

# 1 Conservation tillage vs. conventional tillage: long-term effects on yields in continental, 2 sub-humid Central Europe, Hungary

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## 13 14 Abstract

15 The present study reports novel data concerning Conservation Tillage (CT) in the continental sub-humid climate  
16 zone in Central Europe (Hungary), an area which has been mostly neglected in the course of previous CT  
17 studies. The results of a 10 year (2003-2013) comparative study of mouldboard ploughing tillage (PT) and CT  
18 (no inversion, using a reduced number of tillage operations and leaving min. 30% crop residues on the soil  
19 surface) types are reported. Our extensive monitoring system has provided new and detailed information  
20 concerning technologies and yields both from the first, transitional period and, over the following years, of  
21 adapted technology. Our results suggest that tillage type was a more important factor in the question of yields  
22 than either the highly variable climate of the studied years, or the diverse slope conditions of the plots. During  
23 the first three years of technological changeover to CT (2003–2006) a decrease of 8.7% was measured,  
24 respective to PT. However, the next seven years (2007–2013) brought a 12.7% increase of CT yields. Our study  
25 revealed key factors in the initial reduction of crops during the technological change, and may accordingly serve  
26 as a guideline for the shortening or avoidance of decline in the transitional period.

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28 Keywords: conservation agriculture, crop yield, winter wheat, maize, oil seed rape, weed control  
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## 30 1. Introduction

31 The main objective of Conservation Agriculture is to reverse the process of soil  
32 degradation and to conserve or improve available soil, water and biological resources. It is a  
33 combination of environmental conservation and enhanced and sustained agricultural  
34 production (FAO). The success of Conservation Agriculture technologies has been verified by  
35 their worldwide application over 125 million hectares (Friedrich et al. 2012). They are  
36 especially widespread in the Americas and Australia. Conservation Tillage (CT) is a set of  
37 practices that uses a reduced number of tillage operations with no inversion, leaving a  
38 minimum of 30% crop residues on the soil surface, which increases water infiltration and  
39 reduces erosion. Nevertheless, conservation tillage can be transition towards Conservation  
40 Agriculture (FAO). The dissemination of CT technologies had a relatively late start in Europe;  
41 nevertheless in 2010 CT tilled areas reached 22.7 million hectares (EU-28 + Iceland, Norway,  
42 Switzerland, Montenegro), which comprised 26% of arable land (Eurostat 2010). The  
43 advantages of CT in erosion prevention and water management, and its effects on soil  
44 properties with a positive ecological and economic outcomes led to an increasing trend  
45 towards the spread of CT areas (Álvaro-Fuentes et al. 2007, Basch et al. 2008, Field et al.  
46 2007, Holland 2004, Kassam et al. 2009, Lahmar 2010, Morris et al. 2010, Prasuhn 2012,  
47 Verch et al. 2009). Costs are reduced due to the omission of ploughing – a technique  
48 consuming a large amount of diesel oil –, by the employment of combined machines and by  
49 decreasing the number of passes. A decrease in the expenses even in the case of an unchanged  
50 yield results in extra profit, which could be important for the farmers during the technological  
51 shift. On the other hand, investigations were divided concerning yields. Several studies  
52 reported a minimum 5–10% increase in yields straight away, from the first year (Bescansa et  
53 al. 2006, De Tourdonnet et al. 2007, Košutić et al. 2005, Su et al. 2007, Wang et al. 2012).  
54 Others draw attention to the hazards of long term conservation tillage: yields may drop due to

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55 the increase of weeds and, occasionally, slug infection (El Titi 2003, Turley et al. 2003).  
56 Management decisions in appropriate to local conditions may be a key factor in decreasing  
57 yields as well (Koch and Stockfish 2006, Su et al. 2007). According to Soane et al. (2012) CT  
58 yields depend largely on soil quality, local geographical conditions and the weather of the  
59 studied year. Consequently, it is difficult to predict whether a farmer might expect increasing  
60 or decreasing yields after moving to CT. On the basis of 47 European studies, Van den Putte  
61 et al. (2010) concluded that conservation tillage reduces crop yields by 4.5%.

62 The majority of the analyses were carried out in Northern and Western Europe, under cool  
63 and wet climate conditions (Anken et al. 2004, Armand et al. 2009, Koch and Stockfish 2006,  
64 Turley et al. 2003, Verch et al. 2009, Vullioud et al. 2006), and in the Mediterranean  
65 southern– southwestern part of the continent (Kassam et al. 2012, Melero et al. 2009, Moreno  
66 et al. 2006, Pagliai et al. 1995, Soane et al. 2012). On the other hand, there is a scarcity of data  
67 on continental, sub-humid East Central Europe. (Birkás et al. 2004, Grigoras et al. 2011,  
68 Madarász et al. 2011, Šíp et al. 2009, Videnović et al. 2011).

69 During the last decade, following the international trend, there has been a dynamic increase  
70 in the number of farmers shifting to CT technology in Hungary. We estimate that today some  
71 kind of CT is used on approximately 50% of cropland in Hungary. At least a quarter of these  
72 users, however, are not conscious CT users (i.e. they lack any proper training or experience).  
73 Accordingly, an increasing amount of scientific information is necessary to determine the  
74 relations between tillage practices and physical, chemical, and biological soil factors that  
75 affect plant and pest ecology (Gebhardt 1985).

76 At the beginning of our research, an experiment was set up in 2003, as part of the SOWAP  
77 (Soil and Surface Water Protection Using Conservation Tillage in Northern and Central  
78 Europe) project (2003-2006) (Kertész et al. 2007, Lane 2007) to study the conventional  
79 (mouldboard Ploughing Tillage; PT) and CT (with no inversion, using a reduced number of  
80 tillage operations and leaving min. 30% crop residues on the soil surface) in a comparative  
81 manner. Our main objective was to monitor the changes observed on both the PT and CT  
82 parts of the plot-pairs and observe evolution of the yields. Our study provides a direct  
83 comparison of PT and CT tillage types under controlled conditions. Statistical analysis was  
84 used to determine the effect of several variables on the yields of both tillage types, allowing  
85 an investigation into the reasons for the changing yields.

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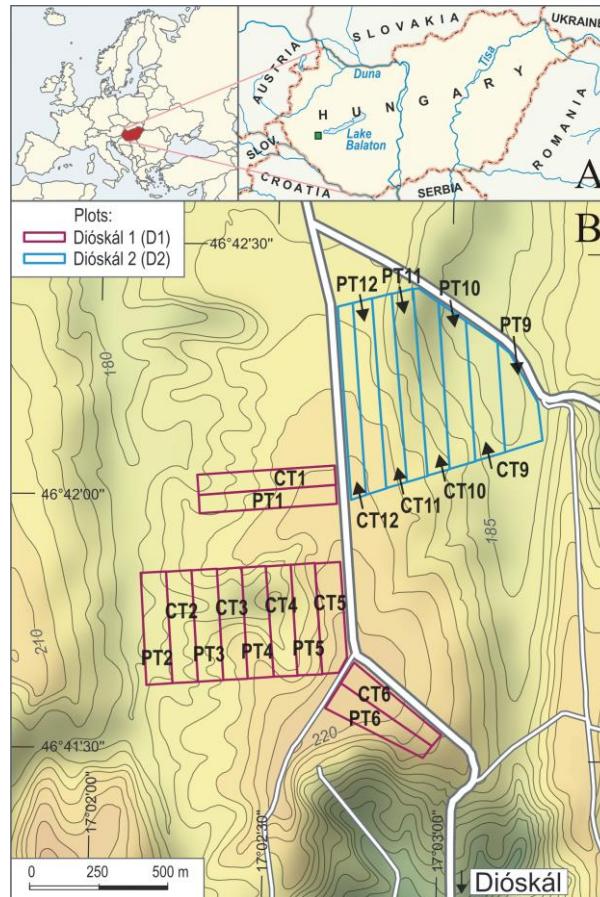
## 87 **2. Material and methods**

### 88 **2.1. The study area**

89 The study area is located in western Hungary, about 20 km southwest of Lake Balaton, near  
90 the village of Dióskál (Fig. 1A). The landscape is hilly (178–223 m a.s.l.) with slopes between  
91 1 and 17%. The parent material is loess, and the soils are Luvisols (Table 1). Soil profiles are  
92 eroded on the convex, upper part of the slopes, while thick soil sections are typical on the  
93 lower, concave slopes due to sedimentation.

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**Fig. 1.** A: Location of the study area (green rectangle). B: Setting of the experimental sites. CT 1–12: Conservation tillage plots; PT 1–12: Ploughing tillage plots

**Table 1.** Physical and chemical properties of the cultivated layer. Data result from a pit representative for the experimental field. The analysed samples were taken in spring, 2004. SOM: Soil Organic Matter; C/N: ratio between carbon and nitrogen; Clay = < 2  $\mu\text{m}$ ; Silt = 2–20  $\mu\text{m}$ ; Sand = 20–2000  $\mu\text{m}$

Depth	pH	pH	SOM	C/N	CaCO <sub>3</sub>	Bulk density	Clay	Silt	Sand
cm	H <sub>2</sub> O	KCl	%	%	%	g cm <sup>-3</sup>	%	%	%
0-15	7.35	6.54	2.33	49.47	0.00	1.38	8.78	48.91	42.31
15-30	7.29	6.56	1.82	43.45	0.00	1.56	9.48	52.14	38.38
30-45	7.15	6.26	1.10	34.59	0.00	1.61	11.53	52.70	35.76

Mean annual temperature between 2003 and 2013 was 11°C, and the duration of the frost-free season varied between 180–200 days. Long-term mean annual precipitation is 700 mm. However, it was only 619 mm in the studied time interval. In the growing season 430 mm precipitation can be expected (Hajósy et al. 1975) compared to the average of 396mm measured for the studied period. (Table 2).

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**Table 2.** Climate data of the experimental site during the studied time interval (2003–2013). Data of the local automatic weather station (by CWi Technical Ltd).

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Ø2003– 2013
Mean air temperature April–Sept. (°C)	18.6	16.5	16.6	17.2	18.3	17.4	18.1	16.8	18.4	18.5	17.8	17.7
Mean annual air temperature (°C)	11.0	10.2	10.0	10.6	11.9	11.8	11.2	10.2	11.1	11.8	11.2	11.0
April–Sept. precipitation (mm)	253	331	519	458	449	383	362	650	300	323	325	396
Annual precipitation (mm)	423	607	670	589	701	543	641	870	438	491	841	619

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## 2.2. Experimental design and tillage systems

119 The study area (104.9 ha) was divided into 10 pairs of CT and PT plots of similar size (~4 ha).  
120 Plots to the west of the road form the Dióskál1 area (D1) and those to the east of the road are  
121 the Dióskál2 area (D2) (Fig. 1B). Plots were designed to include areas of the erosional and  
122 accumulative parts of the slopes for both tillage types, so that the degree of erosion of the  
123 Luvisols would have no differential effect on the yields when comparing PT and CT.

124 The plot design was arranged in 2003 when the SOWAP project initiated, in congruence  
125 with the requirements of agro-ecological and ornithological studies (Field et al. 2007), and  
126 was confined to the land properties of the cooperating local farmers. Tillage occurred along  
127 contour lines at D2 and along the long axis of the plots at D1 due to the variable topography.  
128 Before the experiment, conventional tillage had been applied to the entire area.

129 Due to prior differences of crop-types on areas D1 and D2, we had to apply a somewhat  
130 different crop rotation to the two areas (Table 3).

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**Table 3.** Crop rotation in the study area. Dióskál 1 (D1), Dióskál 2 (D2) experimental sites; W.: Winter; S.: Spring

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
<b>D1</b>	W. wheat	Maize	W. wheat	Maize	W. wheat	Rape	W. wheat	Maize	S. barley	Rape
<b>D2</b>	Maize	W. wheat	Maize	W. wheat	Rape	W. wheat	Rape	W. wheat	Maize	S. barley

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137 This setting allowed a direct comparison of the two tillage types under the influence of  
138 similar external factors. An overview on the cultivation activities and equipment used in the  
139 study areas is provided in Table 4.

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**Table 4.** Cultivation activities and machinery used on the studied experimental sites, 2003–2013. KM drill: Kuhn Maxima Pneumatic spacing drill; H.: heavy; pl.: plough; Tsr harrow: Trailed spade rotary harrow; V.: Väderstad; 2×: two times

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<b>Dióskál 1 site</b>		<b>Dióskál 2 site</b>	
<b>Ploughing tillage</b>	<b>Conservation tillage</b>	<b>Ploughing tillage</b>	<b>Conservation tillage</b>
<b>2003/2004 Winter wheat</b>		<b>2003/2004 Maize</b>	
Ploughing (Reversible pl.)	Disking ( H. disc-harrow) 2×	Stubble disking (H. disc-harrow)	Stubble disking, (H. disc-harrow)
Stubble disking, (H. disc-harrow)	Sowing (V. Rapid)	Ploughing (Reversible pl.)	Disking (H. disc-harrow)
Seed-bed prep. (H. disc-harrow)		Levelling	Seed-bed prep. (H. disc-harrow)
Sowing (40 yr old mounted drill)		Seed-bed prep. (H. disc-harrow)	Sowing (John Deere)
		Sowing (John Deere)	
<b>2004/2005 Maize</b>		<b>2004/2005 Winter wheat</b>	
Stubble disking (H. disc-harrow)	Green manure sowing, V. Rapid	Ploughing (Reversible pl.)	Disking, Vadarstad Carrier 2x
Ploughing (Reversible pl.)	Disking, Vadarstad Carrier	Levelling (H. disc-harrow)	Sowing (V. Rapid)
Levelling, (V. Rexius roller)	Sowing (John Deere)	Seed-bed prep. (Tsr harrow)	
Sowing (John Deere)		Sowing (V. Rapid)	
<b>2005/2006 Winter wheat</b>		<b>2005/2006 Maize</b>	
Ploughing (Reversible pl.)	Disking (H. disc-harrow)	Liming	Liming
Levelling (H. disc-harrow)	Sowing (V. Rapid)	Stubble disking (H. disc-harrow)	Stubble disking (V. Carrier)
Sowing (V. Rapid)		Ploughing (Reversible pl.)	Disking (V. Carrier) 2x
		Levelling (V. Rexius roller)	Seed-bed prep. (Tsr harrow)
		Seed-bed prep. (Tsr harrow)	Sowing (Seed spacing drill)
		Sowing (Seed spacing drill)	
<b>2006/2007 Maize</b>		<b>2006/2007 Winter wheat</b>	
Stubble disking (H. disc-harrow)	Stubble disking (H. disc-harrow)	Disking (H. disc-harrow) 2×	Disking (V. Carrier)
Levelling (V. Rexius roller)	Levelling (V. Rexius roller)	Sowing (V. Rapid)	Sowing (V. Rapid)
Ploughing (Reversible pl.)	Disking, Vadarstad Carrier 2×		
Levelling (V. Rexius roller)	Sowing (KM drill)		
Seed-bed prep. (Tsr harrow)			
Sowing (KM drill)			
<b>2007/2008 Winter wheat</b>		<b>2007/2008 Oil seed rape</b>	
Ploughing (Reversible pl.)	Multicultivator (V. Top Down)	Stubble disking (H. disc-harrow)	Stubble disking (H. disc-harrow)
Levelling (V. Rexius roller)	Seed-bed prep. (Tsr harrow)	Medium deep subsoiling (Dondi)	Multicultivator (V. Top Down)
Seed-bed prep. (Tsr harrow)	Sowing (V. Rapid)	Levelling (V. Rexius roller)	Sowing (V. Rapid)
Sowing (V. Rapid)		Seed-bed prep. (Tsr harrow)	
		Sowing (V. Rapid)	
<b>2008/2009 Oils seed rape</b>		<b>2008/2009 Winter wheat</b>	
Stubble disking (V. Carrier )	Stubble disking (V. Carrier )	Stubble disking (H. disc-harrow)	Stubble disking (H. disc-harrow)
Ploughing (Reversible pl.)	H. duty cultivator (V. Cultus)	Levelling (V. Rexius roller)	Levelling (V. Rexius roller)
Levelling (V. Rexius roller)	Sowing (V. Rapid)	Disking (H. disc-harrow)	Disking (H. disc-harrow)
Seed-bed prep. (Tsr harrow)		H. duty cultivator (V. Cultus)	H. duty cultivator (V. Cultus)
Sowing (V. Rapid)		Sowing (V. Rapid)	Sowing (V. Rapid)
<b>2009/2010 Winter wheat</b>		<b>2009/2010 Oil seed rape</b>	
Stubble disking (V. Carrier )	Stubble disking (V. Carrier )	Stubble disking (V. Carrier )	Stubble disking (V. Carrier )
Ploughing (Reversible pl.)	Disking (V. Carrier)	Ploughing (Reversible pl.)	H. duty cultivator (V. Cultus)
Levelling (V. Rexius roller)	Seed-bed prep. (Tsr harrow)	Levelling (V. Rexius roller)	Seed-bed prep. (Tsr harrow)
Seed-bed prep. (Tsr harrow)	Sowing (V. Rapid)	Seed-bed prep. (Tsr harrow)	Sowing (V. Rapid)
Sowing (V. Rapid)		Sowing (V. Rapid)	
<b>2010/2011 Maize</b>		<b>2010/2011 Winter wheat</b>	
Stubble disking (V. Carrier )	Stubble disking (V. Carrier )	Stubble disking (H. disc-harrow)	Stubble disking (H. disc-harrow)
Ploughing (Reversible pl.)	H. duty cultivator (V. Cultus)	Levelling (V. Rexius roller)	Levelling (V. Rexius roller)
Levelling (Tsr harrow)	Seed-bed prep. (Tsr harrow)	Disking (H. disc-harrow)	Disking (H. disc-harrow)
Seed-bed prep. (Tsr harrow)	Sowing (K M drill)	Seed-bed prep. (Tsr harrow)	Seed-bed prep. (Tsr harrow)
Sowing (KM drill)	Rolling (V. Rexius)	Sowing (V. Rapid)	Sowing (V. Rapid)
Rolling (V. Rexius)			
<b>2011/2012 Spring barley</b>		<b>2011/2012 Maize</b>	
Stubble disking (V. Carrier )	Stubble disking (V. Carrier )	Stubble disking (V. Carrier )	Stubble disking (V. Carrier )
Ploughing (Reversible pl.)	H. duty cultivator (V. Cultus)	Medium deep subsoiling (Dondi)	Medium deep subsoiling (Dondi)
Levelling (V. Rexius roller)	Seed-bed prep. (Tsr harrow)	Levelling (V. Rexius roller)	Levelling (V. Rexius roller)
Seed-bed prep. (Tsr harrow)	Sowing (V. Rapid)	Ploughing (Reversible pl.)	H. duty cultivator (V. Cultus)
Sowing (V. Rapid)	Rolling (V. Rexius)	Levelling (V. Rexius roller)	Seed-bed prep. (Tsr harrow)
Rolling (V. Rexius)		Seed-bed prep. (Tsr harrow)	Sowing (K M drill)
		Sowing (K M drill)	
<b>2012/2013 Oil seed rape</b>		<b>2012/2013 Spring barley</b>	
Stubble disking (V. Carrier )	Stubble disking (V. Carrier )	Stubble disking (V. Carrier )	Stubble disking (V. Carrier )
Medium deep subsoiling (Dondi)	Medium deep subsoiling (Dondi)	Ploughing (Reversible pl.)	H. duty cultivator (V. Cultus)
Ploughing (Reversible pl.)	Seed-bed prep. (V. Carrier)	Levelling (V. Rexius roller)	Seed-bed prep. (Tsr harrow)
Levelling (V. Carrier)	Sowing (V. Rapid)	Seed-bed prep. (Tsr harrow)	Sowing (Mounted drill)
Seed-bed prep. (V. Carrier)	Rolling (V. Rexius)	Sowing (Mounted drill)	
Sowing (V. Rapid)			
Rolling (V. Rexius)			

147 Until the summer of 2007, when the soil was prepared for oil seed rape (D2), the PT plots  
 148 were ploughed to a depth of 25–30 cm before each crop, in as much as this was allowed by  
 149 the weather conditions. During the same period of time, on the CT plots soil was tilled using a  
 150 non-inversion shallow tillage to a depth of 8–12 cm. Depth of CT tillage exceeded 12 cm only  
 151 in case of heavy disc-harrowing (Table 4). In the autumn of 2007 the PT plots of the area D1  
 152 were ploughed, while on area D2 ploughing was replaced by medium-deep subsoiling (40–45  
 153 cm). On the CT plots of both areas a multicultivator was used, meaning that the soil was  
 154 prepared for sowing in one pass. In October 2008 the soil was very dry in area D2, hence it  
 155 was not possible to plough. As a consequence, a heavy-duty cultivator was used on both PT  
 156 and CT plots. In the extremely wet year 2010 (Table 2) on the D2 area heavy disc-harrowing  
 157 occurred on both cultivation types. In 2011 ploughing (PT plots) and cultivator tillage (CT  
 158 plots) was carried out in area D1. On the other hand, in area D2 primary tillage started with  
 159 medium deep subsoiling, which was followed by an autumn ploughing (PT plots) and a spring  
 160 cultivator tillage (CT plots). In 2012, ploughing (PT plots) and cultivator tillage (CT plots)  
 161 occurred on both areas, which was preceded by medium deep subsoiling in area D1.  
 162 Fertilization, weed-control and harvesting were identical over the entire area.

163 The study was conducted in cooperation with the local farmers (on their land and not on a  
 164 separate experimental area). Therefore, we started with the existing equipment of the  
 165 landowners and had to hire the machines necessary for CT. Later the local equipment could  
 166 be changed for more suitable machines, which had a stabilizing effect on the tillage.  
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### 168 **2.3. Statistical analysis**

169 The statistical analysis covers the period 2007–2013. The initial, transitional period of  
 170 technological change (2003–2006) was excluded from the statistics. ANOVA was calculated  
 171 for the comparison of mean yields of each tillage type. The statistical analysis was carried out  
 172 using IBM SPSS Statistics 20 software.

173 Due to crop rotation, there is no yield data for each crop in each year on each plot. Yield  
 174 data were standardized and compared in pairs using the Scheffe method among the post hoc  
 175 tests. Considering the large standard deviation of yields in each year and the highly variable  
 176 slope of the plots, the effect of the tillage types was studied in the light of these two factors  
 177 (using two-way ANOVA) to reveal any relationship between the yield and the independent  
 178 variables.

179 Independent variables were generated for the variance analysis as follows:

- 180 – tillage type: PT and CT
- 181 – year factor: years were clustered using Pálfai Drought Index (PAI; Pálfai 1988). This  
 182 index has been developed specifically for climate conditions in Hungary, and expresses the  
 183 importance of the distribution of precipitation during the growing season. The higher the  
 184 index value, the greater the drought it expresses (PAI<4 means no drought, PAI>4 means  
 185 slight drought). PAI values for the study area fell between 2.9 and 5.1.

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$$187 \quad \text{PAI} = \frac{\left[ \frac{\sum_{i=\text{apr}}^{\text{aug}} T_i}{5} \right] * 100}{\sum_{i=\text{oct}}^{\text{sept}} (P_i * w_i)}$$

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189 where  $T_i$ =mean monthly temperature (°C);  $P_i$ =monthly precipitation (mm);  $w_i$ =weight constant

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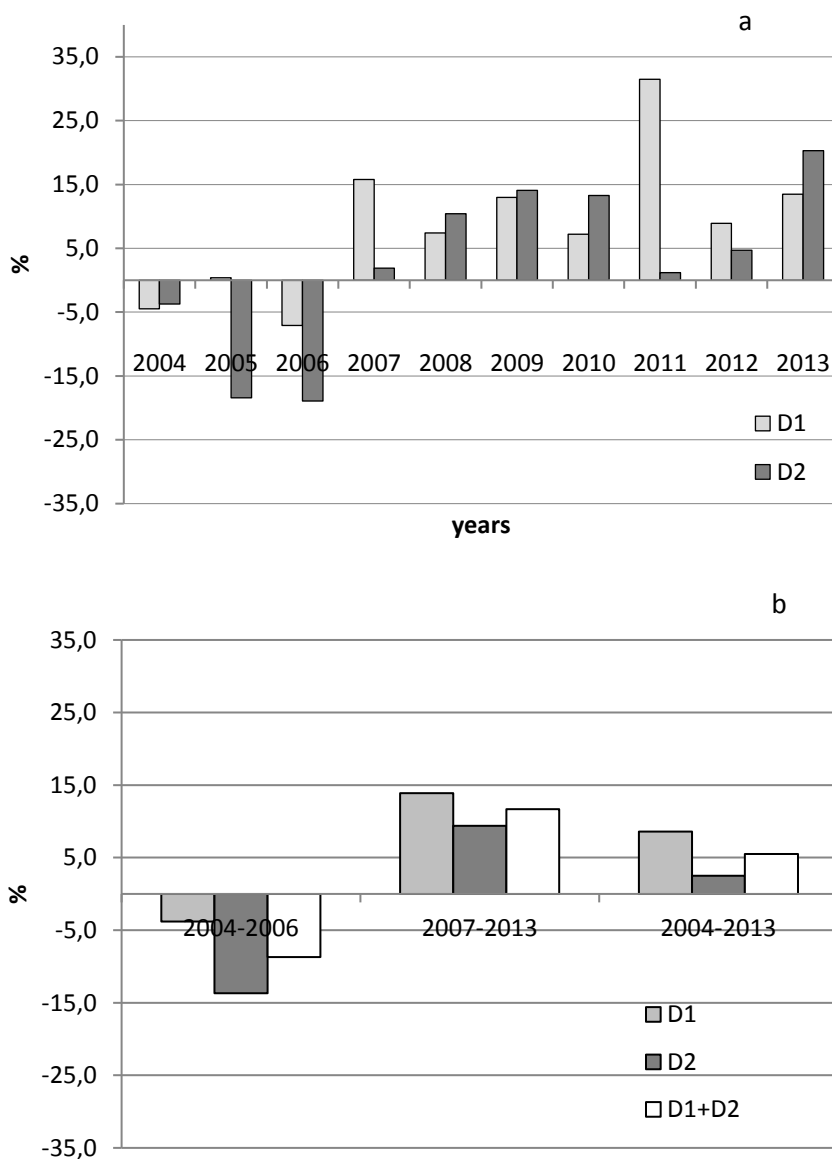
- 191 – slope effect: plots were classified using the proportion of different slope categories  
 192 within their area by ArcGIS 10.0.

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### 194 **3. Results**

195 The overview of the yields of the last 10 years shows that the turning point came after about  
 196 the third year of the experiment (Fig. 2, Table 5). During the first three years, a significant  
 197 loss of production occurred on the CT plots. The decrease was 3.8% on the D1 area, but on

198 the D2 plots, a drop of 13.7% was measured. The largest negative values of wheat and maize  
 199 crops were -18.4% and -18.9% in 2005 and 2006, respectively. After 2006 a spectacular  
 200 change occurred. The following 7 years saw an average yield increase of 13.9% (D1) and  
 201 9.4% (D2) compared to ploughing tillage.  
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**Fig. 2.** Yields of the conservation tillage plots of the Dióskál 1 (D1) and Dióskál 2 (D2) areas expressed as the percentage of the yields of the ploughing tillage plots (a) by year, (b) for the average of the first (2004–2006), the second (2007–2013), and the entire experimental period

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**Table 5.** Yields of ploughing tillage (PT) and conservation tillage (CT) with standard deviation (SD) data of plots. Dióskál 1 (D1), Dióskál 2 (D2) study site

		2004		2005		2006		2007		2008		2009		2010		2011		2012		2013	
		Mg ha <sup>-1</sup>	SD	Mg ha <sup>-1</sup>	SD	Mg ha <sup>-1</sup>	SD	Mg ha <sup>-1</sup>	SD	Mg ha <sup>-1</sup>	SD	Mg ha <sup>-1</sup>	SD	Mg ha <sup>-1</sup>	SD	Mg ha <sup>-1</sup>	SD	Mg ha <sup>-1</sup>	SD	Mg ha <sup>-1</sup>	SD
D1	PT	4.73	0.28	8.67	0.25	4.93	0.31	5.12	0.82	5.24	0.11	3.12	0.17	4.01	0.32	3.76	0.86	5.26	0.34	3.38	0.14
	CT	4.51	0.49	8.71	0.35	4.58	0.40	5.92	0.46	5.62	0.39	3.53	0.19	4.30	0.51	4.95	0.45	5.73	0.20	3.83	0.11
D2	PT	10.63	0.54	5.91	0.65	8.53	0.23	5.10	0.15	3.94	0.06	5.92	0.71	3.20	0.19	4.19	0.92	4.86	0.64	4.71	0.37
	CT	10.24	0.54	4.82	0.38	6.92	0.74	5.20	0.17	4.35	0.18	6.76	0.41	3.63	0.10	4.24	0.67	5.09	0.92	5.66	0.27

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### 217 **3.1. Getting started – experiences of the 2003–2006 transitional period**

#### 218 **3.1.1. Area D1 (2003–2006)**

219 In the autumn of the technological shift (2003), the sowing of the wheat was hindered by the  
220 large amount of precipitation (>200 mm in September and October). Yields in 2004 were  
221 somewhat smaller on the CT plots (-4.5%) than on PT plots (Table 5), which might be  
222 attributed to the increase of weeds just before harvest time.

223 In 2004, after the harvest of the wheat, oil seed rape was sown using green manure on D1.  
224 This increased the costs of tillage significantly, although the disking of soil-protecting plants  
225 into the soil had a favourable effect. All these efforts resulted in a minimal surplus of the CT  
226 yield at the time of maize harvest (0.4%). On the other hand, it has to be admitted that this  
227 minor surplus was mainly the result of significant game damage of the PT plots (PT2, PT6).

228 Several reasons stood in the background of the 7.1% deficit of the winter wheat yield of  
229 the CT areas during the 2005/2006 season with respect to the PT. The schedule was very tight  
230 due to the late harvest of maize at the end of October followed by the sowing of wheat in the  
231 beginning of November. The crop residues of the maize (NK Canada) could not be settled,  
232 and hence the stalks were drawn together by the Väderstad Carrier used for the tillage on CT  
233 plots. The first weed control after sowing was late and proved to be ineffective, which led to  
234 major problems on the CT plots later. *Apera spica-venti* (Common windgrass) appeared over  
235 large areas, especially on the CT3, 4, and 6 plots. This weed was the one that had already  
236 caused problems on the D2 plots in the previous year. Naturally, weed invasion was reflected  
237 by the low yields. The greatest difference between the two tillage types,  $-0.8 \text{ Mg ha}^{-1}$  (-16%)  
238 was found in plot-pair № 3.

239

#### 240 **3.1.2. Area D2 (2003–2006)**

241 In 2004, maize was sown in area D2. A minimal deficit of CT yield (3.7%) compared to PT  
242 plots was measured, which was the result of the low productivity of the most weedy plots  
243 (CT10 and 12). On CT12, the largest amount of weeds appeared next to the public road. On  
244 CT10 shallow tillage allowed the survival of *Equisetum arvense* (Common horsetail), which  
245 was difficult to eliminate and led to a reduced yield.

246 In the autumn of 2004, maize was followed by winter wheat. The maize (NK Occitan, with  
247 a long growing season) produced a large mass of stalks under the favourable weather  
248 conditions during the vegetation season: on extensive areas the height of the plants reached 3  
249 m. This caused the first and major problem after the maize harvest: it was difficult to work the  
250 large amount of crop residue into the soil. Ploughing was problematic because the plough  
251 gathered the inadequately chopped stalks. Non-inversion tillage on the CT plots was even  
252 more demanding. The disc gathered the crop residues in front of the compacting roller and left  
253 them behind in large piles.

254 In spring/early summer of 2005, the large mass of crop residues left on the surface caused  
255 a strong fungal infection, which was the most severe on plot-pairs 9–10. At harvest, a clearly  
256 visible fusarium infection was observed on these plots. Another factor in the fusarium  
257 infection may have been the single fungicide treatment of the stock.

258 A further problem was weed infestation of the area. Weed control occurred belatedly,  
259 together with the previously mentioned fungicide treatment. As a consequence of the well-  
260 developed weeds on the CT plots, this late treatment proved to be ineffective. *Apera spica-*  
261 *venti*, and *Cirsium arvense* (Creeping thistle) caused problems over large areas, together with  
262 *Equisetum arvense* on the CT10 plot.

263 The loss of yield was more than 18% on the CT plots compared to the ploughed ones, with  
264 the largest gap of 35% on the CT–PT10 plot-pair.

265 During the third year (2006) maize was sown again. This was the fifth occasion on which  
266 shallow tillage took place on the CT plots (Carrier disc). Disking was late, and dicotyledonous  
267 plants with deeply-penetrating spiky roots capable of breaking the compacted disc pan layer  
268 were not involved in the crop rotation. Moreover, the primary tillage was not preceded by

269 total weed control and the mechanical work of disking could not exercise its weed control  
270 effect because of the short time interval between the two passes.

271 Owing to the large amount of precipitation in May (120 mm), both the maize and the  
272 weeds emerged rapidly. On the CT plots, the weed inventory was exponentially higher with  
273 respect to the PT tillage with inverted soils. Rainy weather again led to a delay in pest control.

274 It was not possible to penetrate the spongy soil when weeds were still small, and spraying  
275 was ineffective because the rainy weather helped the weeds to survive. Weed pressure was  
276 significant on the CT10 (*Equisetum arvense*, *Ambrosia artemisiifolia* (Common Ragweed))  
277 and CT12 plots (*Polygonum aviculare* (Common knotgrass), *Ambrosia artemisiifolia*).  
278 Besides, *Echinochloa crus-galli* (Cockspur grass) appeared in the deeper parts of the CT9.

279 The biggest loss of crops was registered on the CT10 and CT12 plots. Yields were 23–26%  
280 lower than the 8.4 Mg ha<sup>-1</sup> and 8.2 Mg ha<sup>-1</sup> yields on the PT10 and PT12 plots, respectively.

281

### 282 **3.2. Adapted technology – success of the 2007–2013 years**

#### 283 **3.2.1. The D1 area (2007–2013)**

284 In the fourth year of the experiment yields turned for the better. By now the conclusions could  
285 be drawn from the experiences of the first years: an adapted technology was developed to suit  
286 local conditions and adequate equipment was already available. Besides, this period of time  
287 was necessary for the rich soil fauna characteristic of CT tilled areas to appear (Madarász et  
288 al. 2011, Roger-Estradea et al. 2010).

289 In 2007 sowing of the maize occurred on time. Post-emergence weed control was  
290 adequate, which proved to be of major importance in this year of drought. During summer  
291 drought, the maize of CT plots remained green for a longer time than on the PT ones. In other  
292 words, CT tillage was able to retain moisture available for the plants in the soil. This excess  
293 humidity was measurable at harvest: the water content of the maize from the PT plots was  
294 19.7%, while CT maize contained 22.6% water. Standard deviation of the yields of CT plots  
295 was significantly smaller than that of the PT plots (0.46 and 0.82, respectively). This suggests  
296 a higher confidence level of production on the CT plots in dry years.

297 In the autumn of 2007 the maize harvest was followed by a multicultivator tillage on CT  
298 plots. The tillage depth of 20–25 cm had a positive effect by loosening the disc pan developed  
299 during disking in the previous years and had a weed control effect as well. Weed invasion,  
300 which had hitherto been growing year by year, decreased dramatically. Consequently, the  
301 relatively late weed control was effective (31/03/2008), despite the fact that the plants were  
302 less developed than the year before. Finally, the crop of winter wheat was 7% greater on CT  
303 plots than on PT plots.

304 In 2008, a new plant was involved in the winter wheat-maize crop rotation: oil seed rape.  
305 The spiky roots of the dicotyledonous plants penetrated into deeper layers of the soil. This had  
306 a markedly positive effect by loosening the soil and improving its water management and  
307 aeration. As a result of well-performed primary tillage and favourable weather, the crop-  
308 yields were 13% higher on the CT plots compared to the PT plots.

309 In the 2009–2010 season, the rape was followed by winter wheat. The yields were low in  
310 both tillage types (PT=4.01 Mg ha<sup>-1</sup>; CT=4.30 Mg ha<sup>-1</sup>), but CT plots showed a 7.2% surplus.

311 The extremely wet year 2010 was followed by 3 years of drought. In the spring of 2011, a  
312 heavy-duty cultivator was used for primary tillage on the CT, which was closed in one pass,  
313 resulting in a moisture storage effect manifested later.

314 The seeds emerged unevenly at both tillages because the upper soil was practically dry. In  
315 some cases the emergence of many plants was as late as June, after the first significant rainfall  
316 event. Weed conditions were also unfavourable, since the lack of rainfall made the first post-  
317 emergence treatment ineffective in both tillage types. A second treatment occurred two  
318 months after sowing. Despite the two weed controls, crop yields remained low. However, soil  
319 conservation tillage paid off the financial resources invested in it (CT: 4.95 Mg ha<sup>-1</sup>), while  
320 ploughing tillage produced a significant loss (PT: 3.76 Mg ha<sup>-1</sup>). The difference between the  
321 tillage types in this year of drought reached 31.5%. It is true, however, that PT6 was an area

322 in which considerable game damage took place. On the other hand, if the pair of the most  
323 damaged plot (PT6–CT6) is removed from the comparison, the difference between the yields  
324 is still significant: 17.4% (PT=4.13 Mg ha<sup>-1</sup>; CT=4.85 Mg ha<sup>-1</sup>).

325 In 2012, the dry weather continued, and for the first time during the program, spring barley  
326 was introduced. CT plants tolerated the dry and often hot weather better, which was again  
327 reflected by the yields with a level of nearly 0.5 Mg ha<sup>-1</sup> (8.9%) excess production.

328 In 2012–2013, rape was planted again. As a consequence of the 2012 drought, soil  
329 preparation for the rape was problematic and sowing posed a great risk. By the time of sowing  
330 the quality of the soil surface was noticeably better on the CT plots. On the PT plots, in  
331 addition to larger clods, the ratio of dust fraction was considerably higher on the soil surface.  
332 Sowing was relatively delayed compared to the previous years and occurred in almost air-dry  
333 soil conditions. This was followed by rolling to smooth the surface, for effective weed  
334 control, soil moisture conservation and to ensure a uniform emergence. Development of the  
335 rape plants on CT areas was obviously better and even under the adverse weather conditions a  
336 yield surplus of 13.5% was achieved.

337

### 338 3.2.2. Area D2 (2007–2013)

339 The change on area D2 was less spectacular than on D1, since only a 2% yield surplus was  
340 achieved in 2007. The extreme drought was a problem during primary tillage. The weed cover  
341 of CT plots was significant in this year, as well. Nevertheless, the development of the plants  
342 was good, and this was assisted by the early weed control (in March). In this way crop loss  
343 could be avoided. The spread of *Apera spica-venti*, *Equisetum arvense* (CT10) and in smaller  
344 patches, of *Cirsium arvense* was significant.

345 In area D2 oil seed rape was introduced in the crop rotation in the autumn of 2007. New  
346 items integrated in the technology had a clear positive effect. Favourable weather conditions  
347 contributed to the positive changes, hence in 2008, peak yields of rape and in 2009 the highest  
348 ever yields of winter wheat were achieved.

349 In the autumn of 2007, on the PT areas only medium-deep subsoiling was carried out  
350 (instead of ploughing), which was followed by levelling and seed-bed preparation with a  
351 rotary harrow, leading to the further breaking-up of soil particles. In the CT areas  
352 multicultivator tillage was employed. As a consequence, the 115 mm precipitation falling  
353 after sowing in September plugged the macropores of the soil of the PT plots. In contrast, in  
354 the soil of the CT plots earthworm fauna proliferated owing to the CT tillage for several years  
355 (Bádonyi et al. 2008, Madarász et al. 2011). Due to the rainfall, earthworms crawled through  
356 the entire tilled layer up to the surface, providing plenty of macropores to accommodate the  
357 subsequent precipitation.

358 The year favoured the cultivation of rape and gave the highest yields of rape to date. The  
359 4.35 Mg ha<sup>-1</sup> yield in CT tillage exceeded by 0.4 Mg (+10.4%) the average yield of the PT  
360 area, with very low standard deviation values.

361 In 2008/2009 winter wheat was produced. In the autumn of 2008, ploughing of the highly  
362 desiccated soil was not possible, hence preparation for sowing was the same everywhere,  
363 regardless the plot type (Table 4). In addition to the favourable weather conditions during the  
364 growing season, the good forecrop (rape), the autumn weed control, the top-dressing, the  
365 double fungicide treatment and the application of growth regulator and foliar-feed secured  
366 the high yields. Weed conditions were also favourable owing to the deeper tillage and to the  
367 early weed control. CT tillage exceeded PT tillage by 14.1%.

368 In 2010, after rape in 2008 and winter wheat in 2009, rape was sown again, which cannot  
369 be considered a sensible choice. Its disadvantages soon manifested themselves. Pesticide  
370 treatment was already required in autumn, and yields decreased by almost 18% compared to  
371 the results of two years previously. Despite all of this, the CT plots again performed better in  
372 this extreme wet year and showed more than 13% yield surplus, with a surprisingly low  
373 standard deviation (SD=0.1).

374 Sowing of the winter-wheat was hindered by the rainy weather (August: 154 mm;  
 375 September: 151 mm). Along with the pest control treatments, weed control was late, but the  
 376 fungicide treatments occurred on time. The low yields (PT=4.19 Mg ha<sup>-1</sup>; CT=4.24 Mg ha<sup>-1</sup>)  
 377 of winter-wheat were the consequence of the dry weather prevailing since November 2010  
 378 and the unusually hot weather during the flowering period in 2011 (unfavourable for  
 379 fertilization). 2011 was the driest year of the studied period (438 mm). CT plots reached a  
 380 surplus of only 1.2% under these unfavourable conditions (with the ploughing being skipped  
 381 on PT plots). In 2012, owing to good timing, weed control of the maize could be done in one  
 382 pass. Unfortunately, the drought led to a very early harvest with low yields. Soil conservation  
 383 tillage produced a surplus of 4.7% in comparison with the conventional tillage (PT=4.86 Mg  
 384 ha<sup>-1</sup>; CT=5.09 Mg ha<sup>-1</sup>).

385 In 2012–2013 spring barley was produced, encouraged by the positive cultivation  
 386 experiences of the previous year in D1 and due to its role in crop rotation. Before spring  
 387 barley, maize was produced in the area, the chopping and stubble disking of which was  
 388 successful.

389 In spring of 2013, the PT plots were ploughed and multicultivator tillage was carried out  
 390 on the CT plots. At harvest, 1 Mg more crop was collected on CT plots (P=4.71 Mg ha<sup>-1</sup>;  
 391 CT=5.66 Mg ha<sup>-1</sup>) despite the fact that spring barley was laid on significant areas of the CT  
 392 plots, which appeared at harvest as a loss. During cultivation, as a result of professional  
 393 farming techniques, neither fungal nor insect damage occurred and weed conditions were  
 394 favourable.

395

#### 396 4. Discussion

##### 397 4.1. Statistical analysis

398 Considering the yields of the first three years, a deficit of 8.7% was measured, while the next  
 399 seven years brought a 12.7% surplus. Averaging the 10 years together this means an overall  
 400 7.9% higher yield in favour of CT tillage. Remarkable differences were found for each crop:  
 401 winter wheat produced the smallest and the maize the largest yield increase during the 2007–  
 402 2013 period (Table 6).

403

404

405 **Table 6.** Productivity difference of conservation tillage (CT) plots for each crop with respect to plough tilled  
 406 plots for the first (2004–2006), the second (2007–2013), and the entire experimental period. W.: Winter; S.:

407

	Spring		
	2004–2006 Transitional period (%)	2007–2013 Adapted CT (%)	2004–2013 Entire studied period (%)
W. wheat	-10.0	+6.4	-0.4
Maize	-7.4	+17.3	+5.0
Rape		+12.6	+12.6
S. barley		+14.6	+14.6
All	-8.7	+12.7	+7.9

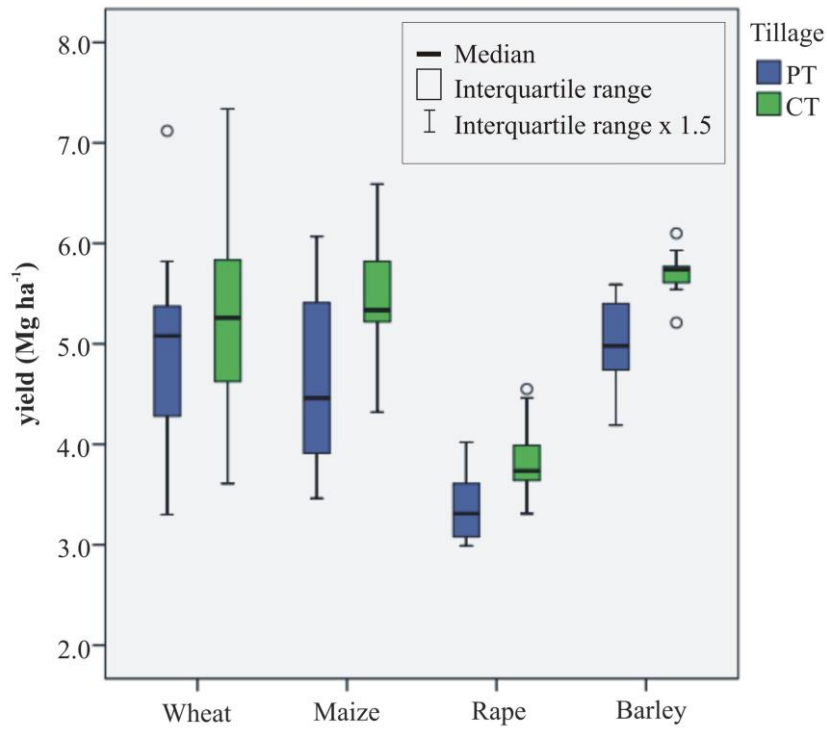
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410 In view of the period between 2007–2013, it can be concluded that each of the four plants  
 411 gave higher yields in case of soil conservation tillage (Fig. 3). Considering the standardized  
 412 yields of all plants, there is a significant difference between the two cultivation methods  
 413 (P<0.01). The difference is not significant for wheat and maize (P<0.05). In the case of rape  
 414 and of spring barley the difference is significant (P<0.01) (Table 7).

415

416



417  
418 **Fig. 3.** Yields and distribution of yield data of ploughing tillage (PT) and conservation tillage (CT), 2007–  
419 2013

420  
421  
422 **Table 7.** Mean yields and standard deviation (SD) of each plant by tillage type (2007–2013) \*\* P<0.01;  
423 Ploughing tillage (PT); Conservation tillage (CT).

	n	Mean yield Mg ha <sup>-1</sup>	SD
W. wheat PT	31	4.93	0.81
W. wheat CT	31	5.27	0.96
Total	62	5.10	0.90
Maize PT	9	4.68	0.91
Maize CT	10	5.44	0.71
Total	19	5.08	0.87
Rape PT	18	3.39**	0.35
Rape CT	18	3.82**	0.35
Total	36	3.61	0.41
S. barley PT	9	5.01**	0.48
S. barley CT	9	5.70**	0.25
Total	18	5.36	0.51

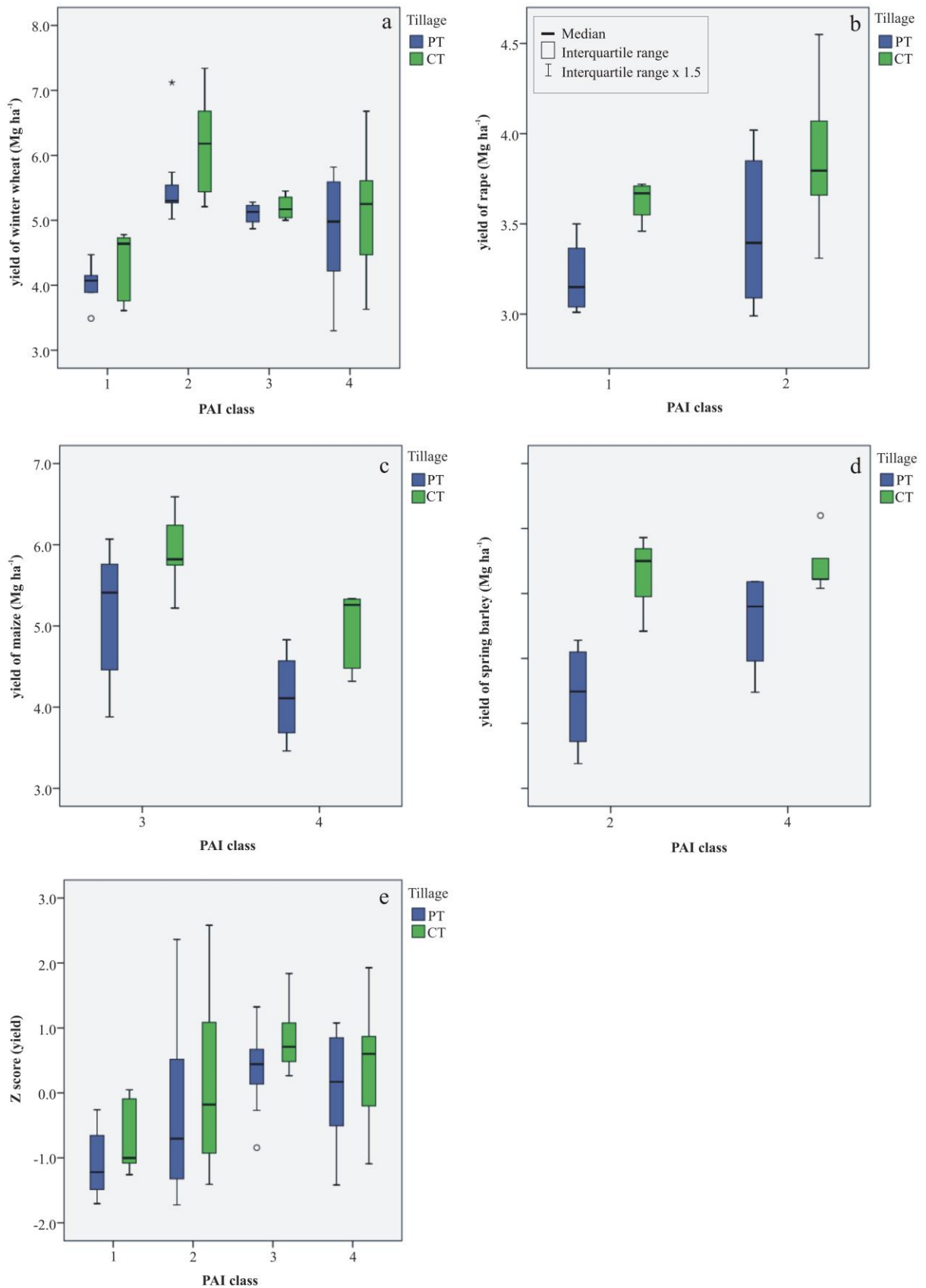
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426 During the studied period, extreme wet and dry years occurred. Therefore, ANOVA was  
427 also run in order to obtain a standardized result for all yields by year factor (PAI class). The  
428 results showed that the character (wet/drought) of the given year played a significant role  
429 (P<0.01). On the other hand, the PAI index generally shows a weak negative or positive  
430 correlation with the yields. Regarding each plant individually, the year-effect was  
431 considerable for all crops except the barley (Table 8, Fig. 4).

432  
433

434 **Table 8.** Change in yields (Mg ha<sup>-1</sup>) (both ploughing and conservation tillage) in relation to year factor  
 435 (PAI). \* P<0.05; \*\* P<0.01; values with the same letter within a row are not significantly different; Winter  
 436 wheat (W. wheat); Spring barley (S. barley); a high value for the Pálfaí Drought Index (PAI) indicates increasing  
 437 aridity.

	PAI class				Mean
	1. PAI<3	2. PAI=3-4	3. PAI=4-5	4. PAI>5	
W. wheat **	4.16 a	5.83 c	5.15 b	4.94 b	5.09
Maize *			5.52 b	4.58 a	5.05
Rape *	3.42 a	3.66 b			3.68
S. barley		5.18 a		5.49 a	5.34

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**Fig. 4.** Yields of winter wheat, maize, rape and spring barley during years of different aridity (year factor (Pálfaí Drought Index, PAI; higher values indicate increasing aridity); z score: standardized yield data)

448 Using the standardized yields for all plants and for each plant, a two-way ANOVA (tillage  
 449 type, PAI) was run. However, the combined effect of the two factors could not be regarded as  
 450 significant (Fig. 4). In other words, the observed yearly differences are not modified by the  
 451 tillage type, and the effect of the tillage type is similar for each year.

452 The slope conditions had no significant effect on crop yields. A two-way ANOVA (tillage  
 453 type, slope) was performed, again with the standardized yields. In a similar way to the  
 454 previous ANOVA analysis the result did not prove the combined effect of these two factors,  
 455 (Table 9, Fig. 5.), namely, the observed slope differences are not modified by the tillage type,  
 456 and the effect of the tillage type is independent of the slope conditions. Accordingly, both the  
 457 yields and the effects of tillage type are independent of topography at this study site.

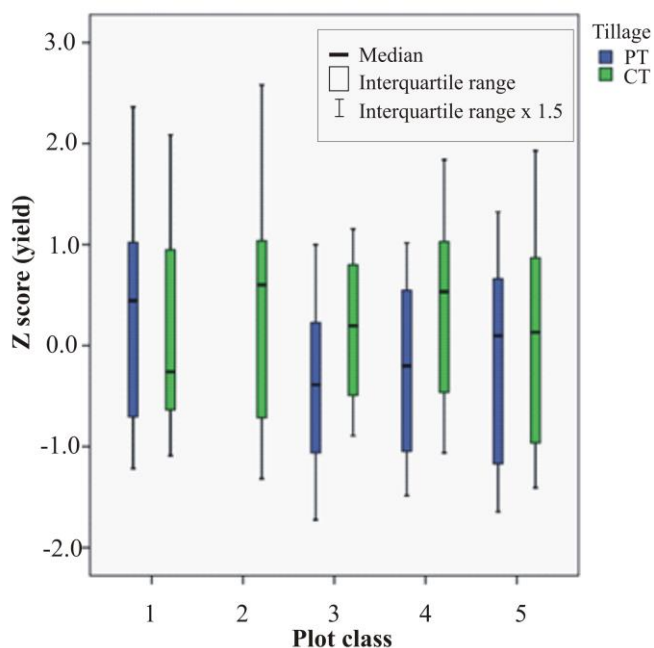
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460 **Table 9.** Percentage of different slope categories and the resulting plot class of the ploughing tilled (PT) and  
 461 conservation tilled (CT) plots. D1.: Dióskál 1; D2.: Dióskál 2

	D1						D2			
Slope	PT1	PT2	PT3	PT4	PT5	PT6	PT9	PT10	PT11	PT12
0-5%	52.4	28.3	25.0	40.9	71.4	65.4	87.5	42.6	23.5	64.9
5-12%	47.6	71.7	75.0	47.3	28.6	34.6	12.5	57.4	74.2	35.1
12%<	0.0	0.0	0.0	11.8	0.0	0.0	0.0	0.0	2.3	0.0
<b>Plot class</b>	<b>4</b>	<b>5</b>	<b>5</b>	<b>4</b>	<b>3</b>	<b>3</b>	<b>1</b>	<b>4</b>	<b>5</b>	<b>3</b>

	D1						D2			
Slope	CT1	CT2	CT3	CT4	CT5	CT6	CT9	CT10	CT11	CT12
0-5%	54.8	30.5	38.5	16.3	62.4	79.7	75.0	16.7	27.7	86.0
5-12%	45.2	66.3	53.8	78.3	37.6	20.3	25.0	82.6	72.3	14.0
12%<	0.0	3.2	7.7	5.4	0.0	0.0	0.0	0.7	0.0	0.0
<b>Plot class</b>	<b>4</b>	<b>5</b>	<b>4</b>	<b>5</b>	<b>3</b>	<b>2</b>	<b>2</b>	<b>5</b>	<b>5</b>	<b>1</b>

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464 **Fig. 5.** Results of two-way ANOVA (tillage type and slope conditions) with standardized yields. Slope factor  
 465 as in Table 9, higher values indicate steeper topography; z score: standardized yield data.  
 466  
 467



468 In conclusion, the climate of the studied years was very variable and the plots of the study  
469 area are not homogeneous physically. These conditions, however, could not eliminate the  
470 effect of tillage type. In general, soil conservation tillage produced higher yields regardless of  
471 the aridity of the year, slope, and crop type.

472

#### 473 ***4.2. Experiences during the technological adjustment and advantages of the adapted CT*** 474 ***compared to PT***

475 Most authors have emphasized the advantages of CT tillage (Holland 2004, Kassam et al.  
476 2012, Melero et al. 2009, Prasuhn 2012), but problems arising during the first years after the  
477 technological change over and difficulties related to the adjustment to CT technology were  
478 not addressed sufficiently. We consider that the sharing of experiences concerning the  
479 technological adjustment may be helpful in shortening the period of adjustment and reaching  
480 the desired level of efficiency sooner at other locations.

481 In our study, a significant 7.8% yield loss was measured in the first 3 years, when several  
482 factors, like insufficient knowledge of the new technology, lack of expertise and the absence  
483 of adequate machines impeded the technological shift. Besides, due to the shallow tillage,  
484 more attention had to be paid to weed invasions, as examined by Koskinen and McWhorter  
485 (1986) as long ago as the 1980s. Our study supports that accurate, relevant and timely weed  
486 control is necessary in CT tillage, otherwise weeds may cause a considerable decrease of the  
487 yield. In our study area, the application of the multicultivator, as suggested by Batesa (2012),  
488 proved to be a successful means of weed control, as against the opinion expressed by Price  
489 and Kelton (2011), who suggested weed control based mostly on the application of chemicals.  
490 The method employed in the present study prevented the use of excess pesticides and thus  
491 reduced environmental loading.

492 Another important source of the initial decline was fungal infection caused by poorly  
493 chopped stalks and the large mass of crop residues left on the surface. During the period  
494 2007–2013, our experiment demonstrated that this problem can be avoided by using adapted  
495 technology and adequate machinery. The proper chopping of stalk residues is a key element  
496 in improving conservation tillage.

497 A positive change was the integration of oil seed rape into the monotonous wheat-maize  
498 crop rotation in the autumn of 2007 and 2008. Statistically, during this 7-year period the year  
499 of production had the most significant effect on the yields, with no detectable correlation with  
500 aridity. The type of tillage is significant in general, but varies from plant to plant. In the case  
501 of wheat and maize, it had no significance, but in the case of rape and barley the connection  
502 could be demonstrated statistically. The effect of the tillage method, when evaluated together  
503 with the year-factor (describing the aridity of each year) and with the slope effect, suggests  
504 that soil conservation tillage provided higher yields independently of the year, plot and plant.

505

### 506 **5. Conclusions**

507 The present study demonstrates the most important advantages of CT under sub-humid  
508 continental climate conditions, and provides experiences of the initial period of reduced yields  
509 during the adjustment to the new technology. European studies mostly focus on the  
510 environmental benefits (in terms of soil and water management) and lower costs of CT tillage.  
511 Our study shows that the technological change may not be as smooth as expected on the basis  
512 of the above studies, and this may result in a considerable decrease in yields. The study also  
513 demonstrates that adaptation of the technology to local conditions is essential. Accordingly,  
514 we suggest that local studies are a prerequisite if farmers and decision makers are to be  
515 provided with appropriate information on the outcomes of a planned change from PT to CT  
516 tillage.

517 The experiences of the 10 years of monitoring the yields on twin PT and CT areas will  
518 provide guidelines to regional farmers and agricultural managers to implement CT technology  
519 while maintaining high yields. Our technology may be adapted by farmers in sub-humid  
520 continental climates where certain factors of production (e.g. slope, precipitation, weeds) are

521 similar to those observed at our experimental site, and may help others to work out their  
522 adaptation methodology in other locations with somewhat different environmental conditions.

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524

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532  
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