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Effect of tillage systems on energy input and energy efficiency for sugar beet and soybean under Pannonian climate conditions

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Abstract: Sustainable cropping systems require efficient usage of fossil energy. This study performed on a long-term field experiment in the Pannonian Basis investigated the energy efficiency of four tillage systems (mouldboard plough (MP), deep conservation tillage (CT_d), shallow conservation tillage (CT_s) and no-tillage (NT)) for sugar beet and soybean production, taking fuel consumption, total energy input (made up of both direct and indirect inputs), crop yield, energy output, net-energy output, energy intensity and energy use efficiency into account. The input rates of fertiliser, chemical plant protection, and seeds were set constant across years; whereas measured values of fuel consumption were used for all tillage treatments. NT required a considerably lower energy input than MP and CT_d as no fuel is needed for tillage and just slightly more fuel for additional spraying of glyphosate. Anyhow, the energy efficiency parameters did not differ between tillage treatments, as theses parameters were mainly determined by energy output, which was considerably higher than the energy input. However, year effects on the energy efficiency were observed for both crops. Nitrogen fertilisation and diesel fuel consumption were identified as the most energy-intensive inputs. Consequently, the energy input for sugar beet was higher than that for soybean, which was identified as a low-input crop. But sugar beet attained a more than 4 times higher net-energy output, a 2.5 times higher energy use efficiency, and an energy intensity for yield production of less than 3 times those of soybean.

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

Soil tillage is one of the highest energy and labor consumer in arable farming (Tabatabaeefar et al. 2009, 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). The establishment of winter wheat with no-tillage on a silty loam Chernozem could reduce both fuel consumption and work time by more than 85% compared to conventional tillage (Moitzi et al. 2013). However, the energy savings of minimum and zero tillage are often offset by higher energy requirements for herbicides and for nitrogen fertiliser with conservation tillage systems (Zentner et al. 2004). Large differences among crops in energy efficiency suggest that crop rotation and crop management can be equally important in determining cropping system energy efficiency (Alluvione et al. 2011). Studies by Hoeppner et al. (2005) and Sartori et al. (2005) showed in an organic management system a by 50% lower energy input than under conventional management. Energy use efficiency rises with crop yield and can be improved by the nutrient management, i.e. the amount and kind of fertiliser (Moitzi et al. 2020a). Deike et al. (2008) found that crop yield and energy efficiency are much more affected by crop rotation than by tillage. Whereas Neugschwandtner et al. (2015) observed for winter wheat both crop rotation and tillage effects with some crop rotation effects consistent over tillage treatments.

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Climate and soil conditions determine 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, however, yields on no-tillage plots can be equivalent or even higher compared to conventional tillage. This suggests that no-tillage may become a crucial adaptation strategy to climate change in drier regions of the world. For developing energy-efficient cropping systems for the Pannonian Basin, detailed information on energy consumption and efficiency of different soil tillage systems for sugar beet (*Beta vulgaris* L.) and soybean (*Glycine max* (L.) Merrill) are rare. A long-term field experiment in the Pannonian Basin with semi-arid climate conditions was installed in 1996 to determine the effects of four tillage systems. The overall objective of the present study was to analyse the crop yield and the energy efficiency related parameters energy output, energy input, net-energy output, energy intensity and energy use efficiency of sugar beet and soybean. It is hypothesised that ploughless tillage systems require less energy and have higher energy efficiency than tillage systems with ploughing.

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, Vienna (BOKU) in Raasdorf (48°14'N, 16°33'E; 153 m a.s.l.). The field is located on the edge of the Marchfeld plain, which is an important 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 10.8 °C, the mean annual rainfall is 568 mm (1995–2018). Long-term rainfall patterns show most rainfall from May to September with monthly values above 63 mm and the highest amount in July (76 mm). Long-term average temperature and rainfall and annual values during the vegetation period of sugar beet (April to October) and of soybean (May to September) are shown in Table 1. The vegetation periods 2010, 2014, 2016 and 2018 were wetter than average, whereas the vegetation period 2011 was very dry.

Experimental design and management. The experiment was established in August 1996 in a split-plot design with soil tillage as main plot factor and crop rotation as sub-plot factor. Soil tillage includes mouldboard plough (MP), deep conservation tillage (CT_d), shallow conservation tillage (CT_s) and no-tillage (NT). The plot size for the tillage systems allows the operation with regular farm machinery (1st replication: 60 × 24 m, 2nd to 4th replication: 40 × 24 m). The sequences of tillage operations are shown in Table 2. The technical working width of the four furrow reversible mouldboard plough was 1.7 m and for the other implements (wing sweep cultivator, subsoiler) 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 adjustment were mounted behind the tine bars. The subsoiler had four fixed tines (tine distance: 75 cm) with wings (34 cm width) at the bottom and a roller harrow for depth adjustment. The yearly input rate of

Table 1. Mean temperature and mean precipitation during growing seasons and complete years

	Pre-crop	Temperature (°C)		Precipitation (mm)	
		growing season[1]	January–December	growing season[1]	January–December
Sugar beet					
2005	winter wheat	16.0	10.0	416	554
2010	winter wheat	15.5	9.8	586	693
2011	winter wheat	16.7	10.9	335	401
2014	soybean	16.4	11.8	688	794
Mean (1995–2018)		16.4	10.8	422	568
Soybean					
2016	rapeseed	19.2	11.3	381	644
2018	winter wheat	20.5	12.2	375	602
Mean (1995–2018)		18.7	10.8	342	568

[1]Period between April (seeding time) to October (harvest time) for sugar beet and between May to September for soybean

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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	power harrow[A] tine harrow[B] (7–9 cm)	power harrow[A] tine harrow[B] (7–9 cm)	power harrow[A] tine harrow[B] (7–9 cm)	–
Seeding	precision seeder (4 cm)	precision seeder (4 cm)	precision seeder (4 cm)	precision seeder (4 cm)
Stubble cultivation	wing sweep cultivator (5–8 cm)	wing sweep cultivator (5–8 cm)	wing sweep cultivator (5–8 cm)	–

[A]sugar beet; [B]soybean

seeds, fertiliser and chemical plant protection (herbicides and fungicides) were kept constant during the period 2005–2018. Seeding of both crops was done with a six-row pneumatic precision seeder in 50 cm row distance. Sugar beet was sown with 100 000 grains/ha (2.5 kg/ha) at the beginning of April. The fertiliser urea (46% N) was applied at a rate of 97 kg N/ha directly before seeding. Sugar beet plants were sprayed against monocotyledonous and broadleaved weeds in three passes at the end of April, in mid-May and the end of May with Phenmedipham (375 g/ha active ingredient (a.i.)), Desmedipham (75 g/ha a.i.) and Ethofumesat (775 g/ha a.i.) in all plots. Three treatments with fungicides (total application rates: Pyraclostrobin, 133 g/ha a.i.; Epoxiconazole, 50 g/ha a.i.; Azoxystrobin, 250 g/ha a.i.; Difenoconazol, 100 g/ha a.i.; Fenpropidin, 375/ha a.i.) were applied against *Cercospora beticola* and *Ramularia beticola* at the end of June, in mid-July and the end of July. In the NT treatment, the non-selective herbicide Glyphosate (1 575 g/ha a.i.) was additionally applied two weeks before sowing. Harvest was performed at the end of October. Soybean was sown with 650 000 grains/ha (140 kg/ha) at in mid-April. Herbicides (Imazamox, 40 g/ha a.i.; Thifensulfuron Methyl Desmedipham, 7.5 g/ha a.i.) were sprayed in two passes for the control of broadleaved weeds. Harvest was performed in mid-September.

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 and stubble processing on August 11th, 2006. 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 (cf. Szalay et al. 2015), which were considered constant for all six years (Table 1), 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

Table 3. Definition of energy efficiency parameters (Hülsbergen et al. 2001)

Energetic parameter	Definition	Unit
Direct energy input (E_d)	input of diesel and lubricant oil	GJ/ha
Indirect energy input (E_i)	seed[A] + mineral fertiliser + chemical plant protection + machines	GJ/ha
Energy input (E)	$E = E_d + E_i$	GJ/ha
Energy output (EO)	energy in the harvested biomass[B] – energy in the seed	GJ/ha
Net energy output (NEO)	NEO = EO – E	GJ/ha
Energy intensity (EI)	EI = E/harvested dry matter yield	MJ/kg
Energy use efficiency (EUE)	EUE = EO/E	GJ/GJ

[A]Energy input for processing, storage and sale of seed, [B]sugar beet root, soybean grain

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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. Constant data sets for direct energy input parameters were also used in other energy efficiency studies (cf. Hülsbergen et al. 2001, Deike et al. 2008, Lin et al. 2017, Moitzi et al. 2019). 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 transportation of the harvest products, the fuel consumption was calculated with the specific fuel consumption coefficient of 0.09 L fuel per ton of harvest products and kilometer according to ÖKL (2019). A distance of 5 km for transportation of the harvest products with a tractor and a trailer was assumed. 2% of the fuel consumption was calculated for the lubrication oil of motors.

Energy efficiency and energy equivalents. Energy efficiency parameters (Table 3) were calculated according to Hülsbergen et al. (2001). The energy content in the harvested sugar beets or soybean grains were set to 16.8 MJ/kg or 23.8 MJ/kg dry matter (Hülsbergen et al. 2001). Yield of sugar beet is shown in fresh matter with an average moisture content of 75%, whereas soybean grain yield is expressed in dry matter. The calculation for the energy equivalent of the embedded energy in farm machinery was done in different tillage systems based on a 100 ha arable farm under Austrian conditions (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 and sugar beet harvester, 2 000–3 000 ha for the implements. The amounts of the used production facilities were multiplied with the energy equivalents (Table 4).

Statistical analysis. All analyses were conducted using IPM ® SPSS ® Statistics 21 (New York, USA). The requirements for analysis of variance (ANOVA) were tested with the Levene test for homogeneity of variances and Shapiro-Wilk test for normal distribution of residuals. The two-factorial ANOVA tests were carried out for crop yield, energy output, net-energy output, energy intensity, energy use efficiency to detect year and tillage effects using a general linear model (GLM). Each year was analysed to detect the tillage effect with one-factorial ANOVA. The multiple comparison test was carried out with the Student-Newman-Keuls procedure ($P < 0.05$).

Table 4. Energy equivalents for production facilities

	Unit	Energy equivalent	References
Direct energy use			
Diesel fuel	MJ/L	39.6	Hülsbergen et al. (2001), Sørensen et al. (2014)
Lubricant oil	MJ/L	39.0	Sørensen et al. (2014)
Indirect energy use			
<u>Mineral fertiliser</u>			
Urea (46% N)	MJ/kg	48.0	Jenssen and Kongshaug (2003)
<u>Herbicide</u>			
Glyphosate	MJ/kg	454	Green (1987), CIGR (1999)
Herbicide for broadleaf weed control	MJ/kg	259	Saling and Kölsch (2008)
<u>Fungicide</u>	MJ/kg	180	Saling and Kölsch (2008)
<u>Seed</u>			
Sugar beet	MJ/kg	98.0	Hülsbergen et al. (2001)
Soybean	MJ/kg	23.8	Rathke et al. (2007)
<u>Machinery</u>			
Mouldboard plough	MJ/ha	1 796	Biedermann (2009)
Conservation tillage-deep	MJ/ha	1 810	Biedermann (2009)
Conservation tillage-shallow	MJ/ha	1 810	Biedermann (2009)
No-tillage	MJ/ha	1 640	Biedermann (2009)

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RESULTS

Total fuel consumption. The total area-based fuel consumption was for sugar beet 2.2-fold (MP and CT_d), 2.5-fold (CT_s) and 3.2-fold (NT) higher compared to soybean, as sugar beet consumed more fuel for seedbed preparation, spraying of herbicides, harvesting and transportation and compared to soybean also fuel for spreading of fertiliser and spraying of fungicides is needed (Table 5). The total fuel consumption was for both crops highest with MP and CT_d and lowest with NT, with CT_s showing intermediate values. It was for MP and CT_d by 1.3-fold for sugar beet and by 1.9-fold for soybean higher compared to NT. Comparing MP and CT_d, substitution of the plough through a subsoiler and a wing sweep cultivator in CT_d could not reduce the fuel consumption. Main differences between tillage treatments arose form the fuel consumption for tillage treatments and seeding, which was for sugar beet or soybean at 35.1 or 32.5 L/ha for MP and CT_d, at 23.0 or 20.4 L/ha for CT_s. The fuel consumption for seeding of NT was at 2.1 L/ha for both crops. Seeding was the only tillage operation where NT had a slightly higher fuel consumption than the other treatments. Additionally, NT consumed more fuel for spraying of herbicides. The shallow cultivation with wing sweep cultivator in CT_s reduced the total fuel consumption by 12.1 L/ha (9%) to 121.0 L/ha for sugar beet and by 12.1 L/ha (21%) to 47.8 L/ha for soybean. The lowest total fuel consumption was measured in NT with 102.2 L/ha for sugar beet and 31.5 L/ha for soybean which is 24% and 48% lower than in MP and CT_d treatments.

Total energy input. The total energy input was with sugar beet about two-third higher for all tillage treatments than with soybean. Sugar beet needed a higher energy input for fuel, lubricant, fertiliser and chemical plant protections, whereas the energy input through seeds was higher for soybean (Table 6). The total energy input was for both crops highest with MP and CT_d and lowest with NT, with CT_s showing intermediate values. It was for MP and CT_d by 6% for sugar beet and by 9% for soybean higher compared to NT. Main differences between tillage treatments arose form the differences in the direct energy input (fuel and lubricant). NT had a slightly higher energy demand for chemical plant protection. The ratio of direct energy to indirect energy (in %:%) was in the tillage treatments for sugar beet or soybean at 43:57 or 32:68 (MP and CT_d), 40:60 or 27:73 (CT_s), 35:65 or 19:81 (NT), respectively. The highest share on the total energy input in sugar beet had fuel and lubricant (ranging from 35% to 42% on the total energy input). Fertiliser had also with a range of 38% to 40% a high share. Whereas, the highest share in soybean was with the seeds (ranging from 44% to 47% of the total energy input), which required in case of sugar beet just about 1% of the total energy input. The energy input which is allocated to machinery required for sugar beet

Table 5. Diesel fuel consumption (L/ha) for sugar beet and soybean cultivation in different tillage systems

Operation	Sugar beet				Soybean			
	MP	CT_d	CT_s	NT	MP	CT_d	CT_s	NT
Ploughing[A]	18.8	–	–	–	18.8	–	–	–
Wing sweep cultivator[A]	–	9.4	6.7	–	–	9.4	6.7	–
Subsoiling[A]	–	9.4	–	–	–	9.4	–	–
Seedbed preparation[B]	8.6	8.6	8.6	–	6.0	6.0	6.0	–
Seeding[C]	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.1
Spreading of fertiliser[D]	1.5	1.5	1.5	1.5	–	–	–	–
Spraying of herbicides[D]	6.0	6.0	6.0	8.0	4.0	4.0	4.0	6.0
Spraying of fungicides[D]	6.0	6.0	6.0	6.0	–	–	–	–
Harvesting[D]	53.0	53.0	53.0	53.0	22.0	22.0	22.0	22.0
Transport (5 km)[D]	31.5	31.5	31.5	31.5	1.4	1.4	1.4	1.4
Stubble cultivation[A]	5.7	5.7	5.7	–	5.7	5.7	5.7	–
Total	133.1	133.1	121.0	102.1	59.9	59.9	47.8	31.5

MP – mouldboard plough; CT_d – deep conservation tillage; CT_s – shallow conservation tillage; NT – no-tillage; [A]Szalay et al. (2015); [B]With power harrow in sugar beet (Szalay et al. 2015) and with tine harrow in soybean (ÖKL 2019); [C]Own data (unpublished); [D]ÖKL (2019)

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Table 6. Direct and indirect energy input (GJ/ha) for sugar beet and soybean cultivation in different tillage systems

	Sugar beet				Soybean			
	MP	CT_d	CT_s	NT	MP	CT_d	CT_s	NT
Direct energy								
Fuel, lubricant	5.20	5.20	4.72	4.04	2.42	2.42	1.93	1.27
Indirect energy								
Seed	0.25	0.25	0.25	0.25	3.33	3.33	3.33	3.33
Fertiliser	4.66	4.66	4.66	4.66	–	–	–	–
Chemical plant protection	0.47	0.47	0.47	1.12	0.01	0.01	0.01	0.73
Machinery	1.80	1.81	1.81	1.64	1.80	1.81	1.81	1.64
Total	12.38	12.39	11.91	11.71	7.56	7.57	7.08	6.97

MP – mouldboard plough; CT_d – deep conservation tillage; CT_s – Shallow conservation tillage; NT – no-tillage

14% to 15% and for soybean 15% to 26% of the total input. The energy share caused by chemical plant protection was for sugar beet or soybean at 3% or 0.1% for MP, CT_d and CT_s and at 10% or 11% for NT, respectively.

Yield and energy output. The mean values of yield and energy output over all soil tillage treatments and years were for sugar beet 70.3 t/ha and 295.2 GJ/ha and for soybean 3.22 t/ha and 73.7 GJ/ha. Consequently, the mean energy output of sugar beet was 4.01-fold higher than that of soybean (Table 7). No tillage × year interactions were detected. Both the yield and the energy output of sugar beet and soybean were not affected by the tillage system, but there was a year effect. The yield and energy output of sugar beet ranked among years as follows: 2005 ≥ 2014 ≥ 2010 and 2011; and for soybean as follows: 2016 > 2018. The range of yield and energy output between years was much higher than that between tillage systems with 10.20 t/ha *vs.* 5.98 t/ha for sugar beet and with 42.8 GJ/ha *vs.* 24.9 GJ/ha for soybean.

Energy efficiency. The mean values of the net-energy output over all soil tillage treatments and years were for sugar beet 283.0 GJ/ha and for soybean 66.4 GJ/ha. Consequently, the mean net-energy output of sugar beet was 4.26-fold higher than that of soybean (Table 7). No tillage × year interactions were detected. The mean values of the energy intensity over all soil tillage treatments and years were for sugar beet 0.70 MJ/kg and for soybean 2.41 MJ/kg. Consequently, the mean energy intensity for the yield production of sugar beet was just less than a third of that of soybean (Table 7). The mean values of the energy use efficiency over all soil tillage treatments and years were for sugar beet 24.4 GJ/GJ and for soybean 10.1 GJ/GJ. Consequently, the mean energy use efficiency of sugar beet was 2.42-fold higher than that of soybean (Table 7). As for yield and energy output, there were no differences between tillage treatments for the energy efficiency parameters net-energy output, energy intensity and energy use efficiency. The year effects of energy efficiency parameters were ranked the same as for yield and energy output. The sugar beet in the conservation tillage systems CT_d, CT_s and NT showed an overall 6.3% lower energy intensity and 7.4% higher energy use efficiency than in MP (not significant). The ranges of the energy efficiency parameters between the years were higher than between the tillage systems, with exception for the energy intensity of soybean. They amounted to 42.8 GJ/ha *vs.* 25.1 GJ/ha for the net-energy output, 0.11 MJ/kg *vs.* 0.06 MJ/kg for the energy intensity and 3.6 GJ/GJ *vs.* 2.0 GJ/GJ for the energy use efficiency of sugar beet. For soybean the respective ranges were 31.6 GJ/ha *vs.* 3.6 GJ/ha for the net-energy output, 0.11 MJ/kg *vs.* 0.27 MJ/kg for the energy intensity and 4.3 GJ/GJ *vs.* 1.0 GJ/GJ for the energy use efficiency of soybean.

DISCUSSION

Total fuel consumption. The total diesel fuel consumption was between 55% (MP) and 69% (NT) lower in soybean than in sugar beet, which is mainly caused by the less diesel fuel used for soybean harvest and transport. Sugar beets are bulky crops and require high performance harvester and transport systems. The area based fuel consumption in the tillage systems is determined by the choice of the implements (Moitzi et al. 2019). Mouldboard ploughing is still

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Table 7. Average yield and energy efficiency parameters for sugar beet and soybean as affected by tillage and year

	Sugar beet					Soybean		
	2005	2010	2011	2014	mean	2016	2018	mean
Yield (t/ha)[B]								
MP	72.6	65.5	63.8	70.7	68.1	4.14	2.42	3.28
CT_d	80.5	70.8	67.1	78.1	74.1	3.83	2.53	3.18
CT_s	75.2	63.6	69.7	69.1	69.4	3.89	2.67	3.28
NT	77.0	64.9	64.0	72.1	69.5	3.66	2.59	3.12
Mean[A]	76.3[b]	66.2[a]	66.1[a]	72.5[ab]	70.3	3.88[b]	2.55[a]	3.22
Energy output (GJ/ha)								
MP	305.0	275.3	267.8	297.0	286.3	95.6	54.7	75.1
CT_d	338.0	297.3	281.5	328.0	311.2	88.3	57.5	72.9
CT_s	316.0	267.3	292.8	290.3	291.6	89.7	60.7	75.2
NT	323.0	272.8	268.8	303.0	291.6	84.2	58.7	71.4
Mean	320.5[b]	278.1[a]	277.7[a]	304.6[ab]	295.2	89.4[b]	57.9[a]	73.7
Net-energy output (GJ/ha)								
MP	292.5	262.6	255.4	284.4	273.7	88.0	47.1	67.6
CT_d	325.5	285.0	269.2	315.7	298.8	80.7	49.9	65.3
CT_s	304.0	255.3	280.8	278.1	279.5	82.6	53.6	68.1
NT	311.6	260.8	257.0	290.9	280.0	77.3	51.7	64.5
Mean	308.4[b]	265.9[a]	265.6[a]	292.3[ab]	283.0	82.2[b]	50.6[a]	66.4
Energy intensity (MJ/kg dry matter)								
MP	0.68	0.77	0.79	0.71	0.74	1.85	3.19	2.52
CT_d	0.62	0.70	0.75	0.65	0.68	2.00	3.00	2.50
CT_s	0.65	0.76	0.70	0.72	0.71	1.83	2.67	2.25
NT	0.61	0.73	0.74	0.66	0.69	1.92	2.81	2.36
Mean	0.64[a]	0.74[b]	0.75[b]	0.69[ab]	0.70	1.90[b]	1.79[a]	2.41
Energy use efficiency (GJ/GJ)								
MP	24.7	22.2	21.7	24.0	23.1	12.6	7.2	9.9
CT_d	27.3	24.0	22.7	26.5	25.1	17.7	7.6	9.6
CT_s	26.6	22.5	24.6	24.4	24.5	12.7	8.6	10.6
NT	27.5	23.2	22.8	25.8	24.8	12.1	8.4	10.2
Mean	26.5[b]	23.0[a]	22.9[a]	25.1[ab]	24.4	12.3[b]	8.0[a]	10.1

MP – mouldboard plough; CT_d – deep conservation tillage; CT_s – Shallow conservation tillage; NT = no-tillage; [A]significant differences are shown for the year effect with different letters. [B]fresh matter for sugar beet and dry matter for soybean grain yield

a widely used tillage method by Austrian farmers under difficult conditions (heavy soils in humid regions). Arvidsson (2010) measured a fuel consumption for ploughing to 20 cm depth at around 15 L/ha on the silt loam and around 30 L/ha on a clay soil. With a decrease of the ploughing depth, the fuel consumption can also be reduced (Arvidsson 2010). With the choice of the tillage system, the fuel consumption can be lowered when using CT_s and NT. MP and CT_d with the same area based fuel consumption are differing in their plant residue incorporation. While ploughing created a soil surface without plant residues, CT_d with wing sweep cultivator and subsoiler left plant residues on the soil surface, which may have ecological effects (e.g. mitigation of soil erosion). The implement combination and working depth in CT_d is determining the fuel consumption. Subsoiling (to 35 cm) can break the plough pan and the subsoil compaction, which might lead to a better rooting primarily of sugar beet. Different implements

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for seedbed preparation require different amounts of fuel. Sugar beet requires a fine seedbed and this can be realised with a power-take-off driven implement, e.g. power harrow, whereas soybean does not require such a fine seedbed as sugar beet. The seedbed preparation on a silty loam as in this study can also be done by a tine harrow, which requires less diesel fuel than a power harrow (Poje 1998, ÖKL 2019).

Total energy input. Lin et al. (2017) define a low-input system if the energy input is below 10.0 GJ/ha. The total energy input for sugar beet was with 11.5 GJ/ha to 12.2 GJ/ha above and that of soybean with 6.9 GJ/ha to 7.5 GJ/ha below this threshold. Therefore, soybean production in the Pannonian Basin can be regarded as low-input. Especially the energy inputs for fuel and fertiliser caused the high energy input for sugar beet production. Small differences of the energy input between 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 higher use of chemical plant protection, mainly glyphosate. Shifting of tillage systems with plough to non-inversion tillage systems reduces not only the direct energy input but also the working time (Brunotte and Sommer 2009).

Crop yield and energy output. Environmental factors (years and climate conditions) influenced crop yield and energy efficiency more strongly than tillage practices. Yield variability of agricultural crops in the semi-arid region is mainly caused by water shortage and heat stress (Bodner et al. 2015). Large differences in yield and energy efficiencies are mainly driven by climate, particularly mean annual precipitation and rainfall distribution (Arrieta et al. 2018). Consequently, the lowest sugar beet yield was observed in the driest year (2005). On average across all four years for sugar beet and two years for soybean, no significant differences were observed among tillage treatments for crop yield and energy output. A comparison of crop yield with no-tillage or conventional tillage in a long-term field experiment under humid climate conditions in Switzerland showed higher yields with no-tillage for winter barley, winter wheat, spring pea, spring faba bean, winter pea and no yield differences between tillage systems for sugar beet, silage maize, winter rye, soybean, winter field beans and spring wheat (Martínez et al. 2016). Reduced tillage systems can obtain higher yields in dry regions due to better soil water conservation whereas in wetter regions the yields often are impaired (Pittelkow et al. 2015). In the Pannonian Basin with its semi-arid climate conditions, water is the limiting factor for plant growth. With conservation tillage-systems (CT_d, CT_s, NT) there is a potential to save water in the soil, which was confirmed by a study at same site (Raasdorf) by Thaler et al. (2012). Long-term experiments show in ploughless systems a strong stratification of soil organic carbon in NT with no differences in total carbon stock between NT and MP (Martínez et al. 2016). The increased organic carbon in the topsoil can be an additional explanation for a better soil water conservation in NT. Rusu (2014) found under Pannonian climate conditions for soybean with minimum or conventional tillage compared to no-tillage a by 3–7% or by 17% higher yield, respectively. But there was tendency of higher sugar beet yields with the ploughless deep tillage systems CT_d than with MP, CT_s and NT (not significant), probably as soil tillage up to a depth of 35 cm with a subsoiler facilitated sugar beet rooting. The reduced sugar beet yield in MP in the dry years (2005 and 2011) might be explained by the higher evaporation from the loosened soil and the possible limited sugar beet rooting due to plough pan formation. Ide et al. (1987) found a mean yield increase for sugar beet between 5% and 10% after breaking up a plough pan.

Energy efficiency. The energy efficiency parameters net-energy output, energy intensity and energy use efficiency are mainly determined by the energy output, as the values for the energy input are much lower (Arvidsson 2010). Also in our experiment, the energy output with the harvest products was considerably higher than the energy input, especially in the case of sugar beet. Consequently, differences of the energy input between the tillage treatments did not affect the energy efficiency parameters. The overall year effect on the energy efficiency was greater than the tillage effect, which has also been reported for winter wheat (Moitzi et al. 2019). Nitrogen fertilisation and diesel fuel consumption were identified as the most energy-intensive inputs. Consequently, their efficient use (e.g. using the right nitrogen fertiliser at appropriate doses and balancing nitrogen fertilisation rates with the actual crop requirements; reduced tillage like CT_s or NT) can be the most effective way for decreasing energy input and improving energy efficiency (Moitzi et al. 2020a,b). Under Pannonian climate conditions, sugar beet is more energy efficient than soybean, with a 4.27-fold higher

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net-energy output and a 2.46-fold higher energy use efficiency. The production of soybean also resulted in a 3.50-fold higher energy intensity than for sugar beet production. The higher energy efficiency of sugar beet than soybean is mainly explained by the longer vegetation period of sugar beet and different biomass harvest products (sugar beet: sugar in root; soybean: oil and protein in grain). According to Arvidsson (2010), the net-energy output is the most relevant parameter to determine the efficiency of cropping systems in a world of increasing food and energy demand. In this consideration, sugar beet with CT_d reached the highest net-energy output over all years. For soybean, the highest net-energy output was in the year 2016 with good growing conditions and MP and in the year 2018 with CT_s. Further, the farming system is affecting the energy use efficiency. Alluvione et al. (2011) reported that integrated farming could obtain a by one third higher energy use efficiency than conventional farming, as the energy input was lower but the net energy output was similar. Whereas, Zhang et al. (2015) reported for organic soybean a higher energy input due to mechanical weeding and organic fertilisation than for conventionally produced soybean. Conventional weed management using herbicides rather than mechanical operations might be a option to reduce energy inputs, especially when more than one weed control treatment is required (Deike et al. 2008, Alluvione et al. 2011). Usually there is more mechanisation energy required for organic crops than for conventional ones, as weed control is performed mechanically (Dal Ferro et al. 2017).

Our study showed that the energy input and energy efficiency analysis can provide a synthesis of information on different aspects of cropping systems (e.g. tillage system, nutrient fertilisation, choice of crops in the rotation).

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