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TILLAGE SYSTEM EFFECTS ON WATER USE AND GRAIN YIELD OF WINTER WHEAT, MAIZE AND SOYBEAN IN ROTATION

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ABSTRACT

The increase of water use efficiency is very important, especially in water-limited conditions. The research project, carried out on cambic chernozem soil at Fundulea, in 2008 and 2009, had as the main objective the evaluation of contribution of the deep sub-soiling, done before the implementation of this experiment, and of certain tillage systems on over-winter soil water storage, water use efficiency (WUE) and water use as well as on the yield of winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and soybean [*Glycine* max. (L) Merr.)], in rotation. The following tillage systems were studied: (1) traditional, with moldboard plough (TS); (2) cizel plough tillage (CS); (3) disc/sweep tillage (DS); (4) strip till, only for row crops (ST); and no till (NT). The over-winter soil water storage estimation was based on calculation of the coefficient of rainfall accumulation during winter (CA), and of capacity of soil water conservation (CC). In the case of maize after wheat, CA was 0.6 on plots with deep sub-soiling, 0.6 on plots without deep sub-soiling, 0.6 with TS, 0.6 with CS, 0.7 with DS, 0.7 with ST, and 0.7 with NT. CC was 85 % on plots with deep sub-soiling, 85 % on plots without deep subsoiling, 82 % with TS, 0.84 % with CS, 86 % with DS, 86 % with ST, and 86 % with NT. For soybean after maize, CA was 0.5 on plots with deep sub-soiling, 0.6 on plots without deep sub-soiling, 0.5 with TS, 0.5 with CS, 0.5 with DS, 0.6 with ST, and 0.6 with NT. CC was 77 % on plots with deep sub-soiling, 79 % on plots without deep sub-soiling, 72 % with TS, 78 % with CS, 78 % with DS, 78 % with ST, and 79 % with NT. Water use and water use efficiency showed non significant differences for all crops under this study on both plots with deep sub-soiling and without deep sub-soiling, suggesting that the yield differences were not significantly determined by water supply. The water use average for wheat was: 380 mm with TS, 377 mm with CS, 395 mm with DS, and 382 mm with NT. For maize, water use was 339 mm with TS, 345 mm with CS, 343 mm with DS, 341 mm with ST and 343 mm with NT. For soybean, water use was 320 mm with TS, 315 mm with CS, 317 mm with DS, 314 mm with ST and 319 mm with NT. Water use efficiency from precipitations was: For wheat 13.1 kg $ha^{-1}mm^{-1}$ with TS, 12.1 kg $ha^{-1}mm^{-1}$ with CS, 12.2 kg $ha^{-1}mm^{-1}$ with DS, and 13.3 kg $ha^{-1}mm^{-1}$ with NT. For maize 25.6 kg $ha^{-1}mm^{-1}$ with TS, 25.6 kg $ha^{-1}mm^{-1}$ with CS, 25.3 kg $ha^{-1}mm^{-1}$ with DS, 22.9 kg $ha^{-1}mm^{-1}$ with ST, and 26.1 kg $ha^{-1}mm^{-1}$ with NT. For soybean 6.6 kg $ha^{-1}mm^{-1}$ with TS, 5.5 kg $ha^{-1}mm^{-1}$ with CS, 5.8 kg $ha^{-1}mm^{-1}$ with DS, 5.5 kg $ha^{-1}mm^{-1}$ with ST, and 6.0 kg $ha^{-1}mm^{-1}$ with NT. Yield increases due to deep sub-soiling were: 0.1% for wheat, 1.5% for maize, and 7.3% for soybean. The average yields recorded were: For wheat 4948 kg ha^{-1} with TS, 4536 kg ha^{-1} with CS, 4814 kg ha^{-1} with DS, 5048 kg ha^{-1} with NT. For maize 8743 kg ha^{-1} with TS, 8954 kg ha^{-1} with CS, 8792 kg ha^{-1} with DS, 7940 kg ha^{-1} with ST and 9052 kg ha^{-1} with NT. For soybean 2098 kg ha^{-1} with TS, 1812 kg ha^{-1} with CS, 1846 kg ha^{-1} with DS, 1798 kg ha^{-1} with ST and 1941 kg ha^{-1} with NT. The highest yields were obtained with NT for wheat and maize. WUE was strongly correlated with yield, and had the highest values for wheat and maize with NT. In the case of soybean, we consider that a significant yield increase can be obtained with an efficient weed control and soil protection with adequate amounts of residues from the previous crop.

Key words: deep sub-soiling, tillage systems: traditional, chisel plough, disk/sweep, strip till, no till, over-winter soil water accumulation and storage, crop water use, water use efficiency (WUE).

INTRODUCTION

The yield of field crops is negatively affected in years with lack of rainfall and extended droughts during the vegetation period. These conditions are very frequent in the South-East Plain of Romania (Bărăgan). For normal high yields, efficient tillage systems are required to increase soil water accumulation, storage and its use efficiency, as well as to reduce soil erosion.

Winter wheat – maize – soybean rotation has proven to be an excellent option for the Bărăgan Plain, characterized by very fertile

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soils, in most cases of chernozem types. This crop rotation improves the soil structure and water regime. The climate of this zone is temperate-continental. Mean annual temperatures are of 10–11ºC, mean winter (January) temperatures are of -2ºC, and mean summer (July) temperatures are higher than 22ºC. The mean annual sum of rainfall is 580 mm. The potential evapo-transpiration in March - October period exceeds two-three folds the sum of utile precipitations, so the water factor is restricting for agricultural output. Droughts, which often happen in this zone during the grain formation, cause a lack of balance between evapo-transpiration and soil water absorption, and this stress reduces the yield and its quality (Guş et al., 1998).

In such water limited conditions, the application of certain tillage systems is highly needed to increase the water use efficiency (WUE). Previous research recommended generalization of „alternative tillage depth" (Tianu, 1995) for winter wheat – maize – soybean rotation in this zone.

However this practice preserves insufficient vegetative residues on soil surface to reduce or prevent the erosion. When this research was initiated, the fact that conservation tillage systems have been extended successfully in the last decades all over the world was taken into consideration. Most conservation tillage systems maintain around one third of soil surface covered with vegetal residues resulted from the previous crop. It is part of the „Minimum or/and No Till Tillage System Concept". Vegetal residues on soil surface reduce water evaporation, and therefore favor water accumulation and conservation, which is very important in drought conditions (Hartfield et al., 2001). The residue cover also decreases the wind and water soil erosion (Unger et al., 1988).

The most commonly utilized tillage systems are: „no till"; „reduced till or mulch till"; „ridge till"; and „strip till" (Baker et al., 2002).

The modality of vegetal residue preservation, its retained quantity and orientation are important factors for reducing evaporation and for soil water accumulation and storage (Nielsen et al., 2005). Additionally, the snow management represents a significant part of the cumulated soil water. The standing vegetal residues and stubble play an important role in snow retention, increasing water infiltration and storage in the soil (Aase and Siddoway, 1990).

A sustainable and stable agricultural production requires efficient tillage systems for water capitalization. Water use efficiency (WUE) is considered the main standard for the comparisons of different tillage systems, especially in areas with frequent prolonged droughts and low precipitations during the vegetation period (Hatfield et al., 2001).

The main objective of this research was evaluation of the effect of different tillage systems on the following factors: (1) over-winter soil water accumulation and storage; (2) water use and efficiency; and (3) yield of winter wheat, maize, and soybean, in rotation.

MATERIAL AND METHODS

This research was carried out at the National Agricultural Research and Development Institute Fundulea (NARDI), in 2008 and 2009. The following tillage systems were studied:

(1) traditional, with moldboard plough (TS);

(2) chisel plough tillage – primary tillage executed with chisel implement type without furrow overthrowing (CS);

(3) disc/sweep tillage – it has a combined effect of residues breaking up by the discs along with the primary tillage performed by sweeps, without furrow over throwing (DS);

(4) strip till (ST) – a variant of "No till", applied to row crops. It is executed in fall, opening furrows with width of 1/3 rd of the distance between the rows, so it agitates less the soil and determines a faster soil warming up in spring.

(5) No till (NT) – without any tillage work.

The main characteristics of the soil on which the present research was carried out are presented in Table 1. The crop management sequences and their succession within each tillage type are presented for each crop involved in rotation in Tables 3, 4, and 5.

The effect of different tillage systems was estimated on plots without deep sub-soiling and plots with deep sub-soiling, executed once - only when this research was initiated (summer of 2007).

The previous crop residue (as called secondary product) was threshed and uniformly spread on the respective plot during its harvest.

Table 1. Main characteristics of the soil on which the present research was performed (NARDI Fundulea)

Characteristics of arable horizon:	
Soil type	Cambic chernozem
Clay content (%)	36.50
Bulk density (g cm^{-3})	1.26
Penetration resistance (kg cm^{-2})	28.00
Hydraulic conductivity (mm h^{-1})	49.20

Climatic conditions

The mean temperature of 2007/2008 agricultural year at Fundulea was 0.8ºC higher than the normal (Table 2), positive deviations ranging between 0.5ºC and 3.6ºC. The warmest months were February (2.7ºC deviation), March (3.6ºC deviation), and August (3.0ºC deviation). The highest temperature was recorded in August (25ºC). 2008-2009 year was also warmer, with 1.4ºC higher annual mean than the multi-annual normal and with positive deviations all months, between 0.4ºC and 2.8ºC. The warmest months were December (2.8ºC deviation) and February (2.7ºC deviation). The highest temperature was recorded in July (24ºC).

Total rainfall in 2007/2008 was 470.4 mm, which was 109.3 mm less than the multi-annual mean. The precipitations in fall were in excess, contributing to an important water accumulation in the deeper soil horizons. The January – April period was dry, but the rains in April compensated the soil water reserve, determining a normal growth and development of winter wheat up to harvest, and good conditions for maize and soybean planting and emergence. For these two crops, the water stress occurred in June – August, when the rainfall deficit summed more than 100 mm.

*Table 2***.** Monthly mean temperatures and rainfall in 2007/2008 and 2008/2009 agricultural years

Month	MMA*	2007/2008	Dev.**	2008/2009	Dev.**
Temperature, °C					
Octomber	11.2	11.7	0.5	12.6	1.4
November	5.0	3.3	-1.7	5.8	0.8
December	-0.3	-0.6	-0.3	2.5	2.8
Jannuary	-2.4	-3.1	-0.7	-0.9	1.5
February	-0.3	2.4	2.7	2.4	2.7
March	4.6	8.2	3.6	5.9	1.3
April	11.1	12.7	1.6	11.5	0.4
May	17.0	16.6	-0.4	17.6	0.6
June	20.6	21.9	1.3	21.8	1.2
July	22.5	23.3	0.8	24.0	1.5
August	22.0	25.0	3.0	23.3	1.3
September	17.2	16.6	-0.6	18.5	1.3
MEAN	10.7	11.5	0.8	12.1	1.4
Rainfall, mm					
Octomber	40.4	46.2	5.8	25.9	-14.5
November	44.7	52.7	8.0	27.5	-17.2
December	44.1	62.4	18.3	33.2	-10.9
Jannuary	32.3	15.0	-17.3	69.2	36.9
February	31.2	2.3	-28.9	25.5	-5.7
March	37.6	21.4	-16.2	32.3	-5.3
April	45.0	61.6	16.6	22.1	-22.9
May	59.4	59.9	0.5	35.8	-23.6
June	71.5	30.6	-40.9	103.6	32.1
July	72.3	57.5	-14.8	119.5	47.2
August	51.1	1.6	-49.5	24.6	-26.5
September	50.1	59.2	9.1	43.2	-6.9
MEAN	579.7	470.4	-109.3	562.4	-17.3

*MMA – multi-annual average of 50 years
**Dev. – deviation from multi-annual average of 50 years

Total rainfall in 2008/2009 agricultural year was 562.4 mm, which was only 17.3 mm less than the multi-annual average. In these conditions, winter wheat developed normally up to the stage of yield formation when the water stress period started. The adequate soil water reserve in spring assured a good germination and emergence of maize and soybean crops.

The rainfall in excess in June and July restored the soil water reserve, which allowed a normal crop evolution up to physiological maturity.

Table 3. Tillage systems tested for winter wheat at NARDI Fundulea, in 2008 and 2009

Tillage system	Characteristic operations
Traditional tillage	IN FALL: P_{80} fertilization; moldboard plough; disc; combinator land preparation; planting . IN SPRING: N_{120} fertilization; herbicide application.
Chisel plough tillage	IN FALL: P_{80} fertilization; chisel plough; disc; combinator land preparation; planting . IN SPRING: N_{120} fertilization; herbicide application.
Disc/sweep tillage	IN FALL: P_{80} fertilization; disc/sweep work; disc; combinator land preparation; planting. IN SPRING: N_{120} fertilization; herbicide application.
No till	IN FALL: $P_{80}N_{30}$ fertilization. IN SPRING: N_{90} fertilization; herbicide application.

The soil water reserve, accumulated during the cold season (mainly winter), is an important water source for spring crops, especially during periods with water deficit, which are frequent in the Bărăgan Plain. Within this research, water accumulation was estimated by the coefficient of the precipitations stored in soil, calculated with formula: CI = (Ri – Rf) / Pi, in which Ri (mm) is soil water reserve in spring (initial), Rf (mm) is soil water reserve in fall (final), and Pi (mm) represents the precipitations during the cold season. Soil water storage capacity was calculated using formula: Cc = Ri / (Rf + Pi). It shows relatively how much the soil water reserve in spring represents from the total soil water reserve in fall plus the sum of rainfall.

Plant water use of the winter wheat, maize and soybean crops was determined during the whole vegetation period, depending on deep sub-soiling or not sub-soiling, and different water supply conditions. The evaluations were performed on the basis of soil water balance in the 0-90 cm level.

Water use efficiency (WUE) was calculated using the following formula: WUE = PB/ET (kg $ha^{-1}mm^{-1}$), in which PB is the grain yield (kg ha^{-1}), and ET is water consumption during the vegetation period (mm).

The winter wheat and soybean experimental plots were of 10 m long and 1.5 m wide, and were harvested by combine. The experimental maize plots were comprised 2 rows of 10 m length, chosen from the middle of a larger plot.

Table 4. Tillage systems tested for maize at NARDI Fundulea, in 2008 and 2009

Tillage system	Characteristic operations
Traditional tillage	IN FALL: P_{80} fertilization; moldboard plough; IN SPRING: disc; pre-emergence herbicide application; combinator land preparation; planting IN VEGETATION PERIOD: N_{180} fertilization; post-emergence herbi-cide application; weeding
Chisel plough tillage	IN FALL: P_{80} fertilization; chisel plough; IN SPRING: disc; pre-emergence herbicide application; combinator land preparation; planting IN VEGETATION PERIOD: N_{180} fertilization; post-emergence herbicide application; weeding
Disc/sweep tillage	IN FALL: P_{80} fertilization; disc/sweep plough; IN SPRING: disc; pre-emergence herbicide application; combinator land preparation; planting IN VEGETATION PERIOD: N_{180} fertilization; post-emergence herbicide application; weeding
Strip till	IN FALL: strip opening IN SPRING: total pre-emergence herbicide application; planting plus $P_{80}N_{30}$ fertilization; N_{150} fertilization IN VEGETATION PERIOD: post-emergence herbicide application
No till	IN SPRING: total pre-emergence herbicide application; planting plus $P_{80}N_{30}$ fertilization; N_{150} fertilization IN VEGETATION PERIOD: post-emergence herbicide application

Table 5. Tillage systems tested for soybean at NARDI Fundulea, in 2008 and 2009

Tillage system	Characteristic operations
Traditional tillage	IN FALL: P_{60} fertilization; moldboard plough. IN SPRING: disc; pre-emergence herbicide application; combinator land preparation; planting. IN VEGETATION PERIOD: N_{180} fertilization; post-emergence herbicide application; weeding.
Chisel plough tillage	IN FALL: P_{60} fertilization; chisel plough. IN SPRING: disc; pre-emergence herbicide application; combinator land preparation; planting. IN VEGETATION PERIOD: N_{180} fertilization; post-emergence herbicide application; weeding.
Disc/sweep tillage	IN FALL: P_{60} fertilization; disc/sweep plough. IN SPRING: disc; pre-emergence herbicide application; combinator land preparation; planting. IN VEGETATION PERIOD; post-emergence herbicide application; weeding.
Strip till	IN FALL: strip opening. IN SPRING: total pre-emergence herbicide application; planting plus $P_{60}N_{20}$ fertilization; N_{150} fertilization. IN VEGETATION PERIOD: post-emergence herbicide application.
No till	IN SPRING: total pre-emergence herbicide application; planting plus $P_{60}N_{20}$ fertilization; N_{150} fertilization. IN VEGETATION PERIOD: post-emergence herbicide application.

The yields were reported on a dry weight basis.

The experimental design for each crop in rotation was the split plot with randomized complete blocks design in three replications. The main plots represented sub-soiling and not sub-soiling factor, and the subplots were the tillage systems. Each replication contained 10 plots: 2 factors of sub-soiling * 5 tillage systems. The analysis of variance (ANOVA) was applied, and Duncan test at $P \leq 0.05$ (multiple comparison method) was calculated for estimation of difference significance. Correlations between WUE and average yield were also evaluated. The ET, WUE and PB were separately analyzed for each crop.

RESULTS

Effect of deep sub-soiling and tillage systems on soil water accumulation and storage during the cold season

This research results show that the deep sub-soiling and the tillage systems under study did not affect significantly the soil water accumulation and storage during the cold season (season without vegetation).

When maize followed winter wheat (Table 6), the precipitation water storage was similar for plots without sub-soiling (Ci = 0.6) and for those with sub-soiling (Ci = 0.6). The soil water storage capacity was also equal (Cc = 85%).

When soybean followed maize, higher precipitation water storage was recorded for plots without sub-soiling (Ci = 0.6) than for those with sub-soiling (Ci = 0.5). The soil water storage capacity was 2% higher in plots without subsoiling.

Table 6. Soil water accumulation and storage with deep sub-soiling and without sub-soiling, for two crop rotations, during the cold season

Plots	Maize/Winter wheat		Soybean / Maize	
	Ci	Cc (%)	Ci	Cc (%)
With sub-soiling	0.6	85	0.5	77
Without sub-soiling	0.6	85	0.6	79

The results in Table 7 show that, when maize followed winter wheat, Ci = 0.7 was higher for DS, ST and NT variants than for TS and CS (Ci= 0.6), the Cc% values being also 2-4% higher for DS, ST and NT variants.

Table 7. Soil water accumulation and storage under different tillage systems for maize/winter wheat rotation, during cold season

Tillage system	Maize/Winter wheat				
	TS	CS	DS	ST	NT
Ci	0.6	0.6	0.7	0.7	0.7
Cc (%)	82	84	86	86	86

When soybean succeeded maize (Table 8), Ci values were lower for TS, CS and DS (Ci = 0.5) than for ST and NT (Ci = 0.6) which do not stir or stir less the soil. Cc% value for TS was 6-7% lower than for all the other variants.

So, the reduced tillage systems and soil conservation measures, as vegetal residue retention on soil surface, caused a better soil water storage when compared to the traditional moldboard ploughing. More important was the residue retention on soil surface, which added 2-3 % soil moisture.

Table 8. Soil water accumulation and storage under different tillage systems for soybean/maize rotation, during the cold season

Tillage system	Soybean/Maize				
	TS	CS	DS	ST	NT
Ci	0.5	0.5	0.5	0.6	0.6
Cc (%)	72	78	78	78	79

Effect of deep sub-soiling and different tillage systems on crops water use

Water use varied as follows: 359-406 mm for winter wheat, 299-379 mm for maize, and 244-391 mm for soybean, with significant differences between years. Crops water use was higher in the year higher rainfall during the vegetation period. Thus, the water use recorded in 2008 was: 398 mm for winter wheat, 309 mm for maize, 248 mm for soybean, while in 2009 it was: 369 mm for winter wheat, 374 mm for maize, 386 mm for soybean. Deep sub-soiling did not have a significant influence on plant water use (Table 9). The mean water use of plots with or without sub-soiling was: 384 mm and 383 mm for winter wheat, 328 mm and 356 mm for maize, 316 mm and 318 mm, respectively.

Table 9. Water use of winter wheat, maize and soybean crops on plots with or without deep sub-soiling (mm)

Plots	Year		Water use mean
	2008	2009	
Winter wheat			
With sub-soiling	394 a	374 a	384 a
Without sub-soiling	401 a	364 a	383 a
Maize			
With sub-soiling	280 b	376 a	328 a
Without sub-soiling	338 a	373 a	356 a
Soybean			
With sub-soiling	249 a	382 a	316 a
Without subsoiling	247 b	389 a	318 a

The tillage systems under this study did not have a significant effect on plant water use (Table 10). The average water use of each crop was similar for all tillage systems applied (377-395 mm for winter wheat, 339-345 mm for maize, and 314-320 mm for soybean).

Table 10. Water use of winter wheat, maize and soybean crops under different tillage systems (mm)

Tillage System	Year		Water use mean
	2008	2009	
Winter wheat			
TS	401 a	359 b	380 a
CS	387 a	366 b	377 a
DS	406 a	384 a	395 a
NT	396 a	367 b	382 a
Maize			
TS	299 a	379 a	339 a
CS	313 a	376 a	345 a
DS	310 a	376 a	343 a
ST	307 a	375 a	341 a
NT	319 a	366 a	343 a
Soybean			
TS	249 a	391 a	320 a
CS	244 a	387 a	315 a
DS	249 a	386 a	317 a
ST	244 a	382 a	314 a
NT	255 a	383 a	319 a

Effect of deep sub-soiling and tillage systems on grain yields

The grain yields varied from 4392 to 5423 kg ha^{-1} for winter wheat, from 5117 to 12010 kg ha^{-1} for maize, and from 993 to 2612 kg ha^{-1} for soybean. Generally, the yields responded positively to the amount of rainfall in the grain formation period. Thus in 2008, the average yields were: 5123 kg ha^{-1} for winter wheat, 5964 kg ha^{-1} for maize, and 1247 kg ha^{-1} for soybean, but in 2009, the average yield for winter wheat was lower (4551 kg ha^{-1}), and for maize and soybean much higher, 11429 kg ha^{-1} and 2551 kg ha^{-1} , respectively.

Table 11. Winter wheat, maize, and soybean grain yields obtained with and without deep sub-soiling (kg ha^{-1})

Plots	Year		Average grain yields
	2008	2009	
Winter wheat			
With sub-soiling	5128 a	4550 a	4839 a
Without sub-soiling	5117 a	4552 a	4834 a
Maize			
With sub-soiling	5996 a	11526 a	8761 a
Without sub-soiling	5931 a	11332 a	8632 a
Soybean			
With sub-soiling	1281 a	2650 a	1965 a
Without sub-soiling	1213 b	2451 a	1832 b

Table 12. Winter wheat, maize, and soybean grain yields when different tillage systems were applied, kg ha^{-1}

Tillage System	Year		Average grain yields
	2008	2009	
Winter wheat			
TS	5423 a	4472 b	4948 ab
CS	4682 b	4392 b	4536 c
DS	5023 ab	4605 ab	4814 b
NT	5362 a	4735 a	5048 a
Maize			
TS	6398 a	11088 a	8743 a
CS	6097 a	11812 a	8954 a
DS	6112 a	11472 a	8792 a
ST	5117 b	10763 a	7940 b
NT	6095 a	12010 a	9052 a
Soybean			
TS	1585 a	2612 a	2098 a
CS	1042 c	2582 a	1812 b
DS	1280 b	2412 a	1846 b
ST	993 c	2602 a	1798 b
NT	1335 b	2547 a	1941 b

Deep sub-soiling did not have a significant influence on winter wheat and maize yields, but a significantly higher yield was recorded for soybean, when compared to plots without sub-soiling (Table 11). So, the yields were: 4839 and 4834 kg ha^{-1} for winter wheat, 8761 and 8632 kg ha^{-1} for maize, 1965 and 1832 kg ha^{-1} for soybean.

The grain yields of all three crops were significantly influenced by the tillage systems (Table 12). For winter wheat the yields ranged from 4536 (CS variant) to 5048 kg ha^{-1} (NT variant); for maize from 7940 ST variant to 9052 kg ha^{-1} (NT variant); for soybean from 1798 (ST variant) to 2098 kg ha^{-1} (TS variant).

Effect of deep sub-soiling and tillage systems on use efficiency of water from rainfall (WUE)

WUE had quite constant values for winter wheat (12.0-13.7 kg ha^{-1}mm^{-1}) and soybean (4.1-6.8 kg ha^{-1}mm^{-1}), regardless of the tillage system and water supply. For maize, WUE values varied in a much larger extend (16.9-32.8 kg ha^{-1}mm^{-1}), higher values being recorded for the variants with greater yields due to more abundant rainfall.

The results presented in Table 13 show that deep sub-soiling did not have a significant influence on the efficiency of precipitation water use for any crop. Thus, the average values for winter wheat were equal for both variants, of 12.7 kg ha^{-1}mm^{-1}, for maize 26.1 and 24.1 kg ha^{-1}mm^{-1}, and for soybean 6.1 and 5.1 kg ha^{-1}mm^{-1}.

Table 13. Water use efficiency (WUE) of three crops with and without sub-soiling (kg ha^{-1}mm^{-1})

Plots	Year		WUE average
	2008	2009	
Winter wheat			
With sub-soiling	13.1	12.2	12.7
Without sub-soiling	12.8	12.5	12.7
Maize			
With sub-soiling	21.4	30.7	26.1
Without sub-soiling	17.7	30.5	24.1
Soybean			
With sub-soiling	5.1	6.9	6.1
Without sub-soiling	4.9	6.3	5.6

Water use efficiency (WUE) of winter wheat showed a high significant correlation with grain yield, the correlation being higher plots with deep sub-soiling (Figure 1).

Maize grain yield was also significantly correlated with WUE for both sub-soiling and without sub-soiling plots (Figure 2).

WUE of soybean was highly correlated with grain yield for both sub-soiling and without sub-soiling (Figure 3).

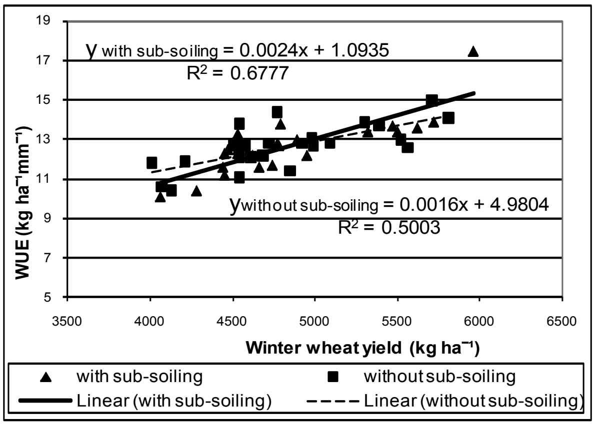

Figure 1. Correlation between winter wheat yield and use efficiency of water from rainfall (WUE)

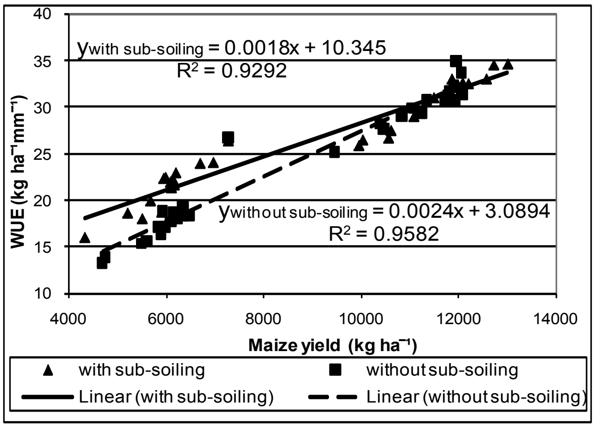

Figure 2. Correlation between maize yield and use efficiency of water from rainfall (WUE)

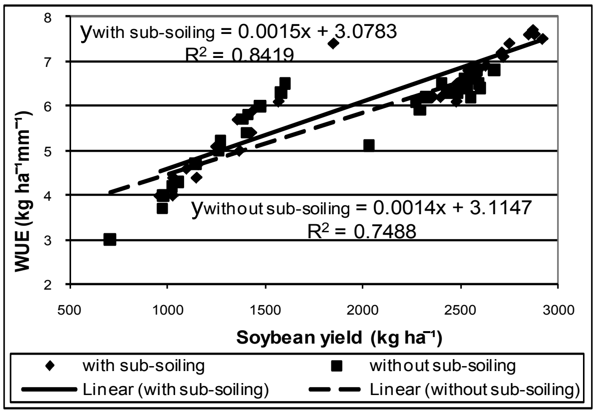

Figure 3. Correlation between soybean yield and use efficiency of water from rainfall (WUE)

Tillage systems influenced significantly the WUE of winter wheat crop (Table 14). The highest value was of 13.3 kg ha^{-1}mm^{-1} (for NT), and the smallest, of 12.1 kg ha^{-1}mm^{-1}, were recorded for CS variant. In maize, tillage systems did not have a significant effect on WUE, the mean values ranging between 22.9 kg ha^{-1}mm^{-1} (for ST) and 26.1 kg ha^{-1}mm^{-1} for NT. Tillage systems influenced signifycantly or highly significantly the WUE of soybean. The highest value was of 6.6 kg ha^{-1}mm^{-1} (for TS), and the smallest, of 5.5 kg ha^{-1}mm^{-1}, was recorded for CS and ST variants.

Table 14. Water use efficiency (WUE) of winter wheat, maize, and soybean crops under different tillage systems (kg ha^{-1}mm^{-1})

Tillage system	Year		WUE average
	2008	2009	
Winter wheat			
TS	13.5 a	12.6 a	13.1 a
CS	12.1 a	12.0 a	12.1 b
DS	12.4 a	12.0 a	12.2 b
NT	13.7 a	13.0 a	13.3 a
Maize			
TS	21.9 a	29.3 a	25.6 a
CS	19.6 b	31.4 a	25.6 a
DS	20.0 ab	30.5 a	25.3 a
ST	16.9 b	28.8 a	22.9 a
NT	19.3 ab	32.8 a	26.1 a
Soybean			
TS	6.4 a	6.7 a	6.6 a
CS	4.3 c	6.7 a	5.5 c
DS	5.2 b	6.3 a	5.8 bc
ST	4.1 c	6.8 a	5.5 c
NT	5.3 b	6.7 a	6.0 b

WUE of winter wheat was significantly correlated with grain yield for TS, and highly significant for CS, NT, and especially for DS variant (Figure 4). WUE values for TS were superior to other tillage systems up to 4903 kg ha^{-1} yield level (for CS), 4967 kg ha^{-1} (for NT), and 5570 kg ha^{-1} (for DS).

WUE of maize was highly significantly correlated with the grain yield in all tillage systems under study (Figure 5). WUE values for TS were superior to other tillage systems up to 9232 kg ha^{-1} yield level (for CS), 9252 kg ha^{-1} (for NT), 9989 kg ha^{-1} (for DS) and 10985 (for ST).

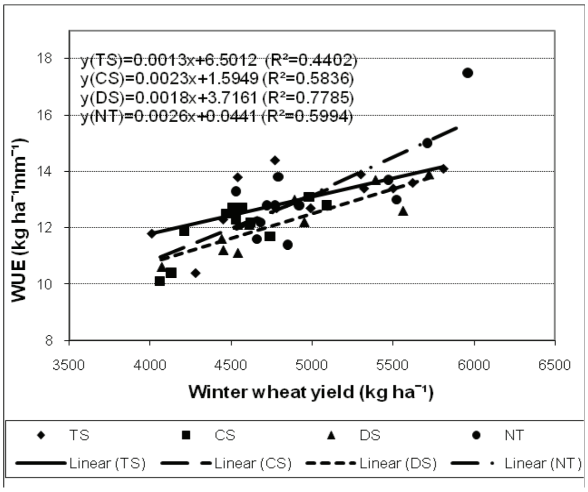

Figure 4. Effect of different tillage systems on winter wheat yield and use efficiency of water from rainfall (WUE)

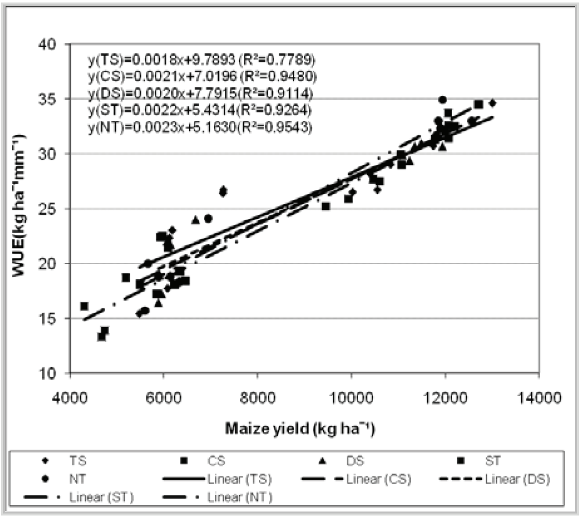

Figure 5. Effect of different tillage systems on maize yield and use efficiency of water from rainfall (WUE)

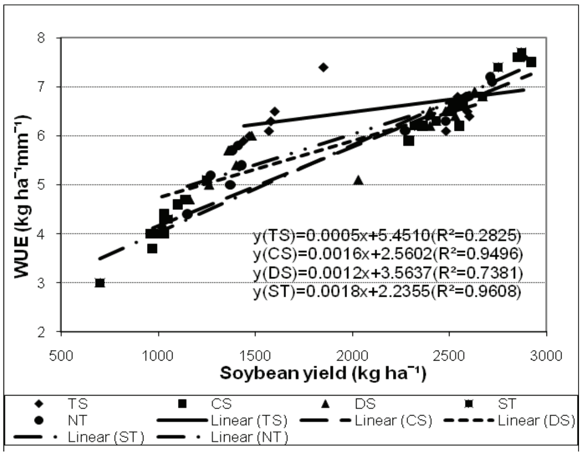

Figure 6. Effect of different tillage systems on soybean yield and use efficiency of water from rainfall (WUE)

WUE of soybean was not significantly correlated with grain yield for TS variant, but highly correlated for all the other tillage systems (Figure 6).

WUE was highly significantly correlated with grain yields in all three crops the strongest correlation being recorded in maize (Figure 7).

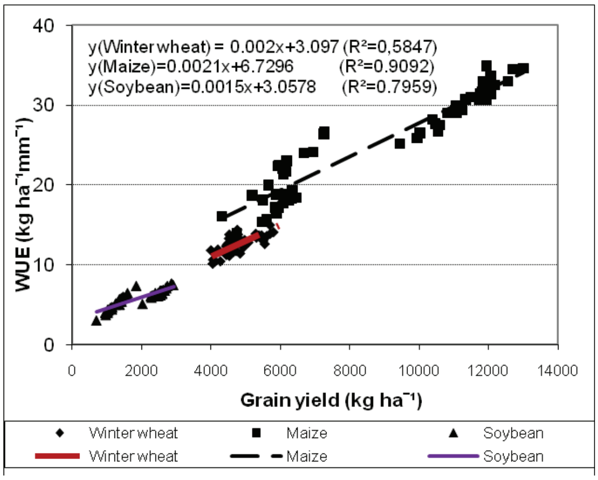

Figure 7. Relationships between grain yield and WUE for winter wheat, maize and soybean, in rotation

DISCUSSION

In areas with reduced or not favorable for agricultural crops distribution of rainfall, efficient tillage systems are required to increase soil water accumulation, storage and its use efficiency, as well as to reduce soil erosion. Winter wheat, maize and soybean yields were highly positively correlated with water use efficiency (WUE), indicating that the yield increase enhances the WUE (Figure 7). WUE was also influenced by the water crop use, as well as by the rainfall during the vegetation period. As we are not able to influence rainfall, we can influence the water use and water storage in soil.

The mean water use of these three crops was not significantly influenced by the deep sub-soiling and any other tillage system under this study (Tables 9 and 10). This research has not estimated what percentage from the total water from precipitation was used by the crops and what was lost by evaporation from soil. It is well known that water lost by evaporation from soil depends on meteorological conditions, soil water reserve level, and soil properties. The crops evapo-transpiration is more affected by the meteorological conditions. The results of this research show that tillage systems which reduce water evaporation from soil increase the grain yields, along with WUE. An efficient way of decreasing water evaporation from soil is to enhance soil coverage with the residue from the previous crop. This residue facilitates also water infiltration and storage (Hatfield et al., 2001).

When the effect of deep sub-soiling was analyzed, a better water soil accumulation and storage in the cold season was recorded only in the case of winter wheat stubble. The explanation is that it confers a more adequate permeability than the maize stubble (Table 6). The tillage systems aimed to soil conservation (NT and ST) determined a higher level of soil water accumulation and storage in cold season, in comparison with the reduced tillage (CS and DS) and traditional moldboard plough (TS), in both wheat and maize stubbles. This is due to differences in soil permeability and vegetal residue retention on the land surface. The mean winter wheat and maize grain yields were not significantly influenced by the deep sub-soiling (Table 11). In soybean, deep sub-soiling significantly increased the grain yield, due to the hardpan breaking, which substantially improved water soil infiltration. The highest winter wheat and maize grain yields were obtained with the NT variant (Table 12). The vegetal residue maintained the soil moisture 2-3% higher than in uncovered soil, but it delayed planting with several days, especially in the cold and humid springs. Similar investigations concluded that the crops growth and development are slower when no-tillage is practiced on humid and cold soils (Vyn et al., 1998), but this lagging gradually diminishes and disappears up to blooming stage. A slower plant growth and development can be considered favorable for more efficient water use, because the soil water reserve is higher later, during the yield elements formation stages. Traditional moldboard plough (TS) determined the highest soybean grain yield, due to its contribution to land preparation for planting without vegetal residues, which may affect the emergence and early plant growth. In the cases of reduced tillage (CS and DS), and systems aimed to soil conservation (NT and ST), the slower soybean plant growth favored the weed concurrence, which significantly reduced the yield of this crop.

The WUE mean values for winter wheat with or without sub-soiling were not significantly different (Table 13), but higher WUE values with sub-soiling at yields higher than 4859 kg ha^{-1} indicate a superior water use from precipitations in this case (Figure 1). WUE mean values for maize and soybean were also statistically similar with and without sub-soiling. The maize grain yield showed a strong correlation with WUE, regardless of deep sub-soiling. Up to a yield level of over 12,000 kg ha^{-1}, WUE is higher with deep sub-soiling (Figure 2). For soybean, the grain yield – WUE correlation was also significant (Figure 3).

The WUE values for winter wheat were significantly superior with NT and TS than with CS and SD, mainly due to lower yields recorded with the last two tillage systems (Table 14).

The WUE for maize was statistically similar with all tillage systems studied. The highest yield and WUE correlation were recorded for NT variant, suggesting that the water use from rainfall was the most efficient for yields over 9300 kg ha^{-1} (Figure 5).

WUE for soybean with TS was significantly better than with the other tillage systems, especially than the conservative ones (Figure 6). This is the result of the fact that the tillage and cropping conditions which increase the yield also favor the WUE. Weed control, especially with efficient herbicide applications for the herbicide tolerant varieties of this crop, is essential in conservative tillage systems to achieve high grain yields and better WUE. For traditional, non herbicide tolerant soybean varieties further research is needed for identifying those with better reaction to vegetal residue presence in conservative tillage, such as NT and ST.

The results presented in this paper reveal that different tillage systems have a different effect on soil water accumulation and storage, plant water use, water use efficiency and grain yield of winter wheat, maize and soybean, in rotation. When tillage systems are chosen for winter wheat - maize - soybean rotation, it is important to consider the interaction of different factors which affect the plant water use and contribute to a better WUE and higher yields. The conservative attributes of no till (NT) system make this variant very attractive. WUE was influenced by different factors of which the most important was the vegetal residue maintenance on land surface, because it contributed significantly to soil water storage, when conservative tillage systems were applied. Higher water storage did not assure higher yields without an adequate weed control, as it was recorded for soybean with the no till (NT) system. In limited water conditions, improvements of agriculture practices which increase the yield also conduct to a better WUE.

CONCLUSIONS

In areas with reduced rainfall or not favorable for agricultural crops distribution of rainfall, efficient tillage systems are required to increase soil water accumulation, storage and its use efficiency, as well as to reduce soil erosion.

Yield increase gradually enhanced the WUE of winter wheat, maize and soybean.

Water use and WUE of these three crops was not significantly influenced by the deep sub-soiling and any other tillage system under this study.

Tillage systems which reduced water evaporation from soil, increased the grain yields, along with WUE.

The tillage systems aimed to soil conservation (NT and ST) determined a higher level of soil water accumulation and storage during the cold season, in comparison with reduced tillage (CS and DS) and traditional moldboard plough (TS), in both wheat and maize stubbles.

Winter wheat and maize grain yields were not significantly influenced by the deep sub-soiling. In soybean, deep sub-soiling significantly increased the yield level, due to the hardpan breaking, which substantially improved water infiltration in the soil.

The highest winter wheat and maize grain yields were obtained with the NT variant and for soybean with the traditional moldboard plough tillage.

The vegetal residue maintained the soil moisture 2-3% higher than in the uncovered soil.

WUE values for winter wheat were significantly superior with NT and TS than with CS and SD; for maize, WUE was statistically similar with all tillage systems under study; for soybean, WUE recorded with TS tillage was significantly better than with all the other tillage systems.

Weed control, especially with efficient herbicide applications, is essential in conservative tillage systems to achieve high grain yields and better WUE.

The conservative attributes of no till (NT) system make this variant very attractive.

WUE was influenced by different factors of which the most important was the vegetal residue maintenance on land surface, because it contributed significantly to soil water storage.

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