to study soil tillage methods as, in Italy, they account for around a third of the energy input on average (Bonari et al., 1992). They also influence the other production factors (Toderi and Bonari, 1986), which in turn contribute differently to total energy costs.

The standard cropping method in Italy (conventional tillage, CT) includes, with slight modifications depending on the crop and type of soil, mouldboard ploughing to a depth of 40 cm, plus a field cultivation, plus one or more harrowing passes and sowing. For the Po Valley farmers, a ploughing of 40 cm depth is usual and well accepted because it has been found that soils ploughed to this depth are able to store more water for the dry summer months and give more constant yields. The adoption of reduced tillage methods gives energy savings of between 32 and 57% in maize (Cantele and Zanin, 1983), and greater savings can be achieved by no-tillage (Sartori and Peruzzi, 1994; Tebrügge et al., 1994).

A change in soil tillage methods also causes a slow, but substantial modification to the soil physico-chemical characteristics (bulk density, porosity, infiltration, moisture content and temperature), which becomes apparent in the medium to long term. Large amounts of crop residues buried in a fairly shallow layer and the greater number of organisms capable of their breakdown result in an increase in the organic matter in the superficial soil layer (0–50 mm). Moreover, it is hypothesised (Kern and Johnson, 1993;

Alvarez et al., 1995) that the greater organic matter content in the soil is linked to less mineralisation and consequently less release of CO_2 into the atmosphere.

In this sense, until the soil reaches a new equilibrium, the positive effect of minimum tillage and no-tillage can be two-fold: reduction of CO_2 emissions owing to the use of less fossil energy and a greater accumulation of C in the soil as a consequence of reduced mineralisation of the organic matter (Balesdent et al., 1990; Reicosky and Lindstrom, 1993; Franzluebbers et al., 1994; Ismail et al., 1994).

Despite this, in recent years reduced tillage and no-tillage have spread relatively little in Italy, especially for winter cereals. It is currently estimated that no-tillage is practised on just over 30 000 ha for cereals and around 3000 ha for soybean, out of a total cultivated area of 2 520 000 ha and 335 000 ha, respectively (Sartori and Peruzzi, 1994).

In northern Italy, it is probable that unfavourable environmental conditions (intense spring rainfall associated with heavy or poorly structured soils), combined with the effects of no-tillage techniques on the soil (reduced temperature, increased moisture content, the presence of abundant crop residues) explain the lack of spread of these methods for spring-sown crops in comparison with other countries.

Often when the farmers change to no-tillage they notice a decreasing yield. The decrease in yield is generally economically greater than the savings obtainable by the reduction in tillage intensity; no-tillage management is also more difficult because of weed control and requires more technical knowledge (Borin et al., 1995). Furthermore, yields are not uniform (steady) and vary in relation to climatic conditions.

A method of minimum tillage which is more feasible in these circumstances is ridge tillage (RT), where the land is set out in permanent ridges. With this method the seeds and young plants do not suffer from problems of waterlogging (Fausey, 1990). The results obtained so far from Italian experiments on maize and soybean are fairly encouraging in terms of crop yields, although they have demonstrated some drawbacks in the achievement of optimal densities of establishment and the need for greater caution in weed control (Borin et al., 1992; Borin and Sartori, 1994).

This paper reports an energy analysis intended to evaluate the efficiency and rationale of soil tillage processes (conventional tillage, ridge tillage and no-tillage) in a long-term trial (eight crop cycles) of maize, winter cereals and soybean in rotation. In particular, the unitary and total energy consumption, crop energy yields and energy conversion efficiency have been analysed. The objective of the study also includes some evaluation of the potential immobilisation of CO_2 in the soil from the various tillage methods, specifically owing to the different use of agricultural machinery. With this aim, the change in soil organic matter content with the continued use of the three tillage methods and the need for fossil fuel in the production process were evaluated.

2. Methods

2.1. *Experiment design and management*

The experiment was carried out in NE Italy, at the Experimental Farm of the Faculty of Agricultural Science of Padova University, situated at Legnaro (45°21′N, 11°58′E) in

Table 1
Main physico-chemical characteristics of the soil (layer 0–400 mm) in the trial

Sand (0.02–2.0 mm) ($g\,g^{-1}$)	0.51
Silt (0.002–0.02 mm) ($g\,g^{-1}$)	0.33
Clay (< 0.002 mm) ($g\,g^{-1}$)	0.16
Total $CaCO_3$ ($g\,g^{-1}$)	0.271
Organic matter ($g\,g^{-1}$)	0.013
pH (H_2O)	7.8

a flat area of the Po Valley. The average temperatures reached maxima of around 26°C in the last 10 days of July and first 10 days of August, and minima of around −1°C in January. Average rainfall for the area is 822 mm $year^{-1}$ and is evenly distributed throughout the year.

The soil is a fulvi-calcaric Cambisol with loamy-silt texture, according to the US Department of Agriculture particle-size distribution limits. Table 1 gives the main physico-chemical characteristics.

The research, still in progress, compares three tillage systems in an experimental area of 4 ha with four replications per treatment. The area was cultivated with maize (*Zea mays* L. (1987, 1989, 1990 and 1993)), soybean (*Glycine max* (L.) *Merr.* (1988, 1991 and 1992 after barley)) and barley (*Hordeum vulgare* L. (1992)). Between 1987 and 1990 only two tillage systems were compared (conventional tillage, CT; ridge tillage, RT), and the third (no-tillage, NT) was added in 1991, splitting the CT plot. This must be taken into account when interpreting the results of the comparisons. The average area of the plots was approximately 0.3 ha and their lengths ranged from 160 to 250 m. The plots were completely randomised and placed side by side.

The CT treatment comprised a 0.4 m deep ploughing in autumn, chisel ploughing during winter and seedbed preparation of two passes with an S-shaped spring bar harrow immediately before sowing at a depth of around 0.1 m. During the maize and soybean growing seasons two row crop cultivations were utilised. The RT treatment consisted of setting out the land in permanent ridges, around 0.2 m high and 0.75 m apart. Cropping operations are reduced to a first operation (carried out at time of sowing) to clean the first 80–100 mm of the top of the ridge of previous crop residues; the second operation is reshaping of the ridge, generally after harvesting. The NT treatment consisted of direct sowing on untilled soil using drills which opened a furrow for seed deposition.

Before the introduction of NT in 1991, sowing was performed with conventional drills in both CT and RT. After this, a no-tillage grain drill was used for barley and soybean in NT and RT; a double disc no-tillage planter in NT and a specific precision planter in RT for maize (Borin and Sartori, 1995).

The number and type of mechanical operations carried out during the eight crop cycles are summarised in Table 2. The following points emerge:

1. the adoption of systems of reduced soil tillage (RT and NT) involves a reduction in the number of crop operations but, in general, more technologically advanced machines are required.
2. The greatest differences in the numbers of crop operations are in those of soil tillage

Table 2
Number and type of mechanical operations carried out during the eight seasons of cropping

Operation	Time	Tractor and implement	Number of operations								
			1987, M	1988, S	1989, M	1990, M	1991, S	1992, B	1992, S	1993, M	Total operations
Conventional tillage											
Ploughing	Winter	66 kW 4WD + mouldboard plough	1	1	1	1	1	1	1	1	8
Fertilising	Apr.	52 kW 4WD + fertiliser distributor	1	1	1	2	1	0	0	0	6
Chisel cultivating	Mar.–Apr.	52 kW 4WD + chisel 2 m width	1	1	1	1	1	1	1	1	8
Harrowing	Apr.	52 kW 4WD + vibro-tiller 3 m width	2	2	2	2	2	2	2	2	16
Weed control	Apr.–May	52 kW 4WD + sprayer	1	1	2	1	1	0	2	1	9
Sowing [a]	Apr.–May	49 kW 2WD + drill 2–3 m width	1	1	1	1	1	1	1	1	8
Row crop cult.	June	33 kW 2WD + weeder 3 m width	1	0	1	1	0	0	0	2	5
Local. fert.	Apr.	33 kW 2WD + fertiliser plac. + drill	1	0	0	0	0	0	0	0	1
Harvesting	Oct.	Combine 147 kW	1	1	1	1	1	1	1	1	8
Straw shredding	Nov.	52 kW 4WD + stalk cutter	1	1	1	0	0	0	0	1	4
Total mechanised operation in the conventional tillage			11	9	11	10	8	6	8	10	73
Ridge tillage											
Ploughing	Nov.	66 kW 4WD + mouldboard plough	1	0	0	0	0	0	0	0	1
Fertilising	Apr.	52 kW 4WD + fertiliser distributor	1	1	1	2	1	0	0	1	7
Rotary hoeing	Mar.–Apr.	50 kW 2WD + rotary cultivator	1	1	0	0	1	0	0	0	3
Furrowing	Nov.–June	33–50 kW 2WD + furrowing plough	2	1	0	1	1	0	0	1	6
Sowing	Apr.–May	66–73 kW 4WD + drill 2–3 m width	1	1	1	1	1	1	1	1	8
Local. fert.	June	33 kW 2WD + fertiliser plac. + drill	1	0	2	1	0	0	0	1	5
Weed control	Apr.–June	52 kW 4WD + sprayer	1	1	4	3	2	1	4	4	20
Harvesting	Oct.	Combine 147 kW	1	1	1	1	1	1	1	1	8
Straw shredding	Nov.	52 kW 4WD + stalk cutter	1	1	1	0	0	0	0	1	4
Total mechanised operation in the ridge tillage			10	7	10	9	7	3	6	10	62
No-tillage											
Sowing	Apr.–May	66–73 kW 4WD + drill 2–3 m width		1	1	1	3				
Weed control	Apr–June	52 kW 4WD + sprayer		0	3	2	5				
Top dressing	June	33 kW 2WD + fertiliser plac. + drill		0	0	1	1				
Harvesting	Oct.	Combine 147 kW		1	1	1	3				
Straw shredding	Nov.	52 kW 4WD + stalk cutter		0	0	1	1				
Total mechanised operation in the no-tillage			2	5	6	13					

M, Maize; S, soybean; B, barley.

[a] The barley sowing was at the end of October

Table 3
Average crop yields ($\mathrm{Mg\,ha^{-1}}$) in the three tillage systems

Crop	CT	RT	NT
Maize [a]	8.07	7.18	5.07
Soybean [b]	3.57	3.07	2.13
Barley [c]	5.48	4.80	4.47

[a] Average of 4 years.
[b] Average of 3 years.
[c] Data from 1 year.

and herbicide distribution; with RT there is a reduction in the number of tillage operations (−69%) compared with CT, and an obvious increase in the herbicide treatments (+122%) required, at least for the first few years after the soil management system has changed.

3. No-tillage demonstrated a further simplification compared with RT both in the number of operations and in the complexity of the machinery required.
4. The machinery required for crop management with reduced tillage systems is simplified both in the number of implements and in tractor power.

Given the long duration of the trial, the mechanical operations and cropping methods adopted in the first years differed somewhat from those used more recently. This can be attributed to improvements in the techniques and the progressive diversification of the systems. Furthermore, there is still a strong possibility of improving techniques in all cropping systems and so further reductions in the intensity and number of crop operations could be foreseeable without any decline in yield.

In all years, crop yields were significantly affected by tillage system; also, a significant interaction 'tillage × year' was found. However, given the objectives of this work, only the average crop yields are considered and are reported in Table 3. The poor yields obtained until now in NT might be the consequence of less favourable soil conditions (e.g. low porosity, low water storage, low temperature, surface water ponding) owing to the shorter history of these plots and more weeds. Because of the high silt content ($0.33\,\mathrm{g\,g^{-1}}$) in the soil and the low initial soil organic matter ($0.015–0.02\,\mathrm{g\,g^{-1}}$), a longer time is expected to be needed before substantial improvement in soil physical property will become evident.

2.2. Energy balance and efficiency

The approach used in the energy analysis followed the analysis model of the IFIAS (International Federation of Institutes for Advanced Study) school, called the Gross Energy Requirement model (Slesser and Wallace, 1982), with the variant that an energy value was also attributed to human labour in the calculation. The latter has the advantage of obtaining homogeneity of the data, even if this is obstructed by the lack of a single evaluation criterion. The approach does not consider energy of environmental origin (radiation, wind, water, etc.), but only that included in the production processes of the various cropping methods.

Table 4
Primary energy incorporated (average) in the main technical means of production

Means	Primary energy ($MJ\,kg^{-1}$) [a]	References
Labour	1.95 [b]	Pimentel and Pimentel, 1979; Jarach, 1985
Tractors and agricultural machines	80.23	Carillon, 1979; Pimentel and Pimentel, 1979; Hornacek, 1979; Malarmé, 1983; Jarach, 1985; Biondi et al., 1989
Diesel fuel	50.23	Carillon, 1979; Pimentel and Pimentel, 1979; Pellizzi, 1984; Jarach, 1985; Biondi et al., 1989
Lubricants	78.13	Carillon, 1979; Jarach, 1985
Fertilisers		Carillon, 1979; Pimentel and Pimentel, 1979; Fluck and Baird, 1982; Jarach, 1985; Triolo et al., 1985
N (urea)	70.14	
N (ammonium)	79.29	
N (nitrate)	113.39	
Phosphorus (46% P_2O_5)	12.8	
Phosphorus (20% P_2O_5)	9.76	
Potash	8.47	
Herbicides (average)	80.29 [c]	Pimentel and Pimentel, 1979; Cantele and Zanin, 1983; Triolo et al., 1985
Diquat	575	
Alachlor	465	
Linuron	296	
Metolachlor	465	
Bromoxynil	395	
Mecoprop	302.7	
Dicamba	470	
Terbuthylazine	209.8	
Ioxynil	395	
Glyphosate	629	
Seeds		Pimentel and Pimentel, 1979
Maize	104.65	
Soybean	33.49	
Barley	27.63	
Maize kernel	14.95	Carillon, 1979; Pimentel and Pimentel, 1979
Barley kernel	13.52	Carillon, 1979; Pimentel and Pimentel, 1979
Soybean kernel	16.87	Pimentel and Pimentel, 1979

[a] Values obtained by elaboration from different researchers.
[b] In $MJ\,h^{-1}$.
[c] For the active ingredients that are not in the table, the value of others from the same family have been used, or an average value.

The active part of the energy balance (output) is made up of the energy content of the grain (kernel). The energy content of the crop residues which were always left on the field is therefore not considered. To determine the output, the dry weight of the harvested grain was transformed into an energy value utilising specific energy coefficients for each crop (Table 4). The passive part (input) includes all the various forms of energy in the production process measured by production factor classes. For each production factor the amount applied was measured and converted into an energy value using average coefficients found in the literature.

The conversion coefficients used are the result of weighting, starting from the values supplied by different researchers (see Table 4). It was considered worth while to use this criterion as the coefficients reported in the literature are often very different. The following criteria were used to quantify the energy of the various factors:

1. indirect mechanisation: the weight of the machinery and equipment was converted into an energy content using a suitable coefficient (80.23 MJ kg^{-1}) and then divided by the estimated life, to allow the hourly energy cost to be calculated.
2. Direct mechanisation was obtained by multiplying the hourly fuel and lubricant consumption by the hours of work in the various cropping operations.
3. Fertilisers, herbicides and seeds were evaluated by multiplying the quantities used by their unit energy cost to the farm, excluding the cost of distribution, which is calculated in the direct and indirect mechanisation and in the labour.
4. Drying was determined by multiplying the amount of evaporated water, to take the product from harvest moisture content to that for storage, by the energy spent to evaporate 1 kg of water (6.36 MJ kg^{-1}).
5. Human energy was counted on the basis of 2.0 MJ h^{-1} (Pimentel and Pimentel, 1979). This value corresponds to the biochemical energy potentially consumable by a person considering coefficients of reduction which take into account the quota not useful for working and the heaviness of the task. This criterion is also confirmed by other researchers (Jarach, 1985), who report energy coefficients of 1.2–2.5 MJ h^{-1}.

The most important parameters calculated starting from the elementary data are reported in Table 5.

2.3. CO_2 balance

The evaluation of the effect of tillage treatments on CO_2 emission was obtained by considering the main variables which are modified by the different cropping methods (i.e. in agricultural machinery diesel consumption and variations to the organic carbon

Table 5
The most important parameters calculated in the energy balance and efficiency

Parameters		Unit measure
Energy requirement	Input	MJ ha^{-1} and MJ Mg^{-1}
Energy output	Output	MJ ha^{-1}
Net energy produced	Output − input	MJ ha^{-1} and MJ Mg^{-1}
Productivity of the energy invested	Output/input	MJ MJ^{-1}
	(Output − input)/input	MJ MJ^{-1}
WEP (work energy productivity)	Output/work energy	MJ MJ^{-1}
HECI (herbicide energy composition index)	Herbicide energy/mechanisation energy	MJ MJ^{-1}

content of the soil). Diesel consumption per hectare was calculated by the following equation:

$$DC = \frac{\mathrm{SDC}\, Pm\, L}{RW}$$

where DC is diesel consumption (in kg ha^{-1}), SDC is specific diesel consumption (in kWh kg^{-1}), Pm is maximum tractor or combine power (in kW), L is engine load as the ratio between the power requirement for an operation and maximum tractor or combine power and RW is overall rate of work (in ha h^{-1}). In particular, SDC was calculated with the following equation (CRPA, 1988):

$$\mathrm{SDC} = 0.4307 - 0.4405L + 0.2933L^2$$

assuming that L varied in relation to type of operation from 0.35 to 0.75.

To determine the savings of CO_2 deriving from diesel combustion (saved $CO_{2[\mathrm{fuel}]}$), the following formula was applied:

$$\text{saved } CO_{2[\mathrm{fuel}]} = 3.106\Delta Q$$

where $\Delta Q = Q_{\mathrm{CT}} - Q_{\mathrm{RT,NT}}$ is difference in the average fuel consumption measured in CT compared with RT and NT (kg), and 3.106 is the coefficient of transformation of diesel into CO_2 under optimal engine functioning conditions (Srivastava et al., 1993).

The soil organic carbon and dry bulk density were measured at the end of trials (1994) by collecting undisturbed soil cores at depths of 0–100, 100–200, 200–300 and 300–400 mm. Four replications per plot in CT and NT and eight in RT (four in the top and four in the bottom of the ridge) were taken. Determination of the savings of CO_2 owing to immobilisation in the soil (stored $CO_{2[\mathrm{soil}]}$) was carried out as follows.

From the analysis of soil organic carbon content (Walkeley and Black method) and dry bulk density, the soil organic carbon content in each tillage system (in the layer 0–400 mm) per hectare was found using the formula

$$\mathrm{C} = 100\mathrm{C}'Bd$$

where C is soil organic carbon content (in Mg ha^{-1}); C$'$ is soil organic carbon content (in g hg^{-1}), B is dry bulk density (in Mg m^{-3}), d is depth (in m) of samples for all tillage systems (0.4 m). The difference in the average carbon content in the 0–400 mm layer in RT and NT compared with CT at the end of the trial was then found. RT and NT not being of the same age, the value was divided by 7 years for RT and 3 years for NT:

$$\Delta \mathrm{C}_{\mathrm{RT}} = \frac{(\mathrm{C}_{\mathrm{RT}} - \mathrm{C}_{\mathrm{CT}})}{7}$$

$$\Delta \mathrm{C}_{\mathrm{NT}} = \frac{(\mathrm{C}_{\mathrm{NT}} - \mathrm{C}_{\mathrm{CT}})}{3}$$

where $\Delta \mathrm{C}_{\mathrm{RT,NT}}$ is the yearly average increase of carbon content in the 0–400 mm soil layer in RT and NT with respect to CT (in Mg ha^{-1} year^{-1}).

Lastly, the stored CO_2 in the soil was calculated:

$$\text{stored } CO_{2[\text{soil}]} = \frac{44}{12} \Delta C$$

where 44 and 12 are the molecular weight of CO_2 and C, respectively.

The overall effect of the systems (saved $CO_{2[\text{total}]}$) was therefore

$$\text{saved } CO_{2[\text{total}]} = \text{saved } CO_{2[\text{fuel}]} + \text{stored } CO_{2[\text{soil}]}$$

3. Results

3.1. Energy input

The average energy input per unit area in the three systems, separated for the different operations for the three crops, is reported in Table 6. The energy cost is directly proportional to tillage intensity (CT > RT > NT). Compared with CT, the total energy saving is 10% with RT and 32% with NT. Of the items which constitute the energy consumption, the most important are: fertilisation for all tillage systems (always around 50% of the total), mechanisation (24% with CT) and drying in RT (19%) and CT (18%). Energy for herbicides increases from CT to the other tillage methods.

The energy input of mechanisation diminishes considerably with the reduction in the number and intensity of the tillage operations (−44% in RT and −61% in NT

Table 6
Distribution of energy input per unit surface area (MJ ha^{-1}) among the productive factors in the three tillage systems

Crop	Mechanisation	Fertilisation	Seeds	Herbicides	Labour	Drying	Total input
Conventional tillage							
Maize [a]	7671	21619	1779	1405	28	8501	41003
Soybean [b]	5660	5995	2791	626	21	0	15093
Barley [c]	4702	1178	4421	0	16	0	10317
Weighted average	6546	13205	2489	937	24	4250	27451
Ridge tillage							
Maize [a]	4821	20405	1779	1879	16	8925	37825
Soybean [b]	3006	5995	2791	1177	11	353	13332
Barley [c]	1111	1178	4421	356	4	0	7069
Weighted average	3676	12598	2489	1425	13	4595	24796
No-tillage							
Maize [c]	3600	17310	1779	1557	9	6831	31086
Soybean [c]	1705	832	2763	898	6	0	6204
Barley [c]	818	1178	4421	0	3	0	6419
Weighted average	2541	9114	2478	1115	7	3416	18672

[a] Average of 4 years.
[b] Average of 3 years.
[c] Data from 1 year.

compared with CT). The saving is obtained through a lower direct energy consumption, owing to fewer operations and the greater working capacity of the machines used in RT and NT.

Labour is the factor which gains most from the use of low energy input (per hectare) cropping methods. In RT and NT labour is 54% and 30%, respectively, of that required in CT. However, the advantage in terms of the overall energy balance is minimal because of the low unit energy cost of labour (1.95 MJ h^{-1}) and the low incidence of this factor in all the systems.

Analysing the different crops, the energy savings attainable in maize with the reduced tillage systems were less than the average of the systems (8% and 24% with RT and NT, respectively). Fertilisation is the most costly operation in terms of energy in all systems, at around 20 000 MJ ha^{-1}, equalling 48–51% of the total energy input. More than 90% of the energy cost of fertilisation is due to the nitrogen. The drying necessary to take the grain to storage moisture content is also very energy intensive for maize (7000–9000 MJ ha^{-1}, 20–23% of the total cost). There were no substantial differences between cropping systems for both these operations, as the fertiliser rates and harvest moisture content of the grain were not different. The effect of mechanisation on the total input differs: 11–13% in NT and RT and 19% in CT. In contrast, the use of herbicides increases from 3 to 6% moving from CT to NT and RT.

The cultivation of soybean with reduced tillage methods involved considerable energy savings, compared with CT: 1760 MJ ha^{-1} (−12%) with RT and 8888 MJ ha^{-1} (−59%) with NT. Comparing CT and RT, the result is due to the large decrease in consumption for mechanisation (2654 MJ ha^{-1}), balanced, however, by increased energy costs for herbicides and drying. Comparison between CT and NT for fertilisation is less

Table 7
Distribution of energy input per unit product (MJ Mg^{-1}) among the productive factors in the three tillage systems

Crop	Mechanisation	Fertilisation	Seeds	Herbicides	Labour	Drying	Total input
Conventional tillage							
Maize [a]	1003	2999	232	185	4	1081	5504
Soybean [b]	1593	1531	799	171	6	0	4100
Barley [c]	858	215	807	0	3	0	1883
Weighted average	1206	2101	516	157	4	540	4525
Ridge tillage							
Maize [a]	685	2931	254	272	2	1234	5378
Soybean [b]	1003	1644	973	419	4	139	4183
Barley [c]	231	245	921	74	1	0	1473
Weighted average	748	2113	607	303	3	669	4442
No-tillage							
Maize [c]	709	3411	351	307	2	1346	6125
Soybean [c]	641	313	1040	338	2	0	2344
Barley [c]	184	265	994	0	1	0	1444
Weighted average	618	1856	689	280	2	673	4118

[a] Average of 4 years.
[b] Average of 3 years.
[c] Data from 1 year.

valid, as the soybean in NT was a second crop which received only a localised phosphate fertilisation at sowing, whereas in CT and RT, the legume was a first crop and abundant base fertilisation was applied. It is therefore more correct to exclude fertilisation from the comparison. In this case, excluding fertilisation, there is an overall saving of 41%.

The biological characteristics of barley allow it to adapt better to RT and NT methods than the other crops because of its root system, growing period and tillering capacity. In fact, the energy saving per unit area compared with CT was 3248 MJ ha^{-1} (−31%) for RT and 3898 MJ ha^{-1} (−38%) for NT.

Considering the energy input per unit product (Table 7), some original aspects emerge:

1. the differences between the energy input of the three systems are less (around −11%). This is due mainly to the yield responses, which penalised the systems with reduced intensity.
2. The composition of the total input is slightly modified: mechanisation, herbicides and seeds have more weight, which is contrasted by a lower incidence of fertilisers and drying.
3. With maize, changing to reduced tillage either does not modify the total input per unit yield (RT) or increases it (NT, +11%).
4. Soybean allows energy requirements to be reduced more than maize and barley, if fertilisation is excluded. The energy input saving was 20% and 21%, respectively, for RT and NT compared with CT.

Table 8
Energy production, balance and efficiency in the three tillage systems

Productive means	Output (MJ ha^{-1})	Output − input (MJ ha^{-1})	Output − input (MJ Mg^{-1})	Output/ input	(Output − input)/ Input	WEP [a]	HECI [b]
Conventional tillage							
Maize	120695	79693	9446	3.06	1.94	4429	0.18
Soybean	60164	45072	12770	4.44	2.99	2917	0.11
Barley	74090	63773	11637	7.18	6.18	4578	0.00
Average	92170	64720	10966	4.09	2.86	3881	0.13
Ridge tillage							
Maize	107348	69524	9572	2.89	1.84	7017	0.43
Soybean	51752	38419	12687	4.23	2.88	4970	0.44
Barley	64896	57827	12047	9.18	8.18	17797	0.32
Average	81193	56397	11050	4.18	3.02	7597	0.42
No-tillage							
Maize	75871	44785	8825	2.44	1.44	8157	0.43
Soybean	35936	29732	14536	5.79	4.79	6205	0.53
Barley	60421	54001	12084	9.41	8.41	23297	0.00
Average	58964	40293	11374	4.57	3.57	9317	0.41

[a] Work energy productivity (output/work energy).

[b] Energy composition index (energy herbicides/energy mechanisation).

3.2. Energy output, balance and efficiency

The energy output is less with the simplified tillage systems because of the lower yield obtained in RT and NT compared with CT, with average reductions of 12% in RT and 37% in NT (Table 8). Among the crops grown, maize had the highest energy output of all the systems. In six crop cycles out of eight, the greatest net energy (output − input) produced per hectare were obtained in CT, with an average weighted difference in comparison with RT of around 8300 MJ ha^{-1} and 24 400 MJ ha^{-1} compared with NT. Once again, the biggest energy gains were supplied, in all the systems, by maize. However, the net energy obtained per unit yield (MJ Mg^{-1} of produce) did not vary between the systems.

The indices of energy transformation (output/input and net energy/input) vary little between CT and RT, tending to increase only when NT is practised (Table 8). The crop which gives the best responses to low energy input cropping methods is barley, where the output/input ratio increases by 28–31% in RT and NT. For maize, the output/input ratio tends to decrease proportionally to the reduction in tillage intensity, whereas for soybean the best result is obtained with NT.

Work energy productivity (WEP) is an index which gives labour efficiency in energy terms (Spugnoli et al., 1993). The values were very high in all the tillage systems as a consequence of the currently high levels of mechanisation which require very little labour. CT has a work energy productivity of around half that of RT and a third that of NT; in each system, the highest values are with the agronomically less demanding crops such as barley and soybean, as was also reported by Spugnoli et al. (1993). The herbicide energy composition index (HECI) shows clearly how changing from CT to NT involves a shifting of energy, mainly from mechanisation to weed control.

3.3. CO_2 balance

Table 9 reports the main operations carried out to evaluate the effect of the tillage reduction on the restriction of CO_2 emissions owing both to the increase of soil organic C content and to the lower use of machinery in the reduced tillage plots.

Table 9
Evaluation of the saved CO_2 in the minimum tillage systems

Tillage systems	CT	RT	NT
Soil organic carbon content (g hg^{-1}) [a]	0.75	0.83	0.75
Dry bulk density (Mg m^{-3}) [a]	1.6	1.58	1.7
Soil organic carbon content (Mg ha^{-1}) [a]	48.3	52.5	50.6
ΔC (kg ha^{-1} year^{-1}) [b]		593	770
Stored $CO_{2[\text{soil}]}$ (kg ha^{-1} year^{-1})		2174	2823
Q (kg ha^{-1} year^{-1})	116	64	43
ΔQ (kg ha^{-1} year^{-1})		52	73
Saved $CO_{2[\text{fuel}]}$ (kg ha^{-1} year^{-1})		162	227
Saved $CO_{2[\text{total}]}$ (kg ha^{-1} year^{-1})		2336	3050
Saved $CO_{2[\text{total}]}$ (m^3 ha^{-1} year^{-1})		1190	1553

[a] Depth of soil 0–400 mm.

[b] Considering 7 years for RT and 3 years for NT.

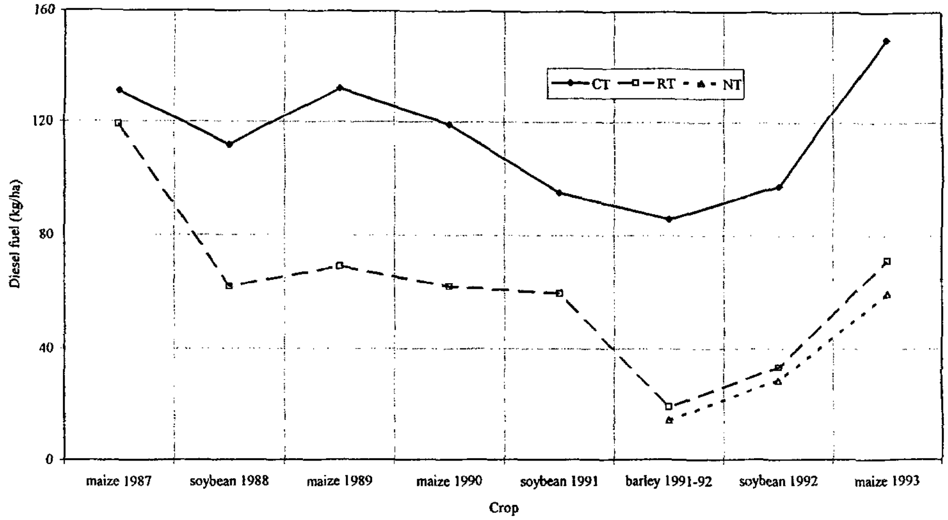

Fig. 1. Annual diesel consumption (kg ha^{-1}) during the trial.

In the 7 years of the trial the unploughed treatments have stored a higher amount of organic carbon in the soil on average than with CT: 593 kg ha^{-1} year^{-1} and 770 kg ha^{-1} year^{-1} for RT and NT, respectively, thanks to the higher organic matter content in the simplified tillage systems. These values are equivalent to a reduced release of gas into the atmosphere of around 2174 kg ha^{-1} year^{-1} and 2823 kg ha^{-1} year^{-1} for RT and NT, respectively. The average annual consumption of diesel for running the machinery in RT and NT was around half and a third that of CT (Fig. 1), with a consequent average saving of 52 kg ha^{-1} year^{-1} and 73 kg ha^{-1} year^{-1}, respectively, corresponding, under normal conditions, to a lower emission of 163 kg ha^{-1} year^{-1} and 227 kg ha^{-1} year^{-1} of CO_2. The sum of the two effects (2336 kg ha^{-1} year^{-1} and 3050 kg ha^{-1} year^{-1} of CO_2 for RT and NT, respectively) is equivalent to the production of CO_2 of 1.3 and 1.7 medium-sized cars covering an average annual distance of 15 000 km.

4. Discussion

The different role that the production factors played in the composition of energy costs of the three crops suggests that the results could be weighted by the proportion of each crop under each system. For example, we wished to analyse the variations of energy input for mechanisation in a simplified rotation maize–soybean. Different proportions of surface area planted with the two crops were hypothesised, passing from a maize/soybean ratio of 6:1 to 1:6. Utilising the average energy costs of mechanisation of the two crops in Table 6, the energy inputs of all the proportions between maize and soybean in the three cultivation systems were calculated. The results are reported in Fig. 2, which shows that reducing the incidence of maize in favour of soybean gives a

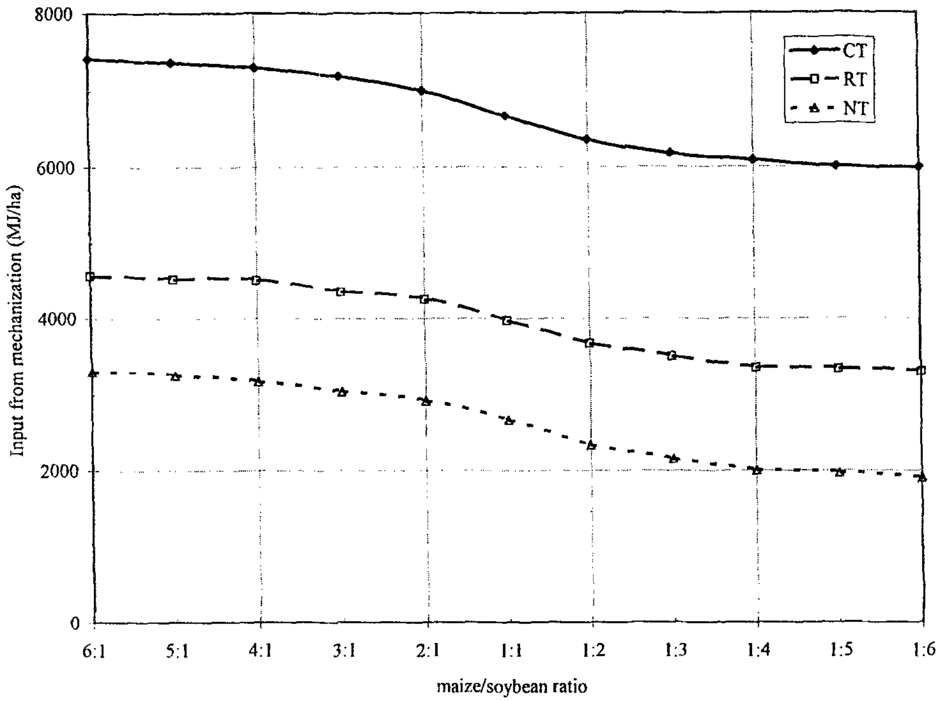

Fig. 2. Effects of the different ratios of farm area cultivated with maize and soybean on energy input from mechanisation.

reduction in energy consumption for mechanisation, but the differences between the three systems of soil tillage are constant for all the ratios between the cereal and the legume. As the other indices analysed displayed analogous trends (not presented), this implies that the results are effectively qualified by the cultivation system. This being so, the three cropping systems differ in complexity, energy costs and performance.

In general, the system based on CT is more demanding in terms of machinery and energy costs, but is able to supply the highest gross and net output. It is therefore preferable when the aim is to maximise yield. The adoption of NT allows a major reduction in the number of mechanical operations and range of machinery, but involves higher energy costs for weed control. RT is intermediate, but nearer CT than NT for energy costs and energy produced. In general, the minimum tillage systems are more suitable when the desire is to contribute towards energy saving and to increase energy use efficiency.

This aspect has, nevertheless, probably been lower than expected. In fact, the differences between the systems in terms of input per unit surface are greatly limited considering the input per unit production because of the lower crop yields. It is therefore necessary to try to increase the productivity of the minimum tillage systems. During the trial it was realised that wider margins for improvement exist for RT and NT than for CT, which is a widespread and consolidated technique. These mainly concern machine technology for ridging, sowing, fertiliser distribution and weed control.

The results have also demonstrated that the energy consumption for mechanisation accounts for less than a quarter of the total balance. Further improvements to the energy efficiency of the minimum tillage systems could therefore be achieved in other ways, for instance, with increased organic matter in the soil and the choice of varieties adapted to reduced fertilisation.

As well as having a different energy balance, minimum tillage can contribute to the reduction of CO_2 emissions in two ways: (1) by increasing the carbon stored in the soil as organic matter and (2) by reducing the requirement for diesel in the crop cycles. The overall result is evaluated as a lower CO_2 emission of between 200 and $300\,m^3\,ha^{-1}\,year^{-1}$. More than 60% of this is due to the accumulation of organic matter in the soil during the trial. This leads to two considerations. First, after a transition period the annual rate of storing organic matter in soils under minimum or no-tillage will decline slowly to zero, so that the consequent immobilisation of CO_2 will gradually decline to zero. Second, a return to ploughing after a period of reduced tillage could cause an additional release of the greenhouse gas caused by the oxidisation of the accumulated organic matter. The reduction in fuel consumption is permanent and is not related to modifications in the soil characteristics.

5. Conclusions

Changing from conventional cropping methods to minimum tillage or no-tillage, on a loamy-silt soil in NE Italy, allowed a considerable energy saving per unit area. If, apart from this objective, an overall improvement of the output/input ratio is desired, a reduction in tillage is not sufficient. It is also necessary to review fertiliser rates, fertilisation techniques and the harvest moisture content of the grain, as these make up a significant part of the energy costs of production. Yields translated into energy terms suffered a diminution of output in proportion to the reduction of inputs. As a consequence, the average energy costs necessary to produce the unit of production remained more or less constant in the three systems.

Under the trial conditions, the lower energy input of minimum tillage methods corresponds to a fuel saving and slower soil organic matter decomposition rate. The sum of these effects gave a reduced emission of CO_2 into the atmosphere. The importance that agricultural activities can have in this context, if related to the other producing industries, is small, but is not insignificant.

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