Effect of two-axle and three-axle sugarbeet tanker harvester on selected soil-physical properties in dry and wet soil conditions

Gerhard Moitzi[1*], Stefan Amon[2], Andreas Klik[3], Andreas Schwen[3]

(1. *University of Natural Resources and Life Sciences, Vienna (BOKU), Department of Crop Sciences, Experimental Farm Groß-Enzersdorf, Schloßhofer Straße 31, 2301 Groß-Enzersdorf, Austria*;
2. *Agricultural school Hollabrunn, Sonnleitenweg 2, 2020 Hollabrunn, Austria*;
3. *University of Natural Resources and Life Sciences, Vienna (BOKU), Department of Water – Atmosphere – Environment, Institute of Hydraulics and Rural Water Management, Muthgasse 18, 1190 Wien, Austria*)

Abstract: The aim of this study was to show the effects of two-axle and three-axle sugarbeet harvester under dry (gravimetric soil water content 20%) and wet (gravimetric soil water content 30%) soil conditions on bulk density, soil penetration resistance and saturated hydraulic conductivity. The practical experiment was carried out in a long-term non-ploughed field with a silty loam soil in the Pannonian region of Austria. The tyre-inflation pressure of the sugarbeet harvester was set to 140 kPa in the front axle and 190 kPa in the middle and rear axles. The total weight of the three-axle harvester was distributed equally with about 20 Mg each axle. Two-axle harvester distributed the total weight of 49.1 Mg to the rear axle with 27.3 Mg and to the front axle with 21.8 Mg. The effects on soil properties are followed: the differences of bulk density (10-15 cm, 25-30 cm, 50-55 cm) between un-wheeled and wheeled treatments with two-axle and three-axle sugarbeet harvesters were small. Under dry conditions, the soil penetration resistance was not affected by the sugarbeet harvester. The soil penetration resistance was higher in the top soil of the wet treatment after rolling with the two-axle sugarbeet than three-axle sugarbeet harvester whereas the subsoil (<23 cm) was not affected, likely because of the decreasing water content. The saturated hydraulic conductivity at 10-15 cm and 25-30 cm was not affected significantly by the sugarbeet harvester traffic, whereas higher values were found in the soil depth 50-55 cm. The three-axle harvester on wet soil reduced the saturated hydraulic conductivity in the top soil below the critical threshold value of 10 cm d^{-1}. The results clearly demonstrated that under dry soil conditions, that two-axle and three-axle sugarbeet harvester with low tire inflation pressure (140 kPa front, 190 kPa middle and rear) did not change the analyzed soil properties. Also, under wet conditions, the effects were small mainly because of the low tyre inflation pressure. As a result of this, we concluded that soil protecting sugar beet harvesting required a good load carry capacity of the soil.

Keywords: sugarbeet tanker harvester, soil moisture conditions, bulk density, soil penetration resistance, saturated hydraulic conductivity

Citation: Moitzi, G., S. Amon, A. Klik, and A. Schwen. 2019. Effect of two-axle and three-axle sugarbeet tanker harvester on selected soil-physical properties in dry and wet soil conditions. Agricultural Engineering International: CIGR Journal, 21(1): 18–27.

1 Introduction

Sustainable agriculture requires physical soil protection. Agricultural soils can be affected in their ecological functions (biomass production, filter, buffer and transformation processes) by soil compaction by farm machinery. Soil compaction modifies the pore size distribution and reduces the average pore size, air and water permeability, with possibly adverse effects on root and plant growth. Resulted effects are yield decrease, rut formation, soil erosion, and increased draft force and fuel consumption in soil tillage. In agriculture, soil compaction are harmful processes which lead to a reduction of site specific productivity, higher greenhouse gas emission and a requirement for greater fuel energy in

Received date: 2018-03-13 **Accepted date:** 2018-09-09
***Corresponding author: Gerhard Moitzi,** University of Natural Resources and Life Sciences, Vienna (BOKU), Department of Crop Sciences, Experimental Farm Groß-Enzersdorf, Schloßhofer Straße 31, 2301 Groß-Enzersdorf, Austria. Email: gerhard.moitzi@boku.ac.at.

tillage processes (Horn et al., 2003). High wheel loads of agricultural machinery caused a risk of soil compaction, especially if traffic was conducted under moist soil conditions. Koch et al. (2008) demonstrated that repeated wheeling or traffic with heavy agricultural machinery negatively affected penetration resistance, macro-pore volume, and air permeability of top- and subsoils.

Subsoil compaction is a major problem due to its persistence. Effects of topsoil compaction can be alleviated in a few years when the soil is tilled. Effects of subsoil compaction persisted much longer and could become permanent (Etana and Håkansson, 1994). Håkansson and Reeder (1994) showed that soil compaction caused by tyre loads of 10 tons could be found down to a depth of 50 cm.

Compaction mainly affects the large pores, which govern the saturated hydraulic conductivity (Arvidsson, 2001). Saturated hydraulic conductivity may be a more sensitive indicator than bulk density (Dawidowski and Koolen, 1987; Horton et al., 1994; Arvidsson, 2001). It is an important parameter in assessing soil structure and in modeling transport processes in the soil. According to Messing (1993), the saturated hydraulic conductivity was a highly variable parameter in space and time. Conservation tillage increased the soil stability (Brunotte, 2007). In conservation tillage systems, a higher soil strength in the topsoil layers was indicated by differences in penetration resistance and the air filled pore volume compared to conventionally tilled fields (Koch et al., 2008). In contrast to mouldboard ploughing, long term shallow-mixing conservation tillage often resulted in an increased bulk density of the untilled layer which was formerly ploughed (Stockfisch et al., 1999).

Sugarbeet harvesting was mainly operated with six-row self-propelled sugar-beet tanker harvester (Bernhardt et al., 2008). Six-row sugarbeet harvesters with total loads on approximately 35 t on two axles caused problems among sugarbeet (*Beta vulgaris L.*) growers regarding the risk of subsoil compaction (Arvidsson, 2001). The study of Arvidsson (2001) showed great effects on soil physical properties but mainly small and insignificant differences in crop yielded after traffic with heavy sugarbeet harvesters compared to no traffic.

The harvest performance of self-propelled sugarbeet harvester can be increased with the hopper capacity and number of lifting aggregates, which results in higher total weights. For the mitigation of potential subsoil compaction, sugar beet harvesters were equipped with large tyres/rubber tracks and/or additional axles for increasing the contact area between soil and tyre/rubber belt (VDI, 2006). Geischeder (2011) investigated five wheeling situations (single pass with rubber belt track – four passes with radial tyre) on soil physical properties and soil stress on a luvisol on loess. He found a smaller impact of the soil stress to the subsoil with increased contact area soil/rubber belt in rubber belt track.

The equipment with a third axle in the six-row self-propelled sugarbeet tanker harvester is a technical contribution to reduce the subsoil compaction risk. Besides of the tillage system (ploughing, conservation tillage), site-specific (especially the soil properties and the soil moisture content during harvest) influenced the bearing capacity of the susceptible soils (Lorenz et al., 2016).

The effect of a third axle in the six-row self-propelled sugarbeet tanker harvester on wet and dry soil conditions was not investigated yet. The objective of this study was to investigate the effect of a two-axle - and a three-axle six-row self-propelled sugarbeet tanker harvester from realistic field traffic in dry and wet soil conditions on soil physical properties (penetration resistance, dry bulk density, saturated hydraulic conductivity). Additional the total-weight, axle-, and wheel-load during harvest were measured. The experiment was conducted on a long-term non-ploughed field in the Pannonian region of Lower Austria.

2 Materials and methods

2.1 Experimental site and machine properties

The experiment was conducted on a field cropped with sugarbeets in north-east of the village Hollabrunn (48°34'33.7''N 16°03'34.3''E), Lower Austria. The mean annual temperature is 9.2°C, and the mean annual precipitation is 519 mm (1981-2010). Compared to the long-term annual average, the experimental year 2015 was a rather dry year with an annual precipitation of 421 mm and a mean annual temperature of 10.7°C. At the time of the experiment (26th September 2015), the cumulative precipitation had a deficiency of 272 mm in comparison to the period 2005-2015 (Figure 1).

The investigated soil was a silty loam with average contents of 22.3% sand, 52.9% silt and 24.7% clay (Table 1) and was classified as chernozem of alluvial origin rich in calcareous sediments. The typical profile comprised an Ah-horizon with 40 cm depth above the C-horizon (parent material).

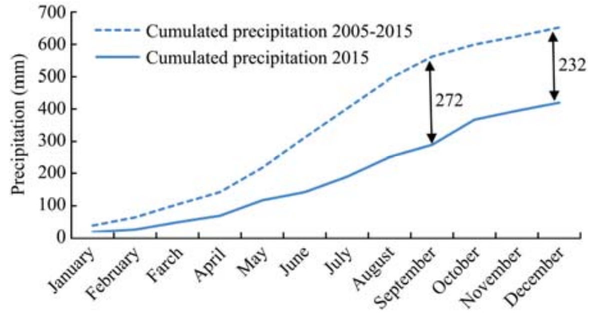

Figure 1 Mean cumulated precipitation for the period 2005-2015 and experimental year 2015

Table 1 Particle size distribution (%) of the investigation plots

	Two-Axle/Wet/Depth (cm)			Two-Axle/Dry/Depth (cm)			Three-Axle/Wet/Depth (cm)			Three-Axle/Dry/Depth (cm)			mean
Particle size	5-15	25-35	45-55	5-15	25-35	45-55	515	25-35	45-55	5-15	25-35	45-55	
2-0.063 mm	22.3	18.3	17.4	23.6	20.9	18.2	26.8	25.5	22.6	24.6	25.8	21.2	22.3
63-2 µm	53.5	56.8	61.2	50.8	53.5	54.9	48.9	49.3	50.1	53.9	48.6	53.8	52.9
<2µm	24.2	24.8	21.4	25.4	25.5	26.8	24.2	25.1	27.2	21.3	25.4	25.0	24.7

Between the pre-crop (summer barley) and sugarbeet, a non-winter-hardy catch crop (mixture of mustard, phacelia and buckweed) was grown and disc-tilled in mid of March. Tillage was done with a wing-share cultivator end of March with 20 cm depth. The sugarbeets were seeded on March 27, 2015 with a pneumatic precision seeder in a row-distance of 50 cm.

Harvesting was conducted on September 26, 2015 with two six-row self-propelled sugar beet tanker harvesters for the company HOLMER Maschinenbau GmbH, Regensburg, Germany: HolmerTerraDos T4-30 with two axles and HolmerTerraDos T4-40 with three axles (Table 2).

Table 2 Technical parameters of the used six-row sugarbeet tanker harvesters

	Unit	Two-axle chassis (Holmer Terra Dos T4-30)	Three-axle chassis (Holmer Terra Dos T4-40)
Engine power	kW (HP)	460 (626)	460 (626)
Chassis		Two hydraulic driven axle	Three hydraulic driven axle
Total mass[1)]	kN/kg	275.6/28100	331.5/33800
Hopper capacity	m^3/t	30/21	45/31
Length	m	12.94	14.98
Height/Width	m	3.98/3.30	3.98/3.30
Axle distance	m	5.70	5.7/2.1
Tire dimension - front		800/70 R38 (Michelin Cerex Bib IF)	800/70 R38 (Michelin Cerex Bib IF)
Tire dimension - middle			1050/50 R32 (Michelin Mega Bib)
Tire dimension - rear		1050/50 R32 (Michelin Mega Bib)	1050/50 R32 (Michelin Mega Bib)

Note: [1)] Measured of the empty sugarbeet harvesters with an in-field installed scale.

Weighing of the axle- and wheel-load was carried out with in field installed scales on a constructed steel fundament. One axle scale consisted of four weighing platforms (each with nominal load of 5 or 6 Mg, respectively). The four weighing platforms were covered with a strong steel plate, on which the sugarbeet tanker harvester tyres rolled. The distance between the two axle scales allowed the simultaneous weighing of the second and third axle of the three-axle sugarbeet harvester.

The tyre-inflation pressure was set to 140 kPa in the front axle and 190 kPa in the middle and rear axle according to the recommendation of the sugarbeet harvester manufacturer. In agricultural practice, the tyre-inflation pressure ranged for self-propelled sugar beet tanker harvesters between 170 and 250 kPa (Schulze Lammers, 2003). Due to the better suitability of slopes and longer tyre durability, the adjusted tyre-inflation pressure is usually adjusted 250 kPa. The effects of decreasing tyre-inflation pressures on reducing soil compaction were investigated in many studies (Weißbach, 2004; Brunotte et al., 2005; Ansorge and Godwin, 2008).

Harvesting was done in offset track driving using diagonal steer: the right or left wheels of the rear axle run between the tracks of the front-axle tyres, thus creating the best conditions for gentle soil preserving. This offset track results in un-, single-, double- and triple-wheeled areas in the field, which were measured with a levelling board. The sugarbeet harvesting was done with a speed of 4.5 km h^{-1}.

The requirements (e.g. reduced tyre-inflation pressure, offset tracking, long-term conservation tillage) for soil protective harvest of sugarbeets were fulfilled.

2.3 Experimental design, measurements

Machine and crop management conditions of this study were designed to reflect real-world practices as close as possible. After harvest of each field length of 196 m the axle- and wheel-load were weighted till the hopper was filled. The two-factorial design (Figure 2) was conducted with the factor soil moisture (wet/dry) and sugarbeet tanker harvester undercarriage systems (two-axle/three-axle).

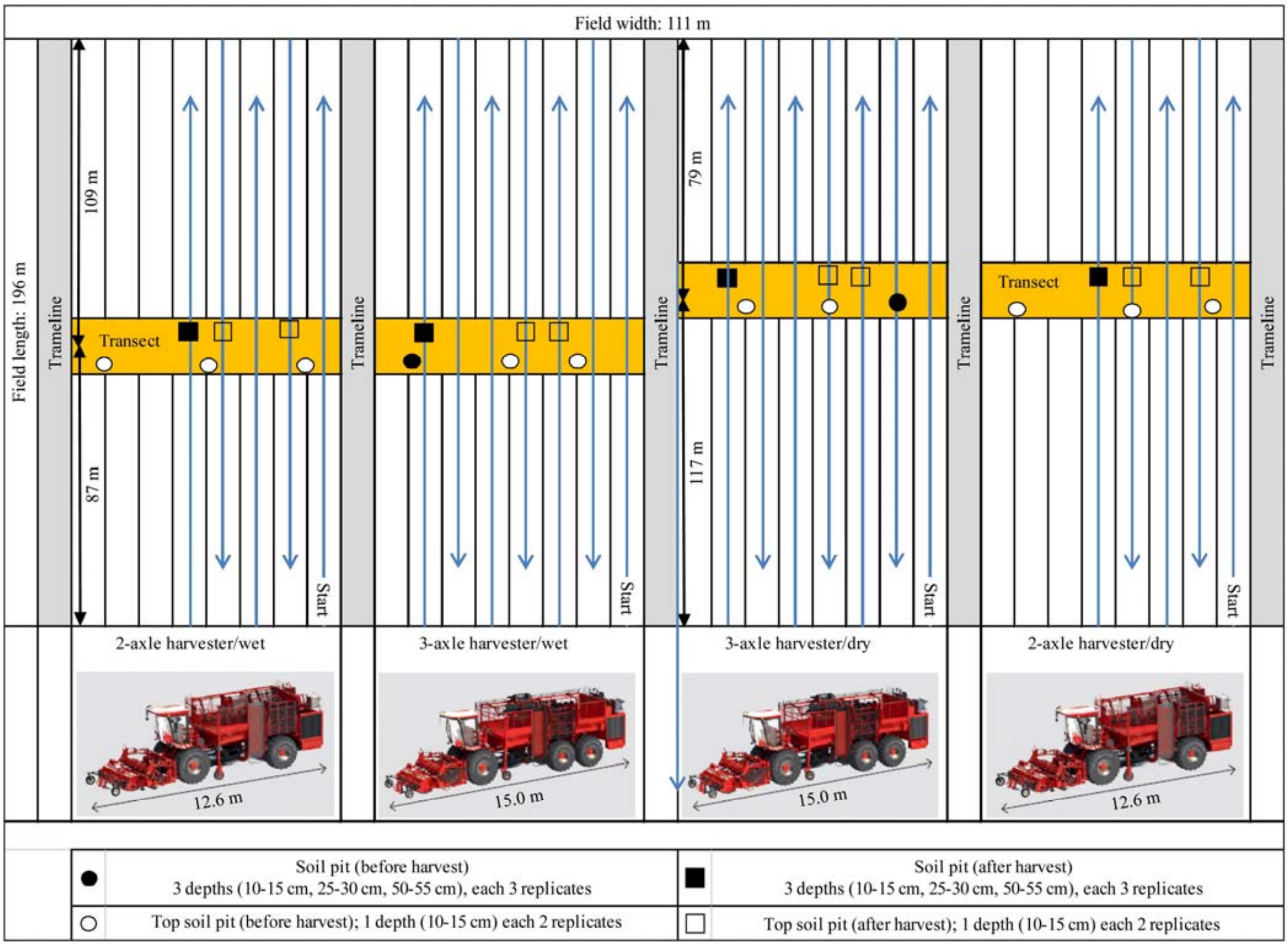

Figure 2 Experimental design with soil sampling locations in the transect

The dry season 2015 represented a good trafficability of the soil. For simulation of wet soil conditions, the plots were irrigated with 96 mm water - splitted in four applications (14 mm at 17th, 30 mm at 18th, 16 mm at 21th, 36 mm on 23nd September). The irrigation was done with an installed impact sprinkler. Soil sampling and penetration measurements were done on 25th September. The soil moisture content in the topsoil (0-5 cm) was measured with a soil water sensor (WET-2, Delta – T Devices, Cambridge, England) at the day of harvest. For the dry plot the average moisture content was 20% and for the wet plot 30%. Soil sampling after harvest was carried out on 28th September.

The experimental design is shown in Figure 2. Before and after the harvesting, pits were digged in each plot to get undisturbed soil core samples (250 cm^3, 80 mm in diameter) in three soil depths (10-15 cm, 25-30 cm and 50-55 cm) with three replicates. Additionally, five shallow pits each in the wet plot and dry plot were digged for sampling in soil depth of 10-15 cm. After sampling, the undisturbed samples were immediately brought to the laboratory and weighted. Particle size distribution, bulk density and saturated hydraulic conductivity (ÖNORM L 165 (1988)) were determined. Soil samples were oven-dried at 105°C until constant mass and soil bulk density as well as soil moisture content were determined. Twelve samples were air-dried to analyze particle size distribution using combined wet sieving and sedimentation method according ÖNORM L 1061-2 (2002). Measurements of the soil resistance were conducted in the field with a vertical penetrometer (Eijkelkamp penetrologger, EM Giesbeek, The Netherlands) fitted with a circular cone of 1 cm^2 with a cone angel of 60°. 40 insertions to a depth of 35 cm were made in each wet and dry transect before harvest (25th September) and after harvest (30th September). The differentiation of un-, single-, double-, and triple-wheeled areas for the insertion of the penetrologger were carried out with a marked leveling board.

2.4 Statistical analysis

All analyses were conducted using IBM® SPSS® Statistics 21. The requirements for analysis of variance were tested with the Levene test and normal distribution of residues. One-factorial analysis of variance was carried out for dry bulk density, water content, soil penetration resistance. For saturated hydraulic conductivity, the geometric means were presented and the analysis of variance was carried out on log-transformed values, since these were more likely to be normally distributed. The multiple comparison test to separate means was carried out with the Student-Newman-Keuls procedure ($p<0.05$).

3 Results and discussion

3.1 Vehicle weight development during harvest

The course of the axle-load and total weight between empty and filled sugarbeet-hopper on the harvester were shown in Table 3.

The three-axle harvester reached a total weight of 60.9 Mg and was 11.8 Mg heavier than the two-axle harvester with total weight of 49.1 Mg. The total weight of the three-axle harvester was distributed equally with about 20 Mg each axle. Two-axle harvester distributed the total weight of 49.1 Mg to the rear axle with 27.3 Mg and to the front axle with 21.8 Mg. With the three-axle undercarriage the maximum wheel-load (10.5 Mg) was 23.3% (=3.2 Mg) lower than the maximum wheel-load (13.7 Mg) of the two-axle harvester. The study of Geischeder (2011) reached similar results for the rear axle. The measured front axle loads were lower in Geischeder (2011) because the lifter unit was lifted down during axle-load weighing.

The three-axle harvester with the higher hopper capacity in this experiment (Table 2) harvested an area of 0.41 ha with a length of 1372 m and working width of 3 m (6 rows, row-distance 0.5 m). In comparison, the two-axle harvester with lower hopper capacity (Table 2) harvested an area of 0.29 ha with a length of 980 m till the hopper was filled. An average yield of 70 Mg ha^{-1} was calculated.

3.2 Bulk density and water content

The bulk densities and the volumetric soil water contents of the two- and three axle harvester wheeled area (Table 4) were associated with total harvester weights of 60 Mg and 47 Mg. respectively.

Table 3 Total weight (Mg) and axle-load (Mg) on the harvest distance between empty and filled hopper

		Distance (m)							
		0	196	392	588	784	980	1176	1372
3-axle harvester	Front axle	13.4	15.1	16.8	17.1	17.4	18.5	19.7	20.9
	Middle axle	13.3	14.6	15.9	17.5	19.1	19.4	19.6	19.5
	Rear axle	7.1	8.3	9.5	11.4	13.2	15.9	18.5	20.5
	Total weight	33.8	38.0	42.2	45.9	49.7	53.8	57.9	60.9
2-axle harvester	Front axle	13.5	15.1	16.6	18.0	19.5	21.8		
	Rear axle	14.6	17.3	20.1	22.7	25.3	27.3		
	Total weight	28.1	32.4	36.7	40.7	44.8	49.1		

Table 4 Mean bulk density and mean volumetric water content

Soil conditions	Depth (cm)	Bulk density (g cm^{-3})			Volumetric water content (cm^3 cm^{-3})		
		Un-wheeled	Two-axle	Three-axle	Un-wheeled	Two-axle	Three-axle
Dry	10-15	1.63 (n[1)]=13)	1.57 (n=7)	1.54 (n=7)	0.33	0.31	0.30
	25-30	1.55[b2)] (n=3)	1.48[a] (n=3)	1.59[b] (n=3)	0.30	0.27	0.29
	50-55	1.35[ab] (=3)	1.27[a] (n=3)	1.44[b] (n=3)	0.22	0.22	0.24
Wet	10-15	1.60 (n=13)	1.59 (n=7)	1.61 (n=7)	0.48	0.49	0.47
	25-30	1.52 (n=3)	1.42 (n=3)	1.46 (n=3)	0.41[b]	0.39[b]	0.31[a]
	50-55	1.32 (n=3)	1.29 (n=3)	1.31 (n=3)	0.18[a]	0.26[b]	0.27[b]

Note: [1)] Number of score samples is the same for the volumetric water content, [2)] Statistically significant differences are shown for the wheeling effect with small letters.

These associated weights were the results of linear interpolation from the data in Figure 2 Table 3, where the harvester became heavier the more sugarbeets were loaded.

The differences in bulk density between treatments were small. Statistically significant differences were found only in the dry treatment in a soil depth of 25-30 cm and 50-50 cm. The two-axle harvester reduced the bulk density in comparison to un-wheeled and three-axle treatment plots under dry conditions. This effect can be explained by the higher wheel-load of the axle (Table 3) in connection with the lower soil water content with higher tendency of deformation. Under wet soil conditions, more pores were filled with water and became rather incompressible (Smith et al., 1997). This could be the possible reason why the high wheel-load of the two-axle harvester did not alter the bulk density statistically significant under wet soil condition. In tendency, the bulk density was smaller after wheeling with the two-axle harvester than three-axle harvester and un-wheeled (Table 4).

The effect of higher wheel-loads on bulk density was also found in Arvidsson (2001), where the traffic with the six-row harvester caused greater subsoil compaction than that with the three-row harvester.

In our practical experiment, it was difficult to set the moisture content exactly with irrigation especially in the subsoil.

The mean gravimetric water content in the soil depths 10-15 cm was in the dry treatment 20% and in the wet treatment 30%. In the dry treatment with the mean volumetric water content ranged from 0.22 to 0.33 cm^3 cm^{-3} allowed trafficability with low risk of soil compaction

The significant differentiation in the soil depths 25-30 cm and 50-55 cm can be explained with different water infiltration in the soil. The 96 mm irrigation water did not reach the subsoil in the un-wheeled treatment before harvest (see Figure 3). The mean gravimetric water content was 13.8%. In the second sampling after three days the gravimetric water content was about 20%. The water infiltrated within these three days into the subsoil.

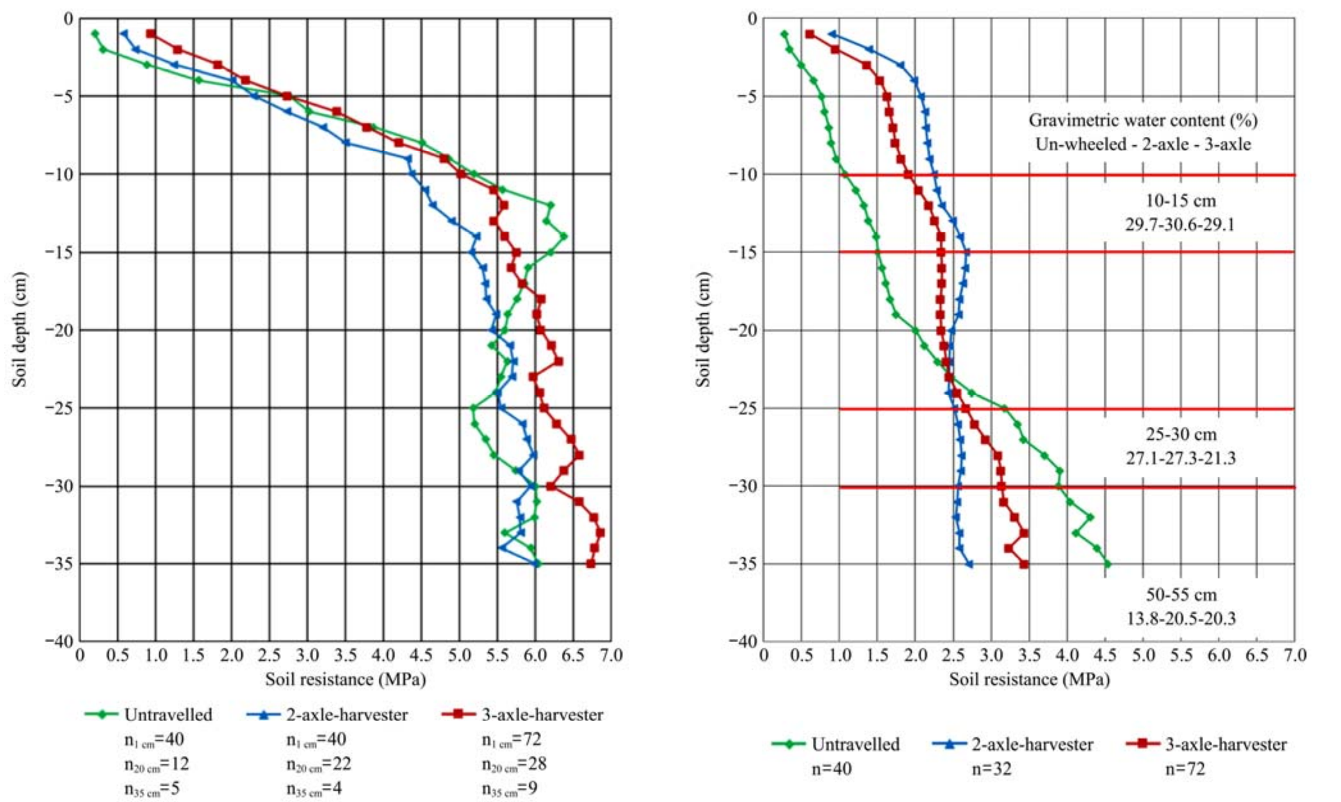

Figure 3 Course of penetration resistance in the dry treatment (left) and wet treatment (right)

3.3 Saturated hydraulic conductivity

Saturated hydraulic conductivity showed high variability in space and time (Messing, 1993) and were determined by the macropores amount (Arvidsson, 2001).

In this study, saturated hydraulic conductivity showed no statistically significant differences between the treatments in the soil depths 10-15 cm and 25-30 cm (Table 5).

Table 5 Geometric means of saturated hydraulic conductivity (mm h^{-1})

Soil conditions	Depth (cm)	Un-wheeled	Two-axle-harvester	Three-axle-harvester	ANOVA[1)]
Dry	10-15	7.0 (n[2)]=13)	19.5 (n=7)	14.9 (n=7)	NS4)
	25-30	18.5 (n=3)	50.1 (n=3)	23.0 (n=3)	NS
	50-55	289.9[b3)] (n=3)	410.9[b] (n=3)	112.4[a] (n=3)	*
Wet	10-15	4.9 (n=13)	5.6 (n=6)	3.3 (n=4)	NS
	25-30	61.6 (n=3)	146.9 (n=3)	313.3 (n=3)	NS
	50-55	58.8 (n=3)	81.1 (n=3)	340.9 (n=3)	P=0.074

Note: [1)] Statistical analysis is made of log-transformed data, [2)] Number of score samples, [3)]Statistically significant differences are shown for the wheeling effect with small letters, [4)] Not statistically significant.

In the subsoil (50-55 cm, dry treatment), the saturated hydraulic conductivity was statistically significant higher under un-wheeled and two-axle-harvester, which was explained by the existing cracks in the soil core where preferential water flow occurred.

Also under wet soil conditions possible preferential water flow was responsible for the higher saturated hydraulic conductivity in the depth 25-30 cm and 50-55 cm after wheeling with two-axle and three-axle harvester.

The saturated hydraulic conductivity was different among dry and wet conditions, likely to different compaction and sealing of macropores in the wet treatments by the harvester wheeling.

Under wet soil conditions in the top soil (10-15 cm), the saturated hydraulic conductivity was lowered by 30% (un-wheeled), 71% (two-axle harvester) and 78% (three-axle harvester) in comparison to dry soil. In contrast, the parameter was increased by 233% (un-wheeled), 193% (two-axle harvester) and 1262% (three-axle harvester) in the soil depth 25-30 cm. In the subsoil (50-55 cm), the wet soil conditions reduced the hydraulic conductivity by 80% for un-wheeled and for the two-axle harvester. In the wet plot with wheeling three-axle harvester, the hydraulic conductivity parameter was 203% higher than that in the dry soil. The differences in the depths 25-30 cm and 50-55 cm were influenced by the different water content (Table 4).

A critical threshold value for harmful soil compaction was derived by Lebert et al. (2004) with a saturated hydraulic conductivity value of 10 cm d^{-1} (= 4.2 mm h^{-1}). In our study, only the mean saturated hydraulic conductivity value obtained in the top soil on the tree-axle-harvester treatment with wet soil conditions was below this threshold value. The other saturated hydraulic conductivity values were above the threshold value.

3.4 Soil penetration resistance

The course of soil penetration resistance differed between dry and wet treatments (Figure 3).

Soil penetration resistance increased with depth in the dry top soil (0-15 cm) and was between 15-35 cm in the range between 5 and 7 MPa. Soil penetration resistance was smaller in the wet treatments. The correlation of the soil penetration resistance with the soil water content was also shown in Sivarajan et al. (2018).

The undercarriage effect on the penetration resistance was small in the dry plots. In each treatment, an increased penetration resistance down to 15 cm soil depth was found, which could be explained by the dry hard soil (Figure 3). Some soil penetration measurements had to be rejected in the dry plots because it was impossible to penetrate into the hard soil (reduced n in Figure 3).

The wheeling with two-axle and three-axle harvester on the wet soil resulted in significantly higher soil penetration resistances in comparison to the un-wheeled control treatment, especially in depths of 0-10 cm and 11-20 cm (Table 6). The water content here was the same before and after harvest.

Table 6 Mean cumulated penetration resistance (MPa) in different soil depths of dry and wet soil conditions

Condition	Depth (cm)	Un-wheeled	Two-axle-harvester	Three-axle-harvester
Dry	0-10	24.8 (n[1)]=40)	24.2 (n=40)	28.3 (n=72)
	11-20	55.3 (n=12)	50.2 (n=22)	52.6 (n=28)
	21-30	53.2 (n=5)	55.0 (n=4)	58.6 (n=9)
	0-30	125.9	124.4	133.5
		n=40	n=32	n=72
Wet	0-10	7.1[a2)]	19.0[c]	15.1[b]
	11-20	15.5[a]	25.3[c]	22.8[b]
	21-30	29.2[a]	25.2[a]	27.1[a]
	0-30	51.8[a]	69.5[b]	64,9[b]

Note: [1)] Number of score samples, [2)] Statistically significant differences are shown for the wheeling effect with small letters.

The penetration resistance down to 23 cm was higher in the two-axle harvester in comparison to the three-axle harvester (Figure 3). Surprisingly, we found an increased soil penetration in the subsoil (>23 cm) of the un-wheeled soil before harvest. This can be explained by the increased soil water content in the subsoil (changing water content in the profile of Figure 3). This water content difference can be explained by water infiltration into this soil depth between the two sampling dates (before and after harvest: 3 days). The penetration resistance in the subsoil (50-55 cm) in the wet treatment was lower after wheeling compared before wheeling, because of the increased water content from 13.8% (before harvest) to 20.4% (after harvest).

The soil penetration resistance was strongly influenced by the soil water content (Table 6). For wet soil conditions, the cumulated penetration resistance was reduced by 59% (un-wheeled), 44% (two-axle harvester) and 51% (three-axle harvester), respectively.

The multiple wheeling of the soil is caused by the offset track driving using diagonal steer (crab steering). The measured track areas were shown in Table 7.

Table 7 Track share of un-wheeled, single- and multiple-wheeled of six-row sugarbeet harvesters with working width of 3 m and 800 mm width of front tires

	Un-wheeled	Single-wheeled	Double-wheeled	Triple-wheeled
2-axle harvester	20 cm (6.7%)	200 cm (66.7%)	80 cm (26.7%)	-
3-axle harvester	-	70 cm (23.3%)	205 cm (68.3%)	25 cm (8.3%)

In dry treatments, there were no significant differences of the cumulated penetration resistance between the un-wheeled, single-wheeled and double-wheeled areas of the two-axle sugarbeet harvester (Table 8).

Table 8 Mean cumulated penetration resistance (MPa) in un-wheeled, single-wheeled and double-wheeled areas of a two-axle and three-axle sugarbeet harvester in different soil depths under dry and wet soil conditions.

Condition	Depth (cm)	Un-wheeled	Single-wheeled		Double-wheeled		Triple-wheeled
			Two-axle	Three-axle	Two-axle	Three-axle	Three-axle
Dry	0-10	24.8 (n[1)]=40)	20.5 (n=15)	24.2[a2)] (n=22)	28.2 (n=14)	35.2[b] (n=15)	27.6[ab] (n=22)
	11-20	55.3 (n=12)	53.4 (n=11)	52.4 (n=13)	47.0 (n=11)	56.9 (n=6)	50.7 (n=11)
	21-30	53.2 (n=5)	55.0 (n=7)	57.6 (n=9)	54.9 (n=9)	59.5 (n=3)	59.4 (n=8)
	0-30	125.9 (n=5)	126.0 (n=7)	130.4 (n=9)	123.3 (n=9)	139.2 (n=3)	134.9 (n=8)
		n=40	n=16	n=24	n=16	n=24	n=24
Wet	0-10	7.1[a]	18.9[b]	11.9[b]	19.0[b]	18.0[d]	15.3[c]
	11-20	15.5[a]	25.9[b]	18.9[b]	24.7[b]	28.0[c]	21.4[b]
	21-30	29.2	24.5	26.2	25.9	30.8	24.0
	0-30	51.8[a]	69.4[b]	57.0[a]	69.7[b]	76.8[b]	60.7[a]

Note: [1)] Number of score samples, [2)] Statistically significant differences are shown for the wheeling effect with small letters.

In the wet treatments, the penetration resistance was statistically significant higher for the single-wheeled and double-wheeled area in comparison to un-wheeled in the soil depth 0-20 cm. There was no significant difference in the soil depth 21-30 cm.

There were also small differences of penetration resistance for the three-axle sugarbeet harvester in dry plots between the un-wheeled and multiple-wheeled areas. Only the double- and triple-wheeled area under dry soil condition in the depth 0-10 cm caused a statistically significant higher penetration resistance. The wheeling effect on penetration resistance was higher in the wet plot. Single and multiple wheeling showed higher penetration resistance than un-wheeled in the depth 0-10 cm and 11-20 cm. No significant differences were observed in the soil depth 20-30 cm.

Long-term differences in soil penetration of high-axle traffic were found in many studies: Arvidsson (2001) found in his study significant differences in penetration resistance between treatments 2-4 years after traffic, which was confirmed by other studies (Alakukku and Elonen, 1994; Alblas et al., 1994; Etana and Håkansson, 1994; Schjønning and Rasmussen, 1994; Stewart and Vyn, 1994). Hammel (1994) reported similar results for penetration resistance measured immediately after traffic compared to three years later. The different results in different years can be possible explained by the process of age-hardening (Dexter et al., 1988).

Arvidsson (2001) mentioned the difficulties in using penetration resistance to measure the effects of soil compaction because of increased aggregate strength through one or more drying cycles.

4 Conclusions

This study showed that under rather dry soil conditions, sugarbeet harvesting with self-propelled six-row sugarbeet tanker harvesters did not impair the soil physical properties (bulk density, soil penetration resistance, saturated hydraulic conductivity). For wet soil conditions, there were significant differences between the two-axle harvester and three-axle harvester on soil penetration resistance. The three-axle harvester on wet soil changed the saturated hydraulic conductivity in the top soil below the critical threshold value of 10 cm d^{-1}. Single and multiple wheeling in wet soil showed higher soil penetration resistance in the top soil.

The lower tyre-inflation pressure (front: 140 kPa and middle/rear: 190 kPa) combined with the long-term conservation tillage on the experimental field were the possible reasons for the small undercarriage-effects. Three-axle sugar beet harvesters reached a higher total weight, which can be distributed on a larger tyre/soil contact area. Two-axle harvester had lower total weights with higher axle load and contact area pressure.

Findings under moist soil conditions indicated a higher risk of potential soil compaction. Therefore, soil protecting sugar beet harvesting requires a good load carry capacity of the soil.

Acknowledgements

The authors gratefully acknowledge the excellent technical assistance of Franz Ecker, Martina Faulhammer and Friedrich Forster as well as Josef Rosner for their management support. We also express our gratitude to the machinery contractor Leo Mastalir for providing the sugar-beet harvesters. For providing the sugar-beet field we thank Erwin and Eva Bernreiter. This study was financially funded by Holmer Maschinenbau GmbH (Germany) and by the federal state Lower Austria.

References

Alakukku, L., and P. Elonen. 1994. Finnish experiments on subsoil compaction by vehicles with high axle load. *Soil and Tillage Research*, 29(2-3): 151–155.

Alblas, J., F. Wanink, J. van den Akker, H. M. G. van der Werf. 1994. Impact of traffic-induced compaction of sandy soils on the yield of silage maize in the Netherlands. *Soil and Tillage Research*, 29(2-3): 157–165.

Ansorge, D., and R. J. Godwin. 2008. The effect of tyres and a rubber track at high axle loads on soil compaction – part 2: multi-axle machine studies. *Biosystems Engineering*, 98(3): 338–347.

Arvidsson, J. 2001. Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden: I. Soil physical properties and crop yield in six field experiments. *Soil and Tillage Research*, 60(1-2): 67–78.

Bernhardt, H., C. Schwarz, and M. Schreiber. 2008. Development of mechanical soil stress by sugar beet harvesters. *Landtechnik*, 63(5): 274–275.

Brunotte, J. 2007. *Konservierende Bodenbearbeitung als Beitrag zur Minderung von Bodenverdichtungen, Bodenerosion, Run-off, und Mykotoxinbildung im Getreide*. Landbauforschung Völkenrode, Germany, Sonderheft 305, ISBN 978-3-86576-029-6.

Brunotte, J., C. Sommer, E. Isensee, and P. Weißkopf. 2005. Soil under pressure. *Landtechnik*, 60(3): 150–151.

Dawidowski, J. B., and A. J. Koolen. 1987. Changes in soil water suction, conductivity and dry strength during deformation of wet undisturbed samples. *Soil and Tillage Research*, 9(2): 169–180.

Dexter, A. R., R. Horn, and W. D. Kemper. 1988. Two mechanisms for the age-hardening of soil. *Journal of Soil Science*, 39(2): 163–175.

Etana, A., and I. Håkansson. 1994. Swedish experiment on the persistence of subsoil compaction caused by vehicles with high axle load. *Soil and Tillage Research*, 29(2-3): 167–172.

Geischeder, R. 2011. Bodenbelastung und Bodenbeanspruchung unterschiedlicher Fahrwerkskonfigurationen. Ph.D. diss., Lehrstuhl für Agrarsystemtechnik, Technische Univ. München, Germany. (in German)

Håkansson, I., and R. C. Reeder. 1994. Subsoil compaction by vehicles with high axle load-extent, persistence and crop response. *Soil and Tillage Research*, 29(2-3): 277–304.

Hammel, J. E. 1994. Effect of high-axle load traffic on subsoil physical properties and crop yields in the Pacific Northwest USA. *Soil and Tillage Research*, 29(2-3): 195–203.

Horn, R., T. Way, and J. Rostek. 2003. Effect of repeated tractor wheeling on stress/strain properties and consequences on physical properties in structured arable soils. *Soil and Tillage Research*, 73(1-2): 101–106.

Horton, R., M. D. Ankeny, and R. R. Allmaras. 1994. Effects of soil compaction on soil hydraulic properties. In *Soil Compaction in Crop Production*, eds. B. D. Soane and C. van Quwerkerk, 141–166. Amsterdam: Elsevier.

Koch, H. J., H. Heuer, O. Tomanoá, and B. Märländer. 2008. Cumulative effect of annually repeated passes of heavy agricultural machinery on structural properties and sugar beet yield under two tillage systems. *Soil and Tillage Research*, 101(1-2): 69–77.

Lebert, M., J. Brunotte, and C. Sommer. 2004. *Ableitung von Kriterien zur Charakterisierung einer schädlichen Bodenveränderung entstanden durch nutzungsbedingte Verdichtung von Böden/Regelungen zur Gefahrenabwehr: Abschlussbericht*. Förderkennzeichen (UFOPLAN) 20071245. 122 p, Umweltbundesamt, Berlin, Germany. (in German)

Lorenz, M., J. Brunotte, T. Vorderbrügge, R. Brandhuber, H. J. Koch, M. Senger, N. Fröba, and F. J. Löpmeier. 2016. Anpassung der Lasteinträge landwirtschaftlicher Maschinen an die Verdichtungsempfindlichkeit des Bodens – Grundlage für ein bodenschonendes Befahren von Ackerland. *Landbauforschung*, 66: 101–144. (in German)

Messing, I. 1993. Saturated and near-saturated hydraulic conductivity in clay soils. Ph.D. diss. Department of Soil Sciences. Swedish University of Agricultural Sciences, Uppsala, Sweden.

ÖNORM L 1061-2. 2002. *Physikalische Bodenuntersuchungen – Bestimmung der Korngrößenverteilung des Mineralbodens. Teil 2: Feinboden*. Wien: Österreichisches Normungsinstitut. (in German)

ÖNORM L 1065. 1988. *Physikalische Bodenuntersuchungen – Bestimmung der Wasserdurchlässigkeit in gesättigten Zylinderproben*. Wien: Österreichisches Normungsinstitut. (in German)

Schjønning, P., and K. J. Rasmussen. 1994. Danish experiments on subsoil compaction by vehicles with high axle load. *Soil and Tillage Research*, 29(2-3): 215–227.

Schulze Lammers, P., 2003. Tyre inflation pressure adaptation of sugar beet harvesters with hoppers. *Landtechnik*, 58(4): 250–251.

Sivarajan, S., M. Maharlooei, S. G. Bajwa, and J. Nowatzki. 2018. Impact of soil compaction due to wheel traffic on corn and soybean growth, development and yield. *Soil and Tillage Research*, 175: 234–243.

Smith, C. W., M. A. Johnston, and S. Lorentz. 1997. Assessing the compaction susceptibility of South African forestry soils. II. Soil properties affecting compactibility and compressibility. *Soil and Tillage Research*, 43(3-4): 335–354.

Stewart, G. A., and T. J. Vyn. 1994. Influence of high axle loads and tillage systems on soil properties and grain corn yield. *Soil and Tillage Research*, 29(2-3): 229–236.

Stockfisch, N., T. Forstreuther, and W. Ehlers. 1999. Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany. *Soil and Tillage Research*, 52(1-2): 91–101.

VDI-Richtlinie 6101. 2006. Maschineneinsatz unter Berücksichtigung der Befahrbarkeit landwirtschaftlicher genutzter Böden/Machinery operation regarding the trafficability of agricultural used soil. Düsseldorf, Germany: Max-Eyth-Gesellschaft Agrartechnik im Verein Deutscher Ingenieure (VDI). (in German)

Weißbach, M. 2004. *Landtechnische Untersuchungen zur Wirkung bodenschonender Fahrwerke an Schleppern und Arbeitsmaschinen mit verschiedenen Radlasten*. Habilitations-Schrift. Universität Kiel, Germany. (in German)