Soil conservation tillage effects on yield and water use efficiency on irrigated crops in Central Italy

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1 **Soil conservation tillage effects on yield and water use efficiency on irrigated**
2 **crops in Central Italy**

4 R. Casa and B. Lo Cascio

6 Authors' address: Prof. R. Casa (corresponding author; e-mail: rcasa@unitus.it) and Prof. B. Lo
7 Cascio, Dipartimento di Produzione Vegetale, Università degli Studi della Tuscia, Via S. Camillo
8 de Lellis, 01100 Viterbo, Italy

9 *With 5 figures and 4 tables*

11 **Abstract**

12 Despite possible agronomic and environmental benefits, the diffusion of soil conservation tillage
13 systems in Italy is currently rather low. The aim of this study was to compare the performance of
14 different soil tillage techniques, in an effort to identify suitable soil management options for
15 irrigated crops in Central Italy. An experiment was carried out on maize and soybean, from April to
16 October in two consecutive years (1993 and 1994) in Maccarese (a coastal location near Rome).
17 The systems compared were: conventional mouldboard ploughing (CT), minimum tillage (MT),
18 ridge tillage (RT) and no-tillage (NT). In 1993 actual crop evapotranspiration (ET) was measured
19 throughout the growing season on NT and CT soybean, using a micrometeorological technique.
20 No significant differences due to soil tillage were found for grain yield and yield irrigation water
21 use efficiency (IWUEy), except for soybean in 1994, in which yields and IWUEy were 59% higher
22 on conservation tillage treatments as compared to CT. In 1994 soybean yield water use efficiency
23 (WUEy) was 10.1 and 9.5 kg ha⁻¹ mm⁻¹ for NT and CT respectively. The results suggest that the
24 adoption of soil conservation tillage is feasible, for the specific cropping system, with equivalent or
25 better performances as conventional tillage.

Key words: soil tillage, evapotranspiration, water use efficiency, *Zea mays* L., *Glycine max* L., Bowen ratio.

running title : Soil conservation tillage in Central Italy

Introduction

Conservation tillage systems, defined as a set of tillage practices in which a substantial part (at least 30%) of the soil remains covered by previous crop residues (Unger 1990), were initially introduced more than 70 years ago in the United States, primarily to contrast soil erosion (Blevins and Frye 1993). Several implementations of these systems, ranging from light tillage carried out only by harrowing (minimum tillage) to almost complete elimination of any kind of soil disturbance (no-tillage), have found application in a wide range of soils and climates (for reviews see e.g. Unger 1990, Blevins and Frye 1993, Holland 2004).

A great number of studies conducted worldwide in the last 40 years, including several sites in Italy (e.g. Toderi and Bonari 1986, Servadio and Marsili 1998, De Vita et al. 2007), have shown that in most cases these systems promote an increase in soil organic matter, reduction of runoff and soil erosion and improved soil-plant water relations (Unger 1990, Blevins and Frye 1993, Hatfield et al. 2001, Holland 2004).

It has been shown that in conservation tillage systems, more water is generally stored in the soil profile as compared to conventional systems, due to lower soil evaporation, increased infiltration and soil conductivity, reduced runoff and deep percolation, mainly as a consequence of the presence of crop residues on the soil surface and of soil structure modifications (Blevins et al. 1971, Hill and Blevins 1973, Tyler and Overton 1982, Munawar et al. 1990, Unger 1990, Blevins and Frye 1993, O'Leary 1996, Hatfield et al. 2001; Shukla et al. 2003, Karamanos et al. 2004). Additionally it has been reported that in conservation tillage, particularly in no-tillage, there is usually a larger presence of biopores than in conventional tillage (Lo Cascio and Venezia 1986).

These are pores, created by the soil macrofauna, that allow easier penetration by water and roots of

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the crops, thereby allowing a increased exploration of the soil profile and improved water use (Venezia et al. 1995, Turner 2004). If these effects are accompanied by similar or higher yields than on conventional tillage, there is a resulting improvement in water use efficiency by adopting conservation tillage systems (Hatfield et al. 2001, De Vita et al. 2007, Moret et al. 2007).

In Italy, as in other Mediterranean countries, the efficient use of water resources has become increasingly important, given the growing competition for water between agriculture and other sectors and also the possible impacts from climate change (Wallace 2000, Norrant and Douguédroit 2004, Katerji et al. 2006). Therefore it is particularly important to promote soil management practices which could bring about an improvement in water use efficiency (Hatfield et al. 2001, Casa 2007).

The adoption rate of conservation tillage in Italy is still very low (ECAAF 2007), in spite of the fact that soil erosion risk in Italy is particularly high (Grimm et al. 2003) and that a large part of the cultivated soils have rather low soil organic matter content (Zdruli et al. 2004).

There is currently renewed interest in the diffusion of conservation tillage systems, also because of their potential to promote the storage of carbon into the soil, in order to contrast carbon dioxide atmospheric increase and mitigate global climate change (Lal 2004, Bernacchi et al. 2005).

However, despite decades of experimentation, there is still a lack of comparative studies to assess the effect of conservation tillage systems specifically on water use efficiency. This could be explained by methodological difficulties in measuring water use concurrently in different soil management systems. For example it is not possible to implement tillage treatments in lysimeters, commonly used for classical agronomic water use efficiency studies (Katerji et al. 2006, Karam et al. 2007).

Among the few methodologies available to study the effect of different tillage systems on water use efficiency there are those based on micrometeorological techniques such as eddy covariance or Bowen ratio energy balance (see for example a recent review by Rana and Katerji 2007). The use of these techniques has the advantage, as compared to the only available alternative, i.e. water balance

1 methods, to provide continuous recording of actual crop evapotranspiration (ET) throughout the
2 growing season. This may give some insights on ecophysiological aspects relevant for
3 understanding differences in crop water status among tillage systems (Casa and Lo Cascio 1997, Lo
4 Cascio and Casa 1997). For example, one hypothesis is that soil structure modifications caused by
5 tillage might affect root water and nutrient uptake, influencing stomatal conductance and
6 evapotranspiration, which is also affected as a result of divergences in canopy development and leaf
7 area index between different tillage systems (Lo Cascio and Casa 1997).

8 Improved nutrient management, in particular of nitrogen, has been often reported as a means to
9 enhance water use efficiency (Katerji et al. 2006, Casa 2007, Di Paolo and Rinaldi 2008) and has
10 been shown to have positive interactions with tillage (Al-Kaisi and Kwaw-Mensah 2007). However
11 the combined effect of soil tillage and N fertilisation on water use efficiency has been relatively less
12 documented (Hatfield et al. 2001).

13 The present study reports the results of an experiment carried out on three different implementations
14 of soil conservation tillage: minimum tillage, ridge tillage, no-tillage in order to compare with
15 conventional tillage (deep ploughing and harrowing) in terms of yield and water use efficiency and
16 in an effort to identify suitable soil management options for a widespread irrigated rotation, i.e.
17 maize-soybean, in Central Italy. Additionally, on maize, two nitrogen fertilisation levels were
18 compared: 0 and 300 kg N ha⁻¹. The four years experiment started in 1991, while the field tests were
19 carried out in the years 1993 and 1994.

21 **Materials and methods**

22 *a) Site, climatic data and experimental design*

23 The field tests were carried out in Maccarese, a coastal location in Central Italy (lat.41°53' N,
24 long.12°10' E alt. 30 m). The site has a Mediterranean climate, strongly influenced by the proximity
25 with the sea, with a mean yearly rainfall of 874 mm, and mean annual air temperature of 15.5 °C.

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The soil is an Eutric Cambisol (FAO-ISRIC-ISSS 1998) with a sandy clay texture (36% clay, 12% silt and 52% sand) and 1.5% organic matter.

Fig. 1 summarizes the trends of temperatures and rainfall during the two consecutive growing seasons when the experiment was carried out, along with historic climatic trends for Maccarese (20 years average data).

The experiment employed a split-split-plot scheme with 3 replicates, having tillage systems (conventional tillage, minimum tillage, ridge tillage and no-tillage) as main plots, crops (maize and soybean) as subplots and N fertilisation only on maize (0 and 300 kg N ha⁻¹) as sub-sub-plots for a total of 12 treatments (Table 1).

The field tests started in 1991, and subsequently tillage systems were always maintained on the same plots, which were 28 x 22 m large. The present paper reports the results for the years 1993 and 1994, i.e. on the third and fourth year of consecutive continuous tillage treatments on a maize-soybean rotation.

b) Soil Tillage Operations

The tillage systems compared were: conventional tillage (CT), minimum tillage (MT), ridge tillage (RT) and no-tillage (NT). CT consisted of a deep ploughing at 35 cm depth using a tractor mounted mouldboard plough and an harrowing at 20 cm depth (two passes). The first harrowing pass was performed using a tractor mounted poly-disc harrow and the second pass was performed using a tractor mounted rotary harrow. Minimum tillage was carried out by employing two orthogonal rotary harrow passes for every year. For the ridge tillage system, ridging with a 0.7 m spacing using a furrow open was carried in 1991 and annually restored by means of a light ridging pass on the following years. No tillage was performed on the NT treatment. On all treatments, except CT, residues of the previous crop were shredded. Tillage operations and dates for the two years are reported in Table 2.

c) Crop Management

1 Crop management was carried out following standard farming practices used in the area as detailed
2 hereafter.

3 P and K fertilisation was carried out for both crops with 120 Kg P_2O_5 ha⁻¹ and 100 Kg K_2O ha⁻¹,
4 prior to tillage except for the NT treatment for which the fertiliser was banded during sowing
5 operations.

6 For all the treatments sowing was carried out by employing a pneumatic precision sod-seeding
7 machine with an interrow spacing of 0.7 m. For soybean the cv Argenta was used, at a rate of 35
8 viable seeds per square metre. For maize the hybrid "Raffaello", FAO class 500, was used at a rate
9 of 12 viable seeds per square metre. In the first year sowing was carried out the 23rd of April for
10 maize and on the 14th of May for soybean. In the second year sowing occurred on the 16th of May
11 for both crops.

12 On all the maize high N treatments (Table 1), fertilisation was carried out employing urea, splitting
13 the total amount into three 100 kg N ha⁻¹ applications administered respectively at the V4, V10
14 (rapid stem elongation) and VT (tasseling) growth stages (Ritchie et al. 1986).

15 A pre-sowing herbicide treatment using Glyphosate (4 l ha⁻¹) was carried out for all treatments
16 except CT. A further pre-emergence herbicide treatment was carried out on soybean using Linuron
17 plus Alachlor (1.5 + 6 l ha⁻¹), and on maize using Metholachlor plus Terbutylazine (5 l ha⁻¹). Post-
18 emergence herbicide treatments were carried out for both crops at flowering using Bentazone (3 l
19 ha⁻¹). Further applications of insecticides, using Phoxim (30 kg ha⁻¹) and Chlorpyrifos (3 kg ha⁻¹)
20 were carried out.

21 Irrigation was applied weekly by means of a solid set fixed sprinkler system, with rainfall rates of
22 about 19 mm h⁻¹, using amounts ranging between 20 to 60 mm at each application as empirically
23 determined according to the standard farm practice. At each irrigation date the amounts applied
24 were duly recorded.

25 *d) Parameters Studied*

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1 In both years, above-ground biomass was sampled every fortnight starting from about one month
2 after sowing. At each sampling date a 0.6 m² quadrat was harvested. Dry weight of each biomass
3 components was then determined after drying in a forced-air oven at 80°C for 72 h. Leaf area was
4 measured using a DeltaT (Cambridge, UK) area meter and divided by the surface area of the land
5 on which plants were harvested to calculate leaf area index (LAI).

6 Maize and soybean yield were determined by harvesting grain or above-ground biomass (for silage
7 maize) in a 30 m² area per each plot. In the first year harvest was carried out on 10 September for
8 silage maize, on 5 October for grain maize and on 15 October for soybean. In the second year
9 harvest was on 29 August for silage maize, on 29 September for grain maize and on 3 November
10 for soybean.

11 Soil moisture was monitored on three dates during the second year using the gravimetric method by
12 collecting soil cores at three depths (0.05, 0.15 and 0.25 m) in each plot. Soil cores were also
13 collected in order to measure soil dry bulk density using a corer with a 100 cm³ volume sample ring
14 at depths of 0.05, 0.15 and 0.25 m. These samples were weighed and dried until they reached a
15 constant weight.

16 Additionally in 1993 direct measurement of actual crop evapotranspiration (ET) was carried out on
17 the CT-S and on the NT-S treatments, in larger plots (each 48 x 69 m). Two Bowen ratio energy
18 balance systems (BREBS, Campbell Scientific, UK) were used, supplemented with additional wind
19 direction and wind speed sensors and a rain gauge. The Bowen ratio energy balance technique is a
20 well established micrometeorological method based on flux-profile relationships, for energy and
21 mass exchange measurement (see e.g. Perez et al. 1999, Todd et al. 2000). The two BREBS were
22 installed, immediately after sowing, towards the eastern edge of the plots in order to maximise fetch
23 during the daytime, when usually sea breeze from West sector prevailed. During these conditions a
24 fetch having an upwind distance to measurement height ratio greater than 22:1 was present, which
25 is considered adequate for the Bowen ratio technique (Heilman and Brittin 1989, Stannard 1997).

26 Data were recorded as 20 minutes flux density averages. Further details on the BREBS systems

used and calculation procedures can be found in a previous report (Casa and Lo Cascio 1997). Erroneous data were rejected by deleting records for periods when fetch was insufficient and when quality check failed, as determined by an algorithm which included the criteria specified by Perez et al. (1999). Remaining data were subject to a gap-filling procedure using the marginal distributed sampling look-up-table algorithm (Moffat et al. 2007). Daily totals of latent heat flux were then calculated on the gap-filled data and converted to ET in mm d^{-1} .

Irrigation water use efficiency (IWUE) was computed as the ratio between grain yield or dry above-ground biomass and the sum of irrigation water plus rainfall during the growing season. Water use efficiency (WUE) was calculated as the ratio of biomass (WUE_b) or yield (WUE_y) to actual crop evapotranspiration as measured by the Bowen ratio systems.

Data were analysed using the ANOVA model for the split-plot experimental scheme employed.

Results

a) Crop Yield

Rather different results were obtained in the two years of the tests for what concerns crop yields, with considerably higher values in the first year as compared to the second. This could be partly due to delayed sowing times in 1994, when an unusually prolonged spring rainy period prevented earlier tillage operations, and led to less favourable conditions during the initial growth stages. Subsequent higher temperatures in 1994 than in 1993 for July and August (Fig. 1), hastened ripening thus shortening the time available for grain filling.

In the first year, no statistically significant effects among soil tillage systems on grain yield were found for both maize and soybean, while N fertilisation resulted in a 14% yield increase for maize (Table 3) in respect to the unfertilised treatment. Total above-ground biomass at harvest was not influenced by soil tillage system for soybean. However dry above-ground biomass for CT-M (25.2 Mg ha^{-1}) and RT-M (23.1 Mg ha^{-1}) were significantly higher (33% on average) with respect to MT-M (17.5 Mg ha^{-1}) and NT-M (18.9 Mg ha^{-1}) treatments. It should be noted that, for maize, above-

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ground biomass data refer to plants harvested at the R4 stage (dough) in agreement with the practice used by the farmers for silage maize production. N fertilisation had an evident effect on this variable in the first year, with a 48% increase over the zero N treatment.

In the second year, lower grain yields (-37%) were recorded for soybean grown on conventional tillage as compared to all other conservation tillage treatments, while no significant differences due to tillage or N fertilisation were found for maize (Table 3). The effect of tillage on total above-ground biomass was only apparent for maize, similarly to the first year, determining lower yields on no-tillage (-25%) in comparison to the other tillage systems. N fertilisation significantly increased silage maize yield (68%) also in the second year. No significant effects of the interactions between tillage systems and N fertilisation were found in the two years of the tests so these data were not reported here.

b) Water Use Efficiency

Differences in biomass and grain yield were reflected in the efficiency of use of water inputs (rainfall plus irrigation), here expressed as Irrigation Water Use Efficiency (IWUE). Statistically significant differences due to soil tillage were only recorded in the second year for soybean, in which yield IWUE was 59% higher for the conservation tillage treatments as compared to the conventional tillage (Table 4). A rather different picture appeared for maize, where in the first year biomass IWUE was lower for NT-M ($32 \text{ kg ha}^{-1} \text{ mm}^{-1}$) and MT-M ($30 \text{ kg ha}^{-1} \text{ mm}^{-1}$) treatments with respect to the RT-M ($39 \text{ kg ha}^{-1} \text{ mm}^{-1}$) and CT-M ($43 \text{ kg ha}^{-1} \text{ mm}^{-1}$) treatments, with an average decrease of 25%. In the second year only NT-M ($15 \text{ kg ha}^{-1} \text{ mm}^{-1}$) showed lower biomass IWUE than the other tillage systems: RT-M ($18 \text{ kg ha}^{-1} \text{ mm}^{-1}$), MT-M ($19 \text{ kg ha}^{-1} \text{ mm}^{-1}$), CT-M ($20 \text{ kg ha}^{-1} \text{ mm}^{-1}$). In both years N fertilisation had a significant effect on IWUE (with an average increase of 44%) except for yield IWUE in the second year.

IWUE is not a very precise indicator of the crop water use efficiency as it disregards the effect of inefficiencies in irrigation application. By computing water use efficiency (WUE) (Table 4), we can better assess the effects of tillage systems on water productivity. Due to the difficulties in the

experimental set-up requiring large plots and complex instrumentation such as the BREBS, actual ET measurements for the whole growing season were only available for CT-S and NT-S in the first year. Actual ET measurements showed that, before crop emergence and during the initial growth period, daily actual ET values were higher for the CT-S with respect to NT-S treatment (Fig. 2). However, from a week after emergence onwards, actual ET was prevalingly higher on the NT-S. Total ET for the whole growing season was 423 mm for CT-S treatment and 467 treatment mm for the NT-S crop. This occurred despite the higher leaf area index (LAI) and above-ground biomass trends recorded on CT-S as compared to NT-S (Fig. 3). Biomass WUE was lower (-25%) for NT-S ($39 \text{ kg ha}^{-1} \text{ mm}^{-1}$) with respect to CT-S ($53 \text{ kg ha}^{-1} \text{ mm}^{-1}$), though grain yield was relatively higher on the no-tillage treatment, so that yield WUE was 6% higher for NT-S ($10 \text{ kg ha}^{-1} \text{ mm}^{-1}$) with respect to CT-S ($9 \text{ kg ha}^{-1} \text{ mm}^{-1}$).

c) Soil moisture and bulk density

The higher actual ET observed on the NT-S crop would suggest improved soil water availability in comparison to the CT-S situation. Unfortunately no detailed soil moisture measurements were available for the first year. Measurements carried out in the second year at three different growth stages (Fig. 4) revealed that before emergence (20 DAS) soil water content was roughly equivalent between NT-S and CT-S, with higher values for CT-S than NT-S at the 25 cm depth. Subsequently, at flowering time (78 DAS), soil moisture was significantly higher in the NT-S as compared to CT-S. In the following soil sampling, carried out during the grain ripening stage (119 DAS), no significant differences in soil water were found between the different tillage systems. Higher bulk density was found in the NT-S treatment as compared to CT-S treatment (Fig. 5), revealing effects on soil structure which could have determined different water retention characteristics between these tillage systems.

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Discussion

Even if further studies would be necessary, to clearly analyse the differences in water use patterns among crops grown on soil subject to different soil tillage systems, the results of the two years field tests showed that soil conservation tillage systems performed similarly or even better than conventional mouldboard ploughing both in terms of maize and soybean grain yields. For soybean, no significant effects due to tillage systems were equally found on final above-ground biomass production. For maize, where this parameter has practical interest particularly in the case of silage maize production, no-tillage (and minimum tillage in the first year) provided inferior results as compared to the other tillage systems. It is worth noting however, that even for soybean, although final dry above-ground biomass did not show significant differences, it appeared that NT-S and MT-S determined lower crop growth and biomass accumulation trends than CT-S and RT-S (Fig. 3). This was apparently compensated by a higher harvest index, so that these differences did not determine an impact on grain yield.

On maize the positive effect of N fertilisation on both grain and biomass yields was evident in the two years of the experiment, but no interaction was found between tillage and fertilisation, suggesting a similar N uptake efficiency among these tillage systems.

The ratio between grain yield and water supplied to the crop by rain and irrigation (IWUE), was similar or better for conservation tillage treatments as compared to conventional tillage and was considerably higher in maize than in soybean. It has been extensively reported that C4 crops such as maize have a higher water use efficiency than C3 crops, and particularly legumes, which sustain the metabolic cost of symbiotic N fixation (e.g. Steduto and Albrizio 2005).

N fertilisation in maize clearly improved irrigation water use efficiency, as previously reported by several other authors (Hatfield et al. 2001, Di Paolo and Rinaldi 2008).

Measurement of actual crop evapotranspiration on soybean showed that differences between no-tillage (NT-S) and conventional tillage (CT-S) varied with crop growth (Fig. 2). During the initial crop growth, around emergence, ET was higher in CT-S than in NT-S. Typically, during this initial

period, evaporation from the soil is larger than plant transpiration. This would suggest higher soil evaporation rates from bare soil (CT-S) than from soil covered by crop residues (NT-S) as already found in several studies in the past (Russel 1939, Hanks and Woodruff 1958, Bond and Willis 1969, Caprio et al. 1985, Enz et al. 1988). Subsequently, when the canopy cover was developed, NT-S had higher or similar ET rates than CT-S. This occurred in spite of the higher leaf area index on CT-S, suggesting an improved water status and a lower degree of water stress in NT-S than in CT-S. This was probably as a consequence of better soil water retention as suggested by soil moisture measurements carried out in the second year (Fig. 4). In the late season, when senescence occurred and plants lost most of their foliage, higher ET rates were recorded on NT-S.

On the whole of the growing season, cumulative ET was roughly similar between the two treatments and the differences found in the ratio between yield or biomass and ET (i.e. WUE) were determined by the value of the numerator in the ratio. Yield WUE was higher in NT-S as compared to CT-S.

In conclusion, the results presented in this study suggest that soil conservation tillage systems could represent a valid option for soybean and grain maize production in Central Italy, with equivalent or higher yields as compared to conventional tillage. However, for maize, above-ground biomass was decreased in the NT and MT treatments, indicating that, for silage maize production, only ridge tillage could provide an alternative to the conventional mouldboard ploughing tillage system.

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For Peer Review

Tables

Table 1. Treatments arranged among tillage systems, crops and nitrogen fertilisation levels.

Treatments	Tillage systems	Crops	N fertilisation (kg ha ⁻¹)
CT-S	Conventional	Soybean	
MT-S	Minimum	Soybean	
RT-S	Ridge	Soybean	
NT-S	No-tillage	Soybean	
CT-M-N0	Conventional	Maize	0
CT-M-N300	Conventional	Maize	300
MT-M-N0	Minimum	Maize	0
MT-M-N300	Minimum	Maize	300
RT-M-N0	Ridge	Maize	0
RT-M-N300	Ridge	Maize	300
NT-M-N0	No-tillage	Maize	0
NT-M-N300	No-tillage	Maize	300

Table 2. Soil tillage operations carried out during the two years of the field tests on maize and soybean and dates in which the operations have been performed

Treatment	Operations			
	Ploughing	Harrowing		Ridging
Conventional tillage (CT)	15 Jan 1993 8 Mar 1994	22 Jan 1993 1 May 1994	30 Mar 1993 3 May 1994	-
Minimum tillage (MT)	-	22 Jan 1993 1 May 1994	-	-
Ridge tillage (RT)	-	-	-	3 Feb 1993 18 Mar 1994
No tillage (NT)	-	-	-	-

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Table 3. Mean values of the grain and dry above-ground biomass yield for the different soil tillage systems and for the two crops in the two years of the experiment^(a).

Treatments	1993		1994	
	Grain yield (Mg ha ⁻¹)	Above-ground biomass (Mg ha ⁻¹)	Grain yield (Mg ha ⁻¹)	Above-ground biomass (Mg ha ⁻¹)
CT-S	4.0	22.2	2.2 _b	9.9
MT-S	4.3	17.5	3.7 _a	7.5
RT-S	4.0	19.8	3.6 _a	10.4
NT-S	4.7	18.4	3.2 _a	10.1
CT-M	11.3	25.2 _a	4.2	12.8 _a
MT-M	10.6	17.5 _b	4.1	12.0 _a
RT-M	9.1	23.1 _a	4.2	11.2 _{ab}
NT-M	10.5	18.9 _b	5.0	9.6 _b
M-N300 ^(b)	11.1 _a	25.3 _a	4.7	14.3 _a
M-N0 ^(b)	9.7 _b	17.1 _b	4.0	8.5 _b

^(a) Means with different letters were significantly different, P<0.05 Duncan's Multiple Range Test.
^(b) M-N300 and M-N0 are means, across all soil tillage treatments, for nitrogen fertilisation treatments on maize. No statistically significant interactions between soil tillage and N fertilisation were found and are not reported here.

Table 4. Mean values of water use efficiency (WUE) and irrigation water use efficiency (IWUE) for the different soil tillage systems and for the two crops in the two years of the experiment ^(a)

Treatments	1993				1994	
	IWUE _y	IWUE _b	WUE _y	WUE _b	IWUE _y	IWUE _b
	(kg ha ⁻¹ mm ⁻¹)	(kg ha ⁻¹ mm ⁻¹)	(kg ha ⁻¹ mm ⁻¹)	(kg ha ⁻¹ mm ⁻¹)	(kg ha ⁻¹ mm ⁻¹)	(kg ha ⁻¹ mm ⁻¹)
CT-S	6.0	33.5	9.5	52.6	3.0b	13.3
MT-S	6.5	26.3			5.0a	10.1
RT-S	6.0	29.8			4.8a	13.9
NT-S	7.1	27.7	10.1	39.4	4.3a	13.5
CT-M	15.5	42.8a			6.6	20.1a
MT-M	14.5	29.7b			6.4	18.8a
RT-M	12.5	39.2a			6.5	17.6ab
NT-M	14.5	32.1b			7.8	15.0b
M-N300 ^(b)	18.8a	43.0a			9.1	27.8a
M-N0 ^(b)	16.5b	29.0b			7.9	16.5b

^(a) IWUE and WUE subscripts y or b refer respectively to yield or biomass basis.

Means with different letters are significantly different, $P < 0.05$ Duncan's multiple Range Test.

^(b) M-N300 and M-N0 are means, across all soil tillage treatments, for nitrogen fertilisation treatments on maize. No statistically significant interactions between soil tillage and N fertilisation were found and are not reported here.

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1 **Figure captions**

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3 **Figure 1.** Trends of temperatures and rainfall for the two growing seasons when the experiment was
4 carried out (1993 and 1994), and historic climatic trends (average of 20 years of data).

5
6 **Figure 2.** Actual evapotranspiration for soybean grown on conventional tillage (CT-S) and on no-
7 tillage (NT-S) measured in 1993.

8
9 **Figure 3.** LAI (top) and dry total above-ground biomass (bottom) for soybean grown on different
10 soil tillage systems in 1993: conventional tillage (CT-S), minimum tillage (MT-S), ridge tillage
11 (RT-S) and no-tillage (NT-S). Bars showing the least significant difference (L.S.D.) at $P<0.05$ are
12 reported on top of the plots at dates where ANOVA revealed significant differences.

13
14 **Figure 4.** Gravimetric soil moisture (weight basis) for different soil tillage systems measured
15 respectively at 20 (left), 78 (centre) and 119 (right) days after sowing (DAS) in 1994 on soybean.

16
17 **Figure 5.** Soil dry bulk density for different soil tillage systems measured at 78 days after sowing
18 (DAS) in 1994 on soybean.

Figure 1. Trends of temperatures and rainfall during for the two growing seasons when the experiment was carried out (1993 and 1994), and historic climatic trends (average of 20 years of data).

1168x806mm (150 x 150 DPI)

Actual evapotranspiration for soybean grown on conventional tillage (CT-S) and on no-tillage (NT-S) measured in 1993.

LAI (top) and dry total above-ground biomass (bottom) for soybean grown on different soil tillage systems in 1993: conventional tillage (CT-S), minimum tillage (MT-S), ridge tillage (RT-S) and no-tillage (NT-S). Bars showing the least significant difference (L.S.D.) at $P<0.05$ are reported on top of the plots at dates where ANOVA revealed significant differences.

839x1187mm (150 x 150 DPI)

Figure 4. Gravimetric soil moisture (weight basis) for different soil tillage systems measured respectively at 20 (left), 78 (centre) and 119 (right) days after sowing (DAS) in 1994 on soybean.

Soil dry bulk density for different soil tillage systems measured at 78 days after sowing (DAS) in 1994 on soybean.