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Comparison of measurement methods for determining the track depth of tractors

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Protecting the soil, which serves as the basis for crop production, is a major challenge in view of the increasing weight of agricultural machinery. In the context of soil compaction, track depth is an important measure. As part of the ARDopt research project, the suitability of various ultrasonic sensors and photogrammetric methods for measuring the track depth was investigated. In addition, the influence of the parameters tire pressure, driving speed and soil moisture on the track depth was investigated.

The continuous measurement of the track depth with commercially available ultrasonic sensors and the calculation of the track depth from digital surface models show a close correlation with the reference measurements. The tire pressure had the strongest influence on the measured track depth. Likewise, as expected, the influence of soil moisture on the track depth could be observed.

Keywords
Tire pressure, track depth, soil compaction, tire-soil interaction

The bulk density of the soil influences its yield potential. It affects water holding capacity, infiltration capacity, penetration resistance for roots, aeration and nutrient availability (Håkansson 2005, Diepenbrock et al. 2016, Amelung et al. 2018, Keller et al. 2019). The pore volume and thus the water holding capacity is reduced by soil compaction. This reduces the ability of the soil to provide water for plant growth over longer periods without precipitation, so that the risk of drought damage increases independently of and in addition to climate change. The infiltration capacity of the soil also decreases with increasing bulk density (Brunotte et al. 2015), so the risk of surface runoff and resulting erosion increases. The reduction in the supply of oxygen caused by increasing bulk density and the increased risk of waterlogging reduce the release of nutrients and the ability of plants to actively acquire them (Amelung et al. 2018, Blum 2019).

The importance of soil for crop production and protection against compaction is also referred to in the German Federal Soil Protection Act (§ 17): „Soil compaction, in particular by taking into account soil type, soil moisture and the soil pressure caused by the implements used for agricultural land use, shall be avoided as far as possible“.

The bulk density of cultivated and uncultivated soils is spatially and temporally variable. The greatest influence on the compaction density of cultivated soils is exerted by the use of agricultural machinery, where compaction takes place in strips in the tracks through the tires (Geischeder 2011). The extent of compaction, i.e. the increase in bulk density under the tracks, is mainly determined by tire pressure, soil moisture, soil type, tire inflation, compaction frequency and indirectly by the wheel loads limiting the tire pressure (Håkansson 2005, Keller et al. 2019). In general, compaction decreases with decreasing tire inflation pressure, increasing soil particle size and decreasing soil

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moisture. Soil particle size is temporally stable but spatially variable. Soil moisture also shows temporal variability. The tire pressure is variable (Schnaufer et al. 1998), but must be adapted to the application scenarios (road travel, field work) and is also determined by the load-bearing capacity of the tire at different wheel loads.

On the one hand, the continuous measurement of soil compaction enables documentation and planning for subsequent tillage operations as well as the optimization of future operations (e. g. crop rotation, technical and organisational measures) with regard to timing or soil moisture. On the other hand, the measured values can serve the driver of the agricultural machine as an indication of the extent of the damage caused when carrying out the current operation. This facilitates both risk assessment and the decision on a possibly necessary adjustment or even interruption of the current task. Last but not least, the measured values can serve for the automation of processes on or in agricultural machines that lead to a reduction of soil compaction under the current conditions (lowering of tire pressure, adjustment of speed and/or working depth).

Soil compaction itself cannot be measured continuously, or only with very high technical effort. It is usually determined at specific points and statically with penetrometers. On the other hand, the depth of the track created during the operation (track depth) can easily be measured as a proxy for soil compaction under the track, as it is directly related to the increase in bulk density due to the reduction in volume at constant mass.

In the research project „Automated control of tire inflation pressure of agricultural tractors“ (ARDopt), the suitability of ultrasonic sensors and photogrammetric methods for measuring the track depth by tractors was investigated in this context. The aim of the study was to compare different measurement methods for determining the track depth of tractors. In addition, the influence of the parameters tire pressure, driving speed and soil moisture was to be determined.

Material and methods

At the University of Applied Sciences Weihenstephan-Triesdorf (Weidenbach, Germany), investigations on track depth were carried out as part of the ARDopt research project. Firstly, different measurement methods were compared under different conditions, and secondly, the influence of tire pressure, driving speed and soil moisture was investigated in different test setups.

Measuring method

The reference value of the track depth was measured along the lanes at six predefined measuring points between a measuring stick placed across the track and the track surface. The depth of the track was recorded as the distance between the deepest point in the middle of the track and the lower edge of the measuring stick placed vertically on the track using a folding ruler. The position of the reference value was determined with a GNSS receiver (Trimble Catalyst, USA) with an accuracy of 10 mm + 1 ppm RMSE (root mean square error) and an Android tablet with the software QField (OPENGIS.ch GmbH, Switzerland). Six reference values were recorded at predefined positions for each test setup (Figure 1).

Figure 1: Aerial view of the test facility after measuring the track depths; tire pressures of 0.5, 0.7, 1.8 and 2.0 bar at a constant driving speed of 4 km/h were compared; the horizontal lines mark the reference points (© J. Poteko)

During the first measurement campaign, the track depth was measured with **two low-cost ultrasonic sensors** HC-SR04 with a measuring range of 20 to 4000 mm, a resolution of 3 mm, an accuracy of 99.8% and a measuring angle of 15° (ElecFreaks, China). The ultrasonic sensors were mounted behind the tractor centrally above and beside the track at the same height of 97 cm (measured from solid ground at a tire pressure of 1.8 bar). Connected to an Arduino Mega 2560 microcontroller (Arduino AG, Italy), the track depths were calculated from the difference in distances recorded by the sensors in the middle of the track and next to the track at a data rate of 9 Hz. For the validation of the measured track depths against the reference values, the measured track depth was processed by averaging within 0.5 and 3 m from the position of the reference.

An **action camera** (GoPro Hero7 Black, USA) was used for the first measurement campaign. It was mounted at a height of 1.5 m directly above the track in order to capture the area in and next to the track (surface section of approx. 2.8 m x 2.1 m). The long side of the camera image was parallel to the direction of travel to ensure sufficient overlap of the photo while driving. The camera took 2 pictures per second. Digital surface models (0.6 mm / pixel (4K 4:3, 4,096 x 3,072 pixels)) were first calculated from the photos using Agisoft Metashape software (Agisoft LLC, Russia). These were then displayed in the QGIS software (qgis.org GmbH, Switzerland) for the calculation of the track depth. An imaginary line perpendicular to the track was drawn above the track at the reference positions. The track depth was calculated as the difference between the lowest point (pixel size 6.8 mm) in the track and the highest point next to the track using five procedures:

- difference between the lowest point in the track and the height outside the track (20 cm off the track),
- difference between the lowest point in the track and the maximum height (in the range up to 20 cm on one side of the lane) outside the track,
- difference between the lowest point in the track and the average height (in the range up to 20 cm on the outer side (on the right in the direction of travel) of the track) outside the lane,
- difference between the lowest point in the track and the maximum height (in the range up to 20 cm on both sides of the track) outside the track,
- difference between the lowest point in the track and the average height (in the range up to 20 cm on both sides of the track) outside the track.

In the second measurement campaign, the track depth was measured using two commercial ultrasonic sensors with a measuring range of 100 to 800 mm, a resolution of 0.25 mm, a repeatability of 0.2 % and a measuring angle of 8° (UFP-800, WayCon Positionsmesstechnik GmbH, Germany) and from 80 to 1600 mm, a resolution of 1 mm, a repeatability of 0.2 % and a measuring angle of 8° (UFP-1600, WayCon Positionsmesstechnik GmbH, Germany). The ultrasonic sensors were mounted behind the tractor centrally above and beside the track (driving direction right) at the same height of 35 cm. The track depths were calculated from the difference in distances measured by the sensor in the middle of the track and the sensor next to the track at a data rate of 9 Hz. For the comparison of the measured track depths with the reference values, the track depths measured with the ultrasonic sensors were processed. The track depths within a radius of 0.5 m, 1 m and 3 m around the reference position were averaged.

A UAV (unmanned aerial vehicle) with integrated camera (DJI Phantom 4 Advanced, China) captured images of the entire test field from a height of 10 m during the second measurement campaign after the test runs. Planning the flight path with the application pix4dcapture (Pix4D S.A., Prilly, Switzerland) and an automatic triggering of the capture ensured an overlap of 90% of the images along and across the flight direction. Digital surface models were calculated from the photos (72 dpi) using Agisoft Metashape software (Agisoft LLC, Russia). These were then plotted in QGIS software for track depth calculation. The track depth was calculated as the difference in altitude between two points within the buffer of 0.5 m around the reference points:

- difference between the lowest and the highest point in the buffered area,
- difference between the 95 % quantile and the 5 % quantile in the buffered area,
- difference between the 90 % quantile and the 10 % quantile in the buffered area.

On the same points, soil moisture was determined inside and outside the track with a soil probe (Delta-T Devices, HH2 Moisture Meter, UK) after driving. Soil conductivity was recorded using a Veris Q 2800 (Veris Technologies, Inc., USA) after measurements were completed throughout the trial field. The conductivity shown in the results was calculated as the mean value within a radius of 5 m from the reference position.

Experimental design

The investigations of the track depth were carried out in two measurement campaigns in October (measurement campaign 1) and December 2019 (measurement campaign 2) on a commercial farm (49°15‘15.7“N 10°51‘44.5“E). In each measurement campaign, different measurement methods were compared under different conditions. The test setups consisted of varied tire pressures, driving speeds and soil moisture.

The trial field was marked with flour on the field in advance (Figure 1). A 25 m long track was measured for each test setup. On the track, six lines perpendicular to the direction of travel with a distance of 5 m were used to define sub-areas for the repetitions of the reference measurement. For each test setup, the test field was passed straight at a constant speed. A framework was mounted on the tractor to attach ultrasonic sensors, GNSS receiver and action camera (Figure 2). While driving, the track depth behind the right rear wheel was measured with ultrasonic sensors and georeferenced with a GNSS receiver (Duro, Swift Navigation, USA) with an accuracy of 10 mm + 1 ppm RMSE. For technical measurement reasons, the UAV flight and the conductivity measurement were only carried out after all the runs on the entire test field.

Figure 2: Measurement setup for recording the reference values of track depth and soil moisture at a measurement point (left); ultrasonic sensors and the action camera on a framework behind the tractor record the track depth, which was georeferenced with a GNSS receiver (right) (© J. Poteko)

In **measurement campaign 1**, the track depth was measured in three areas of the field with different soil moisture. In area 1 (low soil moisture, see Table 1) and in area 2 (high soil moisture, see Table 1) the tire pressures of 0.7 and 1.8 bar were combined with the driving speeds of 4, 8, 12, 16 and 20 km/h. In area 3 (medium soil moisture), tire pressures of 0.4 and 2.0 bar were compared at speeds of 4, 8, 12, and 16 km/h. The tire pressures of 0.7 and 1.8 bar were combined with the driving speeds of 4, 8, 12, 16, and 20 km/h. The tire pressures were set on a Fendt 724 (tires: TM1060, Trelleborg, Sweden, VF 600/60R30 front, VF 710/60R42 rear) before the measurements with a tire pressure system (Reifenregler automatic, Steuerungstechnik StG, Germany). Inexpensive ultrasonic sensors and an action camera were used as sensors for recording the track depth. The measured values of the sensors were checked for normal distribution and a variance analysis was carried out with the program RStudio v1.2 (package ‚aov', Chambers et al., 1992). Subsequently, the influence of the tire pressure within each experimental setup was evaluated with the Students t-test (Park and Wang 2018).

In measurement campaign 2, tire pressures of 0.5, 0.7, 1.8 and 2.0 bar at a driving speed of 4 km/h were investigated. Michelin tires (MachXBib, 600/65R28 front, 710/70R38 rear) were mounted on the tractor (John Deere 6155 R). A tire pressure control system made it possible to set the desired tire pressure before the measurements (tire pressure system with ISOBUS control and 2-wire technology for agricultural tractors, PTG Reifendruckregelsysteme GmbH, Germany). In addition to the reference measurements, commercial ultrasonic sensors and a UAV with integrated camera were used as sensors for recording the track depth. The influence of the tire pressure was evaluated with the Students t-test (Park and Wang, 2018) for each test variant and presented with box plots.

Results

Measurement campaign 1

The reference values collected during the first measurement campaign all show an unexceptional correlation between tire pressure and track depth as well as soil moisture and track depth. The correlation is supported with help of the variance analysis. The speed of the vehicle had no influence on the track depth determined with the reference method (Table 1).

Table 1: Track depths (reference measurements and low-cost ultrasound), soil moisture and conductivities of measurement campaign 1

Field[1)]	Tire pressure bar[a]	Driving speed km/h[b]	Soil moisture Vol%		Conductivity mS/m		Track depth cm		
			in track[c]	out of track[d]	30 cm	90 cm	Reference	US[2)] – buffer[3)] of 0.5 m	US – buffer of 3 m
			n = 6	n = 6	n = 6	n = 6	n = 6	n = 6	n = 6
1	0.7	4	15.6	13.3	n. v.	n. v.	6.3 [a,c]	5.1 [a,c]	6.9 [b]
		8	15.1	13.1	n. v.	n. v.	6.5 [a,c]	5.1 [a,c]	6.8 [b]
		12	14.8	11.8	10.4	7.1	6.7 [a,c]	4.3 [a,c]	7.4 [b]
		16	15.1	13.0	9.7	7.8	6.8 [a,c]	7.9 [a,c]	5.4 [b]
		20	15.1	13.4	14.0	7.8	6.9 [a,c]	6.9 [a,c]	3.9 [b]
	1.8	4	16.6	12.6	9.3	7.9	5.5 [a,c]	7.7 [a,c]	7.0 [b]
		8	19.2	14.9	7.8	8.1	5.3 [a,c]	4.6 [a,c]	5.8 [b]
		12	17.4	14.6	8.3	8.1	5.3 [a,c]	6.8 [a,c]	7.8 [b]
		16	17.3	14.4	8.3	7.9	5.3 [a,c]	5.8 [a,c]	4.8 [b]
		20	16.4	13.2	8.8	8.0	5.7 [a,c]	9.9 [a,c]	4.7 [b]
2	0.7	4	26.9	22.3	97.6	44.0	4.8 [a,d]	2.8 [a,d]	6.4 [a]
		8	26.6	22.9	56.0	23.7	5.5 [a,d]	5.4 [a,d]	6.0 [a]
		12	30.2	27.7	75.2	33.6	5.2 [a,d]	8.3 [a,d]	5.1 [a]
		16	31.4	26.0	85.6	36.9	5.4 [a,d]	5.4 [a,d]	5.3 [a]
		20	32.7	23.6	97.2	50.4	4.9 [a,d]	5.0 [a,d]	8.8 [a]
	1.8	4	27.2	20.7	26.5	14.9	6.9 [a,d]	5.8 [a,d]	4.9 [a]
		8	27.3	23.4	54.1	27.9	6.5 [a,d]	6.7 [a,d]	4.5 [a]
		12	28.2	25.3	93.7	30.5	8.0 [a,d]	6.7 [a,d]	5.3 [a]
		16	31.6	27.8	91.9	40.6	7.6 [a,d]	4.2 [a,d]	4.2 [a]
		20	31.9	28.4	93.7	49.0	7.5 [a,d]	6.6 [a,d]	5.7 [a]
3	0.4	4	22.4	19.0	62.6	15.8	4.2 [a,c]	5.7 [a,c]	5.1 [c]
		8	22.3	19.1	33.7	19.2	3.8 [a,c]	4.6 [a,c]	4.6 [c]
		12	22.8	20.5	24.2	17.9	3.4 [a,c]	7.5 [a,c]	7.3 [c]
		16	20.5	18.6	12.7	16.9	3.6 [a,c]	4.1 [a,c]	5.8 [c]
		20	n. v.	n. v.	n. v.	n. v.	n. v.	n. v.	n. v.
	2.0	4	22.8	17.8	25.0	7.7	7.4 [a,c]	6.3 [a,c]	5.5 [c]
		8	24.8	20.4	29.0	9.4	7.3 [a,c]	5.7 [a,c]	4.9 [c]
		12	23.7	18.1	35.5	9.4	6.6 [a,c]	7.0 [a,c]	6.4 [c]
		16	25.4	19.3	44.9	13.4	7.2 [a,c]	10.4 [a,c]	3.5 [c]
		20	n. v.	n. v.	n. v.	n. v.	n. v.	n. v.	n. v.

[1)] 1 = low soil moisture area; 2 = high soil moisture area; 3 = medium soil moisture area
[2)] US = low cost ultrasonic sensor;
[a] statistically significant influence of tire pressure;
[b] statistically significant influence of speed;
[c] statistically significant influence of soil moisture in the track;
[d] statistically significant influence of soil moisture next to the track.

The measurements with the low-cost ultrasonic sensors, averaged in a 0.5 m radius, are consistent with the measured values of the reference system with regard to the significance of the correlation between tire pressure and track depth. Regardless of driving speed and soil moisture, there is a significant correlation between track depth and tire pressure. In areas with high soil moisture there is a correlation between the soil moisture next to the track and the track depth, in the variants with low and medium soil moisture there is a correlation between the soil moisture measured in the track and the track depth. It remains to be stated that the measured values of the reference method and the ultrasonic sensors partly reveal considerable differences in absolute terms. However, the correlation with the influencing factors (tire pressure, soil moisture) is very similar.

The measured values of the low-cost ultrasonic sensors averaged in a 3 m radius around the reference measuring points differ from the reference values and the values measured in a 0.5 m radius in terms of significance: in the area with low soil moisture, there was a correlation between the track depth and the speed of the vehicle. In the area of high soil moisture there was a correlation with tire pressure and in the area of medium soil moisture there was a correlation with the soil moisture in the track.

In Figure 3, the reference measured values at different tire pressures and soil moisture are plotted against the driving speeds. The figure shows that the track depths in the area of low soil moisture from a speed of 8 km/h are significantly deeper at low tire pressure (0.7 bar) than at high tire pressure (1.8 bar). In areas with medium and high soil moisture, this effect is reversed and shows the expected result: the track is significantly deeper at high tire pressure (1.8 bar) than at low tire pressure. An exception is the measurement in the area of high soil moisture at 8 km/h ($p = 5.3$ %).

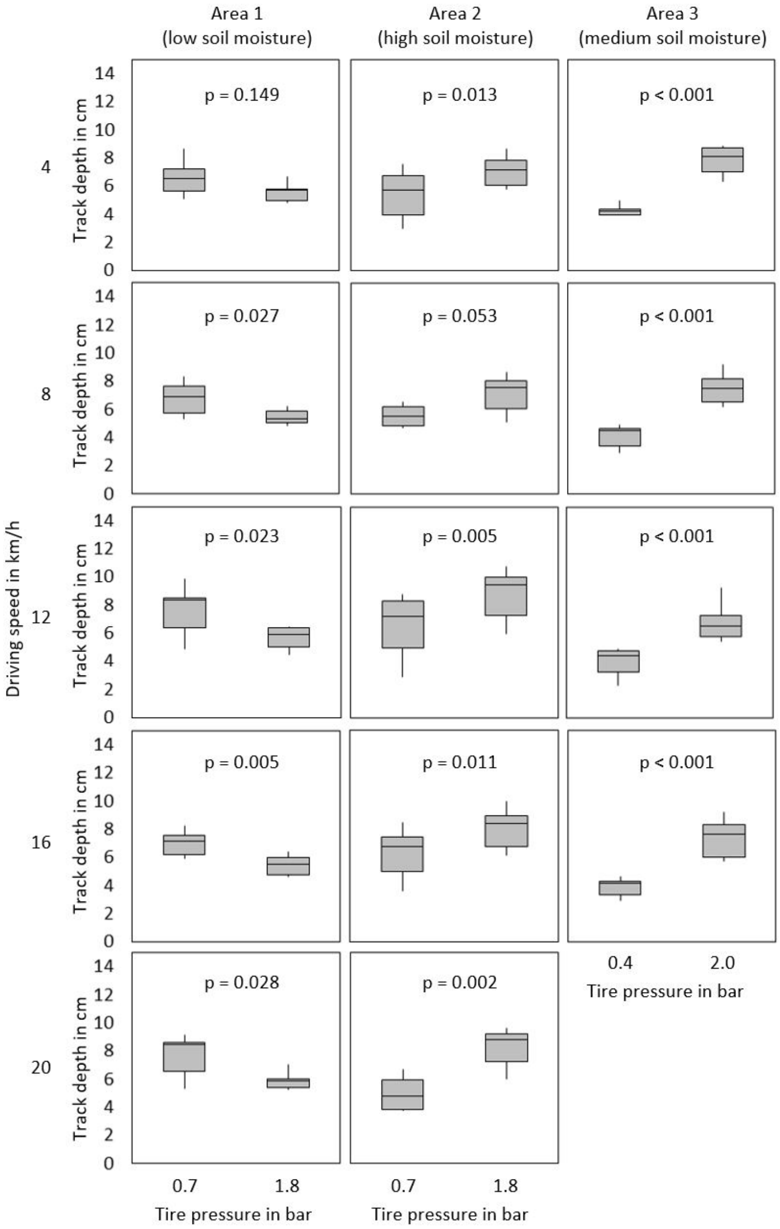

Figure 3: Reference measurements of track depth in measurement campaign 1

When calculating the track depth from the digital surface models generated from the action camera images, the track depths could only be considered for three variants with sufficient overlap of images (Table 2). Due to the insufficient number of images, the computation of digital surface models was not possible. The track depths of the different calculation methods show large differences and are not consistent. A correlation to the tire pressure and the other parameters could not be proven.

Table 2: Track depth from the calculation of the digital surface model (n = 6) of measurement campaign 1

Field[1)]	Tire pressure in bar	Driving speed km/h	Calculation variant[2)]				
			1	2	3	4	5
1	1.8	8	4.8	7.3	4.7	6.3	4.6
2	0.7	8	3.8	6.1	3.8	5.8	3.7
2	1.8	4	3.7	5.5	4.2	5.1	4.1

1) 1= low soil moisture; 2= high soil moisture.
2) Difference between lowest point in the track and (1) the depth outside the track (20 cm beside the track), (2) the maximum depth (in the range up to 20 cm on one side of the track) outside the track, (3) the average depth (in the range up to 20 cm on one side of the track) outside the track, (4) the maximum depth (in the range up to 20 cm on both sides of the track) outside the track or (5) the average depth (in the range up to 20 cm on both sides of the track) outside the track.

Measurement campaign 2

The measurements of the track depth at constant speed and tire pressures of 0.5, 0.7, 1.8 and 2.0 bar showed a clear increase in track depth with growing tire pressure (Table 3). There was almost no difference in soil moisture content between the setups. The differences in the track depths determined with the reference method at low tire pressures (0.5 bar and 0.7 bar) and high tire pressures (1.8 and 2.0 bar) are highly significant. However, the track depths between the two setups with low and high tire pressures do not differ significantly.

Table 3: Track depths and soil moisture content of measurement campaign 2

Driving speed km/h	Tire pressure bar	Soil moisture Vol%		Track depth cm						
		in trackr	out of track	Re-ference	US[1)] – buffer[2)] of 0.5 m	US – buffer of 1 m	US – buffer of 3 m	UAV[3)] – maximum und minimum[4)]	UAV – 95-%- und 5-%-quantiles[5)]	UAV – 90-%- und 10-%-quantiles[6)]
		n = 6	n = 6	n = 6	n = 6	n = 6	n = 6	n = 6	n = 6	n = 6
4	0.5	19.7[a]	15.1[ab]	4.3[a]	0.9[a]	1.3[a]	1.5[a]	12.2[ab]	6.7[a]	5.5[ab]
	0.7	20.0[ab]	16.1[b]	4.9[a]	1.7[b]	1.9[ab]	1.9[ab]	10.4[a]	6.6[a]	5.4[a]
	1.8	21.3[ab]	14.4[a]	7.4[b]	1.8[b]	2.1[b]	2.3[bc]	12.8[ab]	7.4[b]	5.9[b]
	2	21.7[b]	15.6[ab]	7.2[b]	2.8[c]	2.6[c]	2.4[c]	11.7[b]	7.4[b]	5.9[b]

1) US = commercially available ultrasonic sensor.
2) Measured values of the ultrasonic sensor were averaged in the specified buffer from predefined reference position.
3) Surface models from UAV images.
Track depth is the difference between
4) the lowest and highest points,
5) the 95% quantile and the 5% quantile or
6) the 90% quantile and the 10% quantile in the buffered area.
a,b,c the values within each measurement procedure that do not have the same letter are significantly different ($p < 0.05$).

The track depths determined with the commercial ultrasonic sensors differed considerably from the reference values. However, the correlation coefficients for the relationship between the reference and track depths determined with the sensors indicate a close relationship between the variables ($r = 0.77$, 0.83 and 0.97 for the mean values within a radius of 0.5 m, 1 m and 3 m, respectively).

The track depths averaged within 0.5 m of the reference points show three statistically significantly different groups: the track depth at 0.5 bar is lower than at all higher tire pressures. The track depths at 0.7 bar and 1.8 bar do not differ and the track depth at 2.0 bar is significantly larger than at all other tire pressures. The mean values within a radius of 1 m show a similar picture: the track depth at 0.7 bar does not differ from the track depth at 0.5 bar or 1.8 bar.

The track depths determined from the digital surface models of the UAV mission deviate strongly from the reference values as from the measurements with the ultrasonic sensors. The determined track depths are strongly dependent on the calculation method. However, the procedures based on the difference between two quantiles show a close correlation with the reference values ($r = 0.98$ and $r = 0.94$). Both procedures showed a similar result structure in the variance analysis as the reference values. Despite smaller differences in absolute terms, significant differences between the two respective low and high tire pressures can be detected with the two methods.

Figure 4 shows the reference values and the track depths determined with the two sensor systems plotted against the tire pressure. It can be clearly seen that the measured values show different levels depending on both the measurement and calculation methods. It is also noticeable that the absolute differences between the track depths at different tire pressures are by far the greatest with the reference method. The differences between the median track depths at different tire pressures determined with the sensors are much smaller. Individual, incorrect measured values presumably do not have such a strong effect on the result due to the calculation of the median.

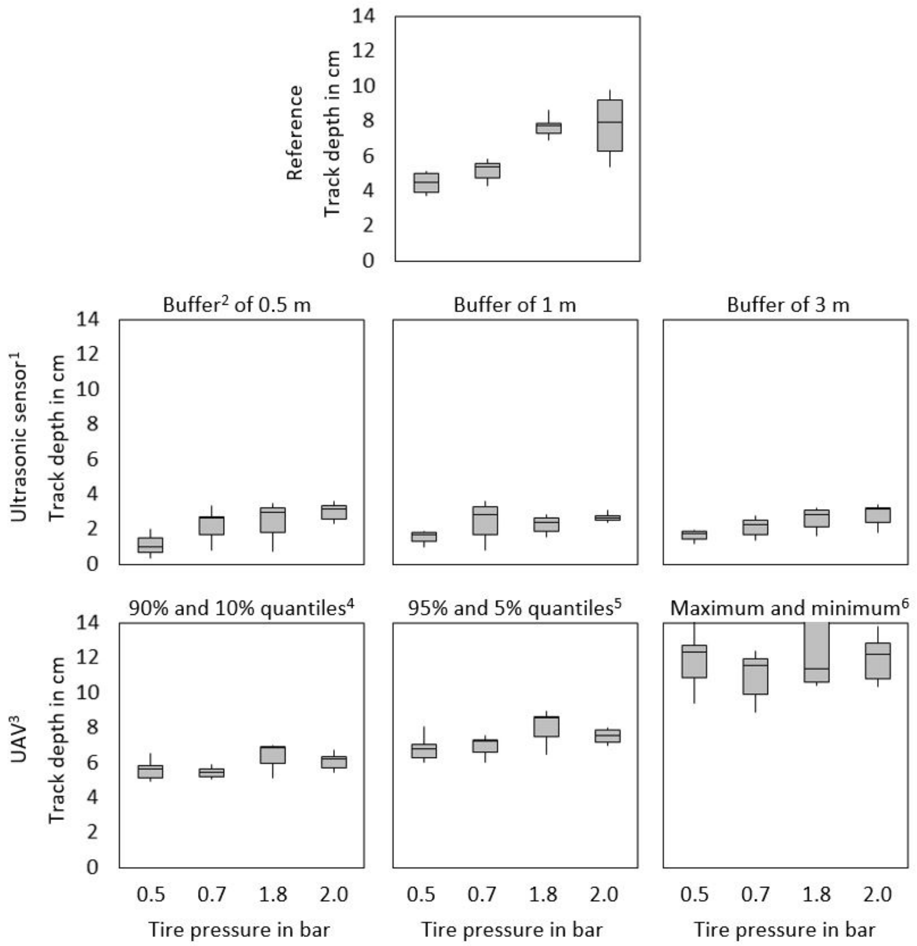

Figure 4: Measurements of track depth at the same speed (4 km/h) and similar soil moisture content (19 to 21 vol%) with three different measurement methods (1 US = commercial ultrasonic sensor; 2 mean value around reference position; 3 measured values from UAV surface model, track depth is the difference between 4 the 90 % quantile and the 10 % quantile, 5 the 95 % quantile and the 5 % quantile or 6 the lowest and the highest point in the buffered area)

Discussion

Comparison of measurement methods for determining the track depth

The manually measured track depth is defined as a difference in height caused by soil settlement after travelling over the soil and is measured between the surface of the uncompacted soil and the tire footprint. The method is used to determine reference values of individual test variants. As this method is labor-intensive and time-consuming, it is only suitable for experimental purposes. In addition, the measured values can only be collected after driving on the field and not while driving, so that it is not suitable for controlling tire pressure systems or generating indications as part of a decision support system.

Ultrasonic sensors, on the other hand, enable the measurement of the track depth while driving. Nolting et al. (2006) mounted ultrasonic sensors under a tractor and in the tires to derive the track depth from the measured values. In terms of installation, however, less effort is involved in installing the ultrasonic sensors as tested in this trial.

The results showed that with the commercial ultrasonic sensors at least the relative increase and decrease in track depth can be recorded due to a close correlation (r = 0.78 to 0.97). However, the measured values deviated strongly from the reference values in absolute terms. The correlation cannot be transferred into a generally valid equation („calibration curve“) due to the small number of measured values. In contrast, the low-cost ultrasonic sensors did not deliver satisfactory results. The differences in the quality of the results are presumably due to differences in the design and signal processing of the sensors. However, these are not evident from the publicly available information on the sensors.

Differences also appeared from the comparison of the photogrammetric methods. In contrast to the reference measurements, the track depths determined with the help of a commercial consumer grade action camera showed no correlation with the tire pressure. In contrast, the measurements from the digital surface model of a UAV camera achieved sufficient accuracy. In particular, the calculation of the track depth as the difference between the 95 % quantile and the 5 % quantile and the 90 % quantile and the 10 % quantile achieved close correlations with the reference (r = 0.98 and r = 0.94). As with the ultrasonic sensors, high absolute differences between reference values and sensor values also occurred here. The measurement procedure, like the reference procedure, is not real-time capable because the measurement data is only available after the end of the flight mission and subsequent data processing. It is therefore only suitable for testing, but provides a much higher density of measured values than the reference method.

Comparison of the influencing variables on the track depth

Measuring the track depth with different methods confirmed that there is a correlation between tire pressure and soil deformation and thus track depth. Almost independently of the speed, a difference was found between the track depths at low and high tire pressures in areas with low, medium and high soil moisture. This confirms the results known from the literature (Bolling 1987, Lebert 2010, Geischeder 2011). When comparing four tire pressures, the track depth increased from 4 cm at low tyre pressure (0.4 bar) to up to 7 cm at high tire pressure (2 bar).

The soil moisture in and next to the lane also affected the track depth. This observation is in line with the studies of Brunotte et al. (2015). It is remarkable that on a dry field, the average track depth was 1.2 cm lower at high tire pressure (1.8 bar) than at low tire pressure (0.7 bar).

Conclusions

There are currently no commercially available systems for measuring track depth that can be used to estimate and map soil compaction. These measurements could serve as a basis for decision support or as a source for automation.

In the ARDopt project, the track depth was recorded by continuous measurements with ultrasonic sensors and photogrammetric techniques. The investigations with a limited number of parameters under settings and conditions that were as constant as possible enabled a methodological comparison. The results show that both measurement methods have the potential for further development towards a market-ready solution. As expected, it was found that tire pressure and soil moisture have a strong influence on track depth and soil compaction. This knowledge and the experience gained from the application of different measurement methods will enable further influence factors such as soil heterogeneity to be investigated in the future.

References

Amelung, W.; Blume, H. P.; Fleige, H., Horn, R.; Kandeler, E.; Kögel-Knabner, I., Kretzschmar, R., Stahr, K.; Wilke, B. M. (2018): Physikalische Eigenschaften und Prozesse. Scheffer/Schachtschabel Lehrbuch der Bodenkunde. Springer Spektrum, Berlin, Heidelberg, S. 213–340. https://doi.org/10.1007/978-3-8274-2251-4_6

BBodSchG (1998): Bundes-Bodenschutzgesetz vom 24.3.1998 BGBL I, Nr. 16, S. 502–510

Blum, W. E. (2019): Boden und globaler Wandel. Springer Spektrum, https://doi.org/10.1007/978-3-662-59742-2

Bolling, I. (1987): Bodenverdichtung und Triebkraftverhalten bei Reifen-Neue Meß-und Rechenmethoden. Dissertation, Technische Universität München, Lehrstuhl für Landmaschinen, S. 289

Brunotte, J.; Schmidt, W.; Brandhuber, R.; Busch, M.; Honecker, H.; Bug, J.; Breitschuh, T.; Schrader, S.; Weyer, T.; Vorderbrügge, T.; Chappuis, A.; Fröba, N.; Löber, M.; Mosimann, T.; Ortmeier, B.; List, M. (2015): Gute fachliche Praxis Bodenbewirtschaftung und Bodenschutz. Bundesministerium für Ernährung und Landwirtschaft, Bonn, S. 119

Chambers, J. M.; Freeny, A; Heiberger, R. M. (1992): Analysis of variance; designed experiments. Chapter 5 of Statistical Models in S eds J. M. Chambers and T. J. Hastie, Wadsworth & Brooks/Cole

Diepenbrock, W.; Ellmer, F.; Léon, J. (2016): Ackerbau, Pflanzenbau und Pflanzenzüchtung: Grundwissen Bachelor. Ulmer Verlag, S. 376

Geischeder, R. (2011): Bodenbelastung und Bodenbeanspruchung unterschiedlicher Fahrwerkskonfigurationen. Dissertation, Technische Universität München, Lehrstuhl für Agrarsystemtechnik, S. 196

Håkansson, I. (2005): Machinery-induced compaction of arable soils. Incidence – consequences –counter-measures. Report No. 109 from the Division of Soil Management, Department of Soil Sciences, Swedish University of Agricultural Sciences, S. 153

Keller, T.; Sandin, M.; Colombi, T.; Horn, R.; Or, D. (2019): Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. Soil and Tillage Research, S. 194, https://doi.org/10.1016/j.still.2019.104293

Lebert, M. (2010): Entwicklung eines Prüfkonzeptes zur Erfassung der tatsächlichen Verdichtungsgefährdung landwirtschaftlich genutzter Böden. Umweltbundesamt, Dessau-Roßlau, S. 96

Nolting, K.; Brunott,e J.; Lorenz, M.; Sommer, C. (2006): Bodenverdichtung: Bewegt sich was? Setzungsmessungen im Unterboden unter hoher Radlast. Landtechnik 61(4), https://doi.org/10.15150/lt.2006.1093

Park, C.; M. Wang (2018): Empirical distributions of the robustified t-test statistics. ArXiv e-prints, 1807.02215. https://arxiv.org/abs/1807.02215

Schnaufer, A.; Kutzbach, H. D. (1998): Variierter Reifeninnendruck. Landtechnik 53(2), S. 78–79, https://doi.org/10.15150/lt.1998.2434

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