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Comparison of energy inputs and energy efficiency for maize in a long-term tillage experiment under Pannonian climate conditions

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Abstract: Sustainable crop production requires an efficient usage of fossil energy. This six-year study on a silt loam soil (chernozem) analysed the energy efficiency of four tillage systems (mouldboard plough 25–30 cm, deep conservation tillage 35 cm, shallow conservation tillage 8–10 cm, no-tillage). Fuel consumption, total energy input (made up of both direct and indirect input), grain of maize yield, energy output, net-energy output, energy intensity and energy use efficiency were considered. The input rates of fertiliser, herbicides and seeds were set constant; measured values of fuel consumption were used for all tillage operations. Total fuel consumption for maize (*Zea mays* L.) production was 81.6, 81.5, 69.5 and 53.2 L/ha for the four tillage systems. Between 60% and 64% of the total energy input (17.0–17.4 GJ/ha) was indirect energy (seeds, fertiliser, herbicides, machinery). The share of fertiliser energy of the total energy input was 36% on average across all tillage treatments. Grain drying was the second highest energy consumer with about 22%. Grain yield and energy output were mainly determined by the year. The tillage effect on yield and energy efficiency was smaller than the growing year effect. Over all six years, maize produced in the no-tillage system reached the highest energy efficiency.

Keywords: plant production; energy analysis; energy efficiency indicators; soil tillage operation; Pannonian basin

Management strategies (e.g. tillage, fertilisation, crop rotation) influence the energy efficiency of plant production (Rathke et al. 2007). With the soil tillage system, the farmer has a management tool to reduce external farm facility input (e.g. diesel fuel) and for adaptation to climate change. Soil tillage is one of the highest energy and labor consumers in arable farming (Moitzi et al. 2014, Szalay et al. 2015). In conventional tillage systems with ploughing, more than 50% of total fuel consumption is usually used for soil preparation and seeding alone (Moitzi et al. 2015). However, the energy savings of minimum and zero tillage in on-farm use of fuel and in machine operation are often offset by higher energy requirements for herbicides and for nitrogen fertiliser with conservation tillage management (Zentner et al. 2004). Climate and soil conditions determines the effects of tillage systems on yield. A global meta-analysis by Pittelkow et al. (2015) showed that no-tillage reduces yields compared to conventional tillage systems in humid climate. In dry climate regions, yields of no-tillage can be equivalent or higher compared to conventional tillage systems. This suggests that no-tillage may become in drier regions of the world a crucial adaptation strategy to climate change. Long-term experiments from Canada showed that organic crop production systems are more energy efficient than conventional management systems because of a 50% lower energy input (Hoeppner et al. 2005). Depending on grain moisture content at harvest,

Table 1. Long-term average temperature and precipitation (1995–2018) and deviations during the growing seasons (April to October) of the experimental years

	1995–2018	2003	2005	2008	2009	2013	2016
Temperature (°C)	16.4	+0.4	–0.5	–0.3	+0.6	+0.1	+0.2
Precipitation (mm)	422	–123	–6	+51	–47	–41	+65

a drying process is often necessary. Up to 48% of the total energy input is allocated to drying (McLaughlin et al. 2000, Moitzi et al. 2015). This energy demand for drying can be lowered by choosing early ripening maize cultivars which reach a high percentage dry matter content of grain earlier.

For determining the effects of four tillage systems in a Pannonian climate region with semi-arid climate conditions, a field experiment was installed in 1996. This study aimed to present and discuss the crop yield, fuel consumption and the energy input (direct and indirect), energy output, net-energy output, energy intensity and energy use efficiency of maize. It is hypothesised that no-tillage (NT) has the lowest energy input with the highest energy efficiency.

MATERIAL AND METHODS

Experimental site and climatic data. The experiment was carried out at the Experimental Station of the University of Natural Resources and Life Sciences (BOKU) in Raasdorf (48°14'N, 16°33'E; 153 m a.s.l.). The field is located east of Vienna, Austria, in the Marchfeld plain, which is an important arable crop production region in the north-western part of the Pannonian Basin. The silty loam soil (pH_{CaCl_2}: 7.6, soil organic carbon: 23 g/kg) is classified as a calcaric chernozem of alluvial origin. The mean annual temperature is 10.7 °C, the mean annual rainfall is 568 mm (observation period: 1995–2018). Deviations during the growing seasons (April to October) of the experimental years are shown in Table 1.

Experimental design and management. The experiment was established in August 1996 in a split-plot design with four replications with the target to perform a long-term comparison of four different tillage systems: mouldboard plough (MP); deep conservation tillage (CT_d); shallow conservation tillage (CT_s) and no-tillage (NT). For this study the maize yield and management data from the year 2003, 2005, 2008, 2009, 2013 and 2016 were used. The pre-crop of maize was winter wheat in all years. The plot size for the tillage systems allows operation with regular farm machinery (1st replication: 60 × 24 m, 2nd to 4th replication: 40 × 24 m). The tillage operations of the four tillage systems are shown in detail in Table 2. The working width of the four furrow reversible mouldboard plough was 1.7 m and for wing sweep cultivator, subsoiler and seedbed combination 3.0 m, respectively. The wing sweep cultivator had seven tines on two bars with tine distance of 84 cm and line distance of 42 cm. Three rotary hoes for crumbling and a wedge ring roller for crumbling and depth control were mounted behind the tine bars. The subsoiler was equipped with four fixed tines (tine distance: 75 cm) with wings (34 cm width) at the

Table 2. Tillage systems with implements and working depths (in brackets)

Tillage operation	Mouldboard plough (MP)	Deep conservation tillage (CT_d)	Shallow conservation tillage (CT_s)	No-tillage (NT)
Primary tillage	mouldboard plough (25–30 cm)	wing sweep cultivator (16–20 cm) subsoiler (35 cm)	wing sweep cultivator (8–10 cm)	–
Seedbed preparation	seedbed combination[a] (7–9 cm)	seedbed combination[a] (7–9 cm)	seedbed combination[a] (7–9 cm)	–
Seeding	precision seeder (4 cm)	precision seeder (4 cm)	precision seeder (4 cm)	precision seeder (4 cm)
Maize stubble cultivation	wing sweep cultivator (5–8 cm)	wing sweep cultivator (5–8 cm)	wing sweep cultivator (5–8 cm)	–

[a]Tine harrow with clump-roller

bottom and a cage roller for depth control. Seeding was done with a six-row pneumatic precision seeder with 75 cm row distance. The yearly input rate of seeds, fertiliser and pesticides were constant during the period 2003–2016. In all treatments, sowing with 80 000 grains/ha at a row distance of 75 cm was performed in mid-April. The sown waxy maize cultivars belonged to the FAO maturity class 300–400. The fertiliser urea (46% N) was applied with a rate of 130 kg N/ha two weeks after seeding. Plants were sprayed against weeds in one pass-over (with Foramsulfuron, 45 g/ha active ingredient (a.i.); Isoxadifenethyl, 45 g/ha a.i.; Sulcotrion, 240 g/ha a.i.; Bromoxyil, 67.5 g/ha a.i.) in mid-May in all plots. Only in the NT treatment, the non-selective herbicide glyphosate (1 575 g/ha a.i.) was additionally applied three weeks before maize sowing. Harvest was performed after reaching physiological maturity in October.

Fuel consumption. The fuel consumption for ploughing, subsoiling, cultivating and seeding was measured with a high-performance flow-meter (PLU 116H; AVL ®, Graz, Austria) in the tractor fuel system. Fuel consumption measurements for ploughing, subsoiling and cultivating (deep, shallow) were conducted with a 92 kW-four-wheel-drive tractor (Steyr 9125, St. Valentin, Austria) on October 28th, 2005. The fuel consumption measurement for precision seeding was carried out with a 59 kW-four-wheel-drive tractor (Steyr 8090, St. Valentin, Austria) on April 6th, 2005. The soil was dry during all these operations. The measured diesel fuel consumption data (Szalay et al. 2015), which were considered constant for all six years, were used for the calculation of the direct energy input parameter, which is determined by fuel and lubricant oil consumption (Table 3). The assumption of constant data is justified by the fact that the tillage processes in the six years were done with the same machinery (tractor and implement) at the same working depth and always in dry soil conditions. McLaughlin et al. (2008) has shown for fuel consumption of primary tillage implements that differences were considerably high between implements whereas differences between years were low. Data of fuel consumption for spraying chemical plant protection (herbicides and fungicides; 2 L/ha for one pass), for the fertiliser spreader and for harvesting were obtained from the Austrian Association for Agricultural Engineering and Landscape Development (ÖKL 2019). For the maize grain transportation with tractor and trailer *via* a distance of 5 km, the fuel consumption was calculated with the specific fuel consumption coefficient of 0.09 L fuel per ton of harvest products and kilometer according ÖKL (2019). 2% of the fuel consumption was calculated for the lubrication oil of motors. The energy demand for the drying process (heating oil and electricity) was calculated by 3.92 MJ/kg water removed down to a mean grain moisture content of 14% (Moitzi et al. 2015).

Energy efficiency and energy equivalents. Energy efficiency indicators were calculated according to Hülsbergen et al. (2001) and Moitzi et al. (2021). The energetic value of maize straw was not considered

Table 3. Diesel fuel consumption (L/ha) for maize production in different tillage systems, average for all years

Operation	Mouldboard plough (MP)	Deep conservation tillage (CT_d)	Shallow conservation tillage (CT_s)	No-tillage (NT)
Stubble cultivation[1]	5.7	5.7	5.7	–
Ploughing[1]	18.8	–	–	–
Wing sweep cultivator[1]	–	9.4	6.7	–
Subsoiling[1]	–	9.4	–	–
Seedbed preparation[2]	6.0	6.0	6.0	
Seeding[3]	2.0	1.9	2.0	2.1
Spreading fertiliser[2]	1.5	1.5	1.5	1.5
Spraying herbicide[2]	2.0	2.0	2.0	4.0
Harvesting[2]	25.0	25.0	25.0	25.0
Transport (5 km)[2]	3.8	3.8	3.8	3.8
Chopping[4]	16.8	16.8	16.8	16.8
Total	81.6	81.5	69.5	53.2

[1]Szalay et al. (2015); [2]ÖKL (2019); [3]unpublished; [3]ÖKL (2019); [4]of stubble and plant residuals after harvest with a flail mower, Moitzi et al. (2015)

because these were chopped in the field after harvesting. The energy in maize grain was set to 18.95 MJ/kg dry matter (DLG 1997). The determination of the energy equivalent (EQ) of the indirect energy in farm machinery was done in different tillage systems (MP, CT_d, CT_s, NT) based on a 100 ha cereals area under Austrian conditions by Biedermann (2009). For this calculation, different estimated technical and economic life time of the machinery were assumed: 10 000 h for the tractor, 3 000 h for the combine harvester, 2 000–3 000 ha for the implements. The amounts of the used production facilities were multiplied with the EQ: for diesel fuel and heating oil for drying an EQ of 39.6 MJ/L and for lubricant an EQ of 39.0 MJ/L were assumed (Sørensen et al. 2014). For urea (46% N) an EQ of 48.0 MJ/kg was set according to Jenssen and Kongshaug (2003). Glyphosate and herbicide for broadleaf weeds was set with 454 MJ/kg (Green 1987, CIGR 1999) and 259 MJ/kg (Saling and Kölsch 2008). EQ for maize seed was set with 100 MJ/kg according to CIGR (1999) and McLaughlin et al. (2000).

Statistical analysis. All statistical analyses were applied using IBM ® SPSS ® Statistics 21 (New York, USA). The assumptions for analysis of variance (ANOVA) were tested with the Levene test for homogeneity of variances and Shapiro-Wilk test for normal distribution of residuals. ANOVA tests were carried out for grain of maize yield, energy output, net-energy output, energy intensity and energy use efficiency to detect year and tillage effects. Overall tillage effect was checked with repeated measures ANOVA, with year as a within-subject factor and tillage as a between-subject factor. Statistically significant differences between means were analysed with the Student-Newman-Keuls procedure ($P < 0.05$).

RESULTS

Total fuel consumption. The total diesel fuel consumption for maize production (Table 3) was at a same level at about 82 L/ha in the tillage systems MP and CT_d. CT_s and NT consumed a total fuel amount of 69.5 L/ha and 53.2 L/ha, respectively. Thus, the total area-based fuel consumption for NT was 34.8% lower than for MP. Comparing MP and CT_d, substitution of the plough with a subsoiler (9.4 L/ha) and a wing sweep cultivator in CT_d could not reduce the fuel consumption. But CT_s consumed 14.7% less fuel than CT_d. The highest amount for tillage and seeding was required for MP and CT_d with about 32.5 L/ha and the lowest for NT with 2.1 L/ha. CT_s was intermediate with 20.4 L/ha.

Total energy input. The total energy input was calculated with about 17 GJ/ha (Table 4). The ratio of direct energy to indirect energy (%:%) was for the tillage treatments: MP – 40:60, CT_d – 40:60, CT_s – 39:61, NT – 36:64. The share of fertiliser energy on the total energy input was at about 36% for all tillage treatments. Drying was the second highest energy consumer with about 22%. The fuel and lubricant share was for the tillage treatments: MP and CT_d – 19%, CT_s – 16%, NT – 13%. About 13% of the total energy input is allocated to seed. The energy input which is allocated to machinery required was for: MP, CT_d, and CT_s – 10%, NT – 9%. The lowest energy input share was with the herbicides at about 1% in MP, CT_d and CT_s. NT required 5% of the total energy input for herbicides.

Grain of maize yield and energy output. Grain of maize yield and energy output ranged between years from 6 698 kg/ha and 111.0 GJ/ha in 2003 to

Table 4. Direct and indirect energy input (GJ/ha) for maize production in different tillage systems, average for all years

	Mouldboard plough (MP)	Deep conservation tillage (CT_d)	Shallow conservation tillage (CT_s)	No-tillage (NT)
Direct energy				
Fuel, lubricant	3.3	3.3	2.8	2.2
Drying	3.7	3.7	3.8	3.9
Indirect energy				
Seed	2.3	2.3	2.3	2.3
Fertiliser	6.2	6.2	6.2	6.2
Herbicide	0.1	0.1	0.1	0.8
Machinery	1.8	1.8	1.8	1.6
Total	17.4	17.4	17.0	17.0

Table 5. Mean grain of maize yield and energy efficiency parameters for maize in tillage systems and years

	2003	2005	2008	2009	2013	2016	**Mean**
Mean corn moisture content (%) at harvest	21.2	22.0	22.8	21.6	27.0	21.0	**22.6**
Grain of maize yield[1] (kg/ha)							
MP	6 562	9 916	9 378	10 465	7 340	7 192	**8 476**
CT$_{d}$	6 513	9 639	10 378	11 302	6 976	6 777	**8 597**
CT$_{s}$	6 397	9 769	9 812	10 939	7 493	6 753	**8 527**
NT	7 322	10 217	8 707	10 165	8 360	7 314	**8 681**
Mean	**6 698**^{A}	**9 885**^{B}	**9 569**^{B}	**10 718**^{C}	**7 542**^{A}	**7 009**^{A}	**8 570**
Energy output[2] (GJ/ha)							
MP	108.7	164.5	155.5	173.6	121.6	119.2	**140.5**
CT$_{d}$	107.9	159.9	172.1	187.5	115.6	112.3	**142.5**
CT$_{s}$	106.0	162.0	162.7	181.5	124.2	111.9	**141.4**
NT	121.3	169.5	144.4	168.6	138.6	121.2	**143.9**
Mean	**111.0**^{A}	**163.9**^{B}	**158.7**^{B}	**177.8**^{C}	**125.0**^{A}	**116.1**^{A}	**142.1**
Net-energy output[3] (GJ/ha)							
MP	92.9	146.7	137.5	155.8	102.5	102.9	**123.1**
CT$_{d}$	91.8	142.2	153.7	169.4	97.3	96.3	**125.1**
CT$_{s}$	90.6	144.8	145.0	164.0	105.4	96.3	**124.3**
NT	105.6	152.2	127.6	151.5	119.3	105.5	**126.9**
Mean	**95.2**^{A}	**146.5**^{B}	**141.0**^{B}	**160.2**^{C}	**106.1**^{A}	**100.3**^{A}	**124.9**
Energy intensity[4] (MJ/kg dry grain[1])							
MP	2.42	1.80	1.93	1.70	2.75	2.26	**2.14**
CT$_{d}$	2.49	1.83	1.81	1.62	2.63	2.36	**2.12**
CT$_{s}$	2.45	1.77	1.84	1.60	2.52	2.32	**2.08**
NT	2.17	1.70	1.96	1.69	2.35	2.15	**2.00**
Mean	**2.38**^{CD}	**1.77**^{AB}	**1.88**^{B}	**1.65**^{A}	**2.56**^{D}	**2.27**^{C}	**2.09**
Energy use efficiency[5] (GJ/GJ)							
MP	6.89	9.25	8.64	9.77	6.28	7.33	**8.03**
CT$_{d}$	6.69	9.05	9.28	10.33	6.33	7.03	**8.12**
CT$_{s}$	6.86	9.39	9.15	10.38	6.60	7.16	**8.26**
NT	7.67	9.78	8.58	9.86	7.14	7.71	**8.46**
Mean	**7.03**^{A}	**9.37**^{B}	**8.91**^{B}	**10.09**^{C}	**6.59**^{A}	**7.31**^{A}	**8.22**

[1]14% moisture content; [2]energy in maize grain – energy in the seed; [3]energy output – total energy input, [4]total energy input/grain of maize yield; [5]energy output/total energy input. Statistically significant differences between years are indicated with capital letters

10 718 kg/ha and 177.8 GJ/ha in 2009, respectively (Table 5) with significant differences between years. Thus it was influenced by climatic conditions. Mean grain of maize yields and mean energy outputs did not differ between tillage systems, neither in a single year nor across all six years. On average, the grain of maize yield for CT$_{d}$ + 121 kg (= +1.4%), for CT$_{s}$ + 51 kg (= +0.6%) and for NT +205 kg (= +2.4%), was higher than for MP (not significant; Table 5). The overall range between years was much higher than between tillage systems: grain of maize yield – 4 020 *vs.* 205 kg/ha, energy output – 52.9 *vs.* 3.4 GJ/ha.

Energy efficiency. Net-energy output was in the range between 90.6 and 169.4 GJ/ha. Year influenced the net-energy output significantly. The highest net-energy output was reached in 2009 and the lowest in 2003, 2013 and 2016. No significant influence of the factor tillage system on the net-energy output was observed in individual years or over all six years. The mean net-energy output was for NT with 126.9 GJ/ha by 3% higher than for MP with 123.1 GJ/ha (not significant, Table 5). The energy intensity ranged between 1.60 and 2.75 MJ/kg dry grain. Over all six years, MP, CT_d and CT_s reached a mean energy intensity around 2.11 MJ/kg dry grain. In NT, the mean energy intensity was about 5% lower with 2.00 MJ/kg dry grain (not significant, Table 5). The energy use efficiency ranged between 6.28 and 10.38 GJ/GJ. Over all six years, no significant influence of the factor tillage system on the energy use efficiency was observed. The mean energy use efficiency was with 8.46 GJ/GJ for NT by 5% higher than for MP with 8.03 GJ/GJ (not significant, Table 5).

DISCUSSION

Total fuel consumption. Area based fuel consumption in the tillage systems is determined by the choice of the implements and the working depth (Moitzi et al. 2013, 2019). In our study, MP and CT_d had the same area based fuel consumption but differ in the incorporation of plant residues. While ploughing generates a soil surface without plant residues, CT_d with wing sweep cultivator and subsoiler leaves plant residues on the soil surface, which has positive ecological effects (e.g. mitigation of soil erosion) but may also foster pests and diseases (e.g. snails, *Fusarium* spp.). Seedbed preparation after ploughing can be done with a power or tine harrow. Szalay et al. (2015) measured a fuel consumption of 8.6 L/ha for seedbed preparation with a power harrow. Tine harrowing for seedbed preparation required less diesel fuel than power harrowing (Poje 1998). For the silty loam soil in this study, a tine harrow is sufficient for preparing a suitable seedbed. Compared to MP, shallow cultivation with wing sweep cultivator (CT_s) reduced the total fuel consumption by about one seventh and NT by about one third.

Total energy input. The total energy input of around 17 GJ/ha was above the threshold value of 10 GJ/ha for a low-input system (Lin et al. 2017). Especially energy for the drying process is responsible for the higher total energy input in comparison to winter wheat on the same site (Moitzi et al. 2019). Energy for drying maize down to storage moisture content can be reduced by choosing early ripening cultivars (Bunting 1972). For winter wheat, which had been fertilised with 130 kg N/ha calcium ammonium nitrate, the total energy input ranged between 8.9 and 9.4 GJ/ha (Moitzi et al. 2019). The high energy input *via* nitrogen fertiliser (36%) in this study is characteristic for conventional cropping systems (McLaughlin et al. 2000, Sartori et al. 2005, Moitzi et al. 2015). A Canadian study showed that a substitution of mineral fertiliser through liquid swine manure reduced total energy input between 42% and 45%. For the mineral fertilised variants (between 60 and 164 kg N/ha) the total energy input ranged between 19.1 and 22.3 GJ/ha, whereas the total energy input of liquid swine manure treatments (surface applied or injected; between 57 and 161 kg N/ha) were just between 10.6 and 12.9 GJ/ha. In a long-term fertilisation experiment in Styria (Austria), the total energy input for maize ranged depending on the rate of mineral nitrogen fertilisation with calcium ammonium nitrate between 22 GJ/ha at 90 kg N/ha and 34 GJ/ha at 210 kg N/ha. The share of the nitrogen fertiliser energy to total energy ranged between 20.7% and 37.2%. Through substitution of mineral fertiliser with 23 to 58 m^3/ha of liquid swine manure, the energy input could be lowered to 15.5 and 20.4 GJ/ha (Moitzi et al. 2015). Small differences between the energy inputs of different tillage treatments were also reported by Deike et al. (2008) on a sandy loam. The small differences in our study may be explained by the compensation of the lower direct input in NT by a higher indirect energy input due to the additional herbicide application. Shifting of tillage systems with ploughing to ploughless systems reduces not only direct energy input but also working time (Szalay et al. 2015). These benefits are the main economic reasons why conservation tillage systems are increasingly practised in semi-arid regions.

Grain maize yield and energy output. The range of grain of maize yield and energy output between years was 4 020 kg/ha and 66.8 GJ/ha, respectively, which is larger than the range between the tillage system with 205 kg/ha and 3.4 GJ/ha, respectively. Crop yield variability in semi-arid regions is mainly caused by soil water shortage and heat stress. Environmental factors (years and climate conditions) influence grain yield and energy efficiency more strongly than tillage practices (Moitzi et al. 2019). On average across all years, no significant differences were observed between tillage treatments for grain of maize yield and energy output. There was a tendency of higher yields with NT than with MP (not significant). Pittelkow et al. (2015) showed, that reduced tillage systems can result in higher yields in dry regions due to better soil water conservation whereas in wetter regions yields are often impaired. In the Pannonian region with its semi-arid climate conditions, usually water is the restricted factor for plant growth. Studies at the same location (Raasdorf) by Thaler et al. (2012) confirmed a better soil water storage capacity in conservation tillage-systems (CT_d, CT_s, NT).

Energy efficiency. The energy efficiency parameters (net-energy output, energy intensity and energy use efficiency) are mainly determined by higher energy output in comparison to lower energy input values (Arvidsson 2010). This is one explanation, why the energy efficiency parameters were not significantly influenced by the tillage system. In semi-arid regions, energy efficiency parameters for maize are mainly affected by the maize yield, which are determined by the amount and seasonal distribution of rainfall, if input rates were set constant for the tillage systems. The range caused by the years was much higher than that caused by the tillage systems: net-energy output: – 51.3 vs. 3.8 GJ/ha, energy intensity: – 0.91 MJ/kg *vs.* 0.14 MJ/ha, energy use efficiency: – 3.50 *vs.* 0.43 GJ/GJ. Hülsbergen et al. (2001) used the parameters energy intensity and energy use efficiency for finding optimum input levels from an ecological point of view. In our study, NT tended to have the lowest energy intensity (2.00 MJ/kg) and the highest energy use efficiency (8.46 GJ/GJ). The lowest energy efficiency was found with MP. The energy efficiency of CT_s and CT_d was between MP and NT. Also, Šarauskis et al. (2014) found the highest energy efficiency in maize cultivation with NT.

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