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Assessing the reversibility of soil displacement after wheeling in situ on restored soils

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Abstract

Land restoration after open-cast mining and construction sites enables maintaining the quantity of agricultural land in the long-term. With the modern gentle restoration techniques, soil is heaped loosely and supposed to consolidate and increase its mechanical resistance in the first few years after restoration. With this study, we investigated the influence of the soil's age after heaping on the susceptibility to compaction of restored soils.

We carried out wheeling experiments with a tractor and a manure trailer on two adjacent restorations of 1 and 3 years after heaping, respectively. Subsequently we observed the soils for 3 months. We assessed soil displacement at the soil surface with digital levelling, and within the soil profile in 25–30 cm depth with a special hydrostatic soil displacement meter (HSDM), which had been developed for this application. In the same depth, soil cores were taken to determine coarse pore content and bulk density, right after the wheelings and at the end of the experiment.

We conducted four wheelings, what caused soil displacements at the soil surface of ca. 11 mm on both restorations. The HSDM provided us reliable data for the 3-year-old restoration, only. Total soil displacement after the four wheelings was ca. 5 mm in 28 cm depth. Our subsequent observations revealed the complete decline of the soil displacements caused by the wheelings within 18 days at the soil surface as well as in the soil profile. The levelling results revealed the same recovery from the displacements at the soil surface for both restorations independently of their ages.

For the soil physical parameters, we found differences between the two restorations. Only the 3-year-old restoration showed less coarse pores and higher bulk density in the track than beside the track right after the wheelings, while the 1-year-old restoration did not. At the end of the experiment, coarse pore content and bulk density in the tracks stayed approximately the same, as right after the wheelings, particularly the track of the 3-year-old restoration did not show any recovery. Because of the partly contradictory results of soil displacement measurements and soil physical parameters, we recommend further research on soil deformation and the regeneration of restored soils.

Keywords: Soil displacement; Land restoration; Soil compaction; Hydrostatic soil displacement meter; Field experiment

1. Introduction

Land restoration after the exploitation of raw material or the installation of construction sites is an important measure to maintain the quantity of agricultural land in the long-term. This is particularly

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true in regions, where construction activity and urban sprawl threatens the available agricultural land, as e.g. in the Swiss Central Plateau. Soil removal, dislocation and restoration affect soil structure and make it very susceptible to compaction. Formerly, the main problem with restored soils was compaction due to traffic with heavy construction machines during the restoration process (Hossner, 1988; Harris et al., 1996; Friedli et al., 1998). Awareness of this problem increased in the 1990s, not only with farmers, but also with soil protection authorities and constructors. In Switzerland, several guidelines and manuals of land restoration were published (e.g. Salm, 1996; FSK, 2001) and great progress was achieved in the restoration technique. Recently restored soils usually do not suffer from compaction, in the contrary, mostly they are very loose and show accordingly low mechanical bearing capacity (Schäffer et al., 2007). It is a common hypothesis that restored soils consolidate under their own weight and that re-established biological processes (root growth, activity of micro-organisms) support aggregate formation (Lebert and Springob, 1994). These processes of consolidation and aggregation are thought to increase mechanical bearing capacity and decrease the restored soil's susceptibility to compaction. Most Swiss restoration guidelines recommend extensive grassland with only a few management steps and light vehicles for 5 years after restoration. After this time, there are no more restrictions in agricultural management on restored soils. However, this rule of 5 years is not based on scientific findings about the regeneration of secondary soil structure and mechanical bearing capacity. It is rather a political compromise between the economic interest of making most agricultural use of a restored soil as soon as possible and the ecological interest of supporting pedogenetic processes for a possibly long time period.

The question arises, if the improved restoration techniques have solved the problem of soil compaction on restored soils, or if this problem is only delayed to the moment when usual agricultural management restarts with the corresponding machinery. Another question is, whether the prescription of 5 years extensive management after restoration is sufficient, or, if even an earlier transition to conventional agricultural management is acceptable. A final question is, if a restored soil that has extensively been used for several years can recover from compaction after a time period that is suitable for agricultural management, i.e. from one management step to the other (between weeks or months).

There are only few measurement approaches that allow continuous observation of the soil's recovery from compaction at exactly the same place for a certain time period. Recent research focuses on the assessment of soil deformation accompanied with compaction. Several authors studied soil deformation in uniaxial compression tests with undisturbed soil samples in the laboratory (Rogasik, 1990); sometimes with the application of optical methods like X-ray computed tomography (Kremer et al., 2002). Soil deformation has rarely been measured directly in the field. Rut depth was measured to assess the effects of different axle loads and types of tyres (Håkansson and Medvedev, 1995; Arvidsson and Ristic, 1996). Different authors adapted plate sinkage tests known from road construction to measure soil deformation in the field (e.g. Alexandrou and Earl, 1997; Okello et al., 1998). Other attempts were made with a stress–strain-transducer (SST) connected to a displacement transducer system (DTS) (Kühner, 1997; Wiermann et al., 1999; Horn and Rosteck, 2000). The SST was fixed to a rod and with this placed horizontally into the soil from a soil pit. The other end of the rod was connected to the DTS, which recorded the displacement of the SST and corrected it after the lever law. With this device, Horn et al. (2003) showed the effects of repeated wheeling. Each wheeling added to the total soil displacement although the first wheeling had the greatest influence.

Arvidsson and Andersson (1997) and Arvidsson et al. (2000) used a hydrostatic system to assess vertical soil movement during wheeling. They installed test probes filled with silicon oil laterally from a soil pit at three different depths. Each test probe was equipped with a separate sensor to determine the hydrostatic pressure in the probe. With the same technique, Arvidsson et al. (2001) verified model computations of the compaction depths caused by wheeling with sugar beet harvesters. Equally, with this device and in combination with soil stress measurements, Keller et al. (2002) proved the positive effects of on-land ploughing in contrast to conventional ploughing to avoid subsoil compaction. Tobias et al. (2001) also used a hydrostatic device to assess soil displacement under wheel loads at different levels within the soil profile. Their device had one single pressure sensor that could be connected to 12 different measuring lines. The authors distinguished elastic and plastic deformation and proved persistent displacements after the wheelings for several days. In addition, they observed height changes of the soil surface after different numbers of wheelings (with same wheel load) by digital levelling, which showed that the amount of soil displacement corresponded to the number of wheelings.

As the examples show, most in situ measurements of soil deformation have only been used to analyse the compaction process, so far. Tobias et al. (2001) continued their observations for several days after wheeling, but after ca. 6 days their measurements showed strong drifts because of the mechanical design of their hydrostatic device. However, compacted soil can naturally be loosened by changes of water content (swelling and shrinking), changes of soil temperature (particularly freezing) and biological factors (root growth and bioturbation of soil animals) (Håkansson and Reeder, 1994; Wiermann and Horn, 2000). Different studies stress the positive effect of earthworms (e.g. Langmaack et al., 1999; Larink et al., 2001). Several authors analysed the swelling–shrinking behaviour of agricultural soils in the laboratory and modelled it in shrinkage curves (e.g. Olsen and Haugen, 1998; Coquet, 1998; Groenevelt and Grant, 2002; Flowers and Lal, 1999). Aluko and Koolen (2001) proved the high effect of freezing and thawing to increase soil volume changes with subsequent swelling and shrinking. However, the effects of the physical regeneration processes have not been quantified so far and, particularly, the time needed for natural recovering of compacted soils is very uncertain and supposed to last for several years or even decades (Håkansson et al., 1987; Wiermann and Horn, 2000).

This paper presents the results of a field experiment on two restored soils of different age, where soil displacement was observed during 3 months after wheeling. This enabled us the repeated observation of the soil at exactly the same points. We ascertained soil displacement at the soil surface by digital levelling and within the soil profile with a completely revised update of the hydrostatic soil displacement meter used by Tobias et al. (2001). In the background of the experiment were the three questions mentioned above arising from the state of the art of soil restoration in Switzerland. We set our focus on soil displacement and its decrease as an indicator of the restored soils' susceptibility to compaction and a potential recovery from compaction. We particularly wanted to know, if the soil displacement caused by our wheeling experiments decreased and the time needed for this. In addition, we were interested in potential differences of the decrease of soil displacement between the two restorations of different age.

2. Materials and methods

2.1. Hydrostatic soil displacement meter

The basic principle of the hydrostatic soil displacement meter (HDSM) is the principle of communicating vessels. In the HSDM, the probes were not communicating, but connected with a pressure difference gauge that measured the difference of the hydrostatic pressures at both sides. This principle was adopted from the device used by Tobias et al. (2001). With the new HSDM, most of the operational problems of the former device, like air enclosures in the tubes and the missing possibility of separate steering of the single measuring lines, could be eliminated.

The hardware of our new prototype comprised a control device, a pressure difference gauge, 14 probes, connecting tubes and separate control valves for each of the probes (Fig. 1). The probes consisted of transparent plexiglass (PMMA), because the level of the measuring liquid was checked with an optical method. The probes had a cylindrical shape with a diameter of 50 mm and a height of 45 mm. The width of the plexiglass walls was 4 mm. The size of the probes was thus comparable to that of many stones we found in our test sites. Each probe was connected to two Teflon tubes; one at the top of the probes, for air balance with the atmosphere, and one in the wall of the cylinder, 8 mm above the bottom of the probe, to connect the measuring liquid to the central pressure difference gauge (Fig. 2). The tubes had an internal diameter of 6 mm and an external one of 8 mm. With these dimensions, capillary effects could be avoided.

The hydrostatic principle requires a free, stable surface of the measuring liquid within the probes. We installed a laser pointer in the cylindrical wall and at the opposite side a unit of eight photodiodes (Fig. 2). The laser and the diodes were attached in the way that, allowing for the refraction of the laser beam, the diodes received the laser light only, if the liquid level was between 31 mm (lowest diode as receiver) and 42 mm (highest diode as receiver) from the bottom of the probe. We used silicon oil, which had a smaller capillary tension and a lower freezing point than water. The latter

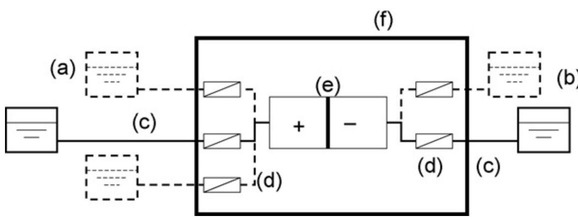

Fig. 1. Principle of the hydrostatic soil displacement meter (HSDM): (a) measuring probes; (b) reference probes; (c) Teflon tubes filled with measuring liquid; (d) control valves; (e) pressure difference gauge; (f) control device. The currently active measuring line (connection of measuring and reference probe) is indicated with the continuous lines. The dashed lines indicate currently inactive measuring lines.

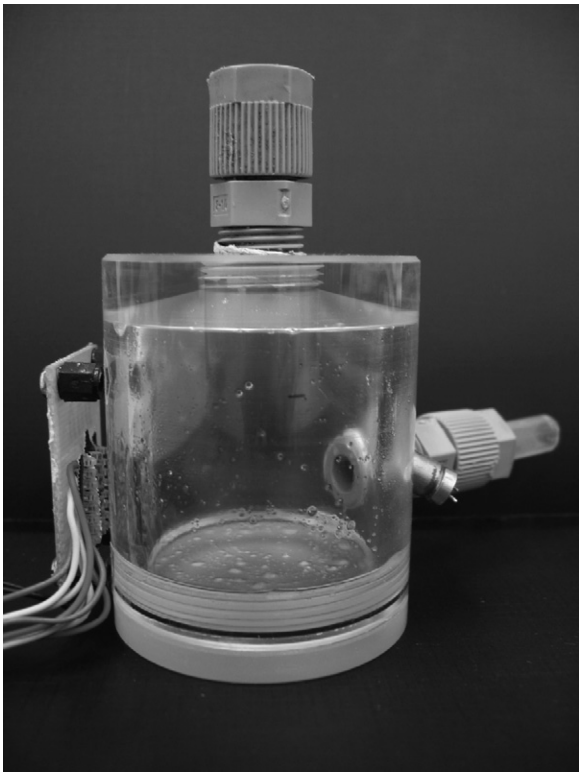

Fig. 2. One of the 14 plexiglass probes of the hydrostatic soil displacement meter (HSDM) with the two connections to the tubes (top and right side), laser pointer to the right and photodiode unit to the left.

was decisive for our experiments during wintertime. We used a separate vacuum pump to fill the probes with silicon oil through the tube in the cylindrical wall until the highest diode detected the liquid level. Then we closed the valves. As the valves reacted with a small time delay, the liquid level rose above the highest diode. Afterwards, we opened the valves again to let the liquid flow back by gravity until the level within the probes was again detected by the highest diode. The air tube was open during the whole filling process.

The pressure difference gauge was selected after the expected soil displacement. We chose a piezo-resistive gauge deltabar S PMD 235 with a maximum measuring range of 10 cm. As the connection of the pressure difference gauge to the single probes was steered with separate valves, we were free in connecting each probe at the minus-side of the gauge to any probe at the plus-side of the gauge. This enabled a function check and confirmed the measuring accuracy of the whole system at any time during the experiment. For the field experiments, 2 reference probes were fixed in a predetermined height and 12 measuring probes assessed the vertical soil movements. We always ran two measuring cycles, where all the measuring probes were connected to either and the other reference probe. Car batteries fed the control device during the time of the measuring cycles (ca. 2 h). We used a Gardena irrigation computer as a timer to run the batteries only during the measuring time.

Tests in the laboratory climate chamber revealed that temperature had no influence on the measuring accuracy within a range of +30 and −10 °C. We ascertained a standard deviation of 0.1 mm for a single measurement. This error holds for each single value from the continuous measurements during the wheelings (see Section 2.3). During the subsequent observation in the following months, we recorded 120 single values for each combination of a measuring probe to a reference probe and day; and determined the average value for the final reporting. The scattering of the single values caused a standard deviation of 0.6–0.8 mm for the average values.

2.2. Test site

Our test site was located in the Swiss Central Plateau near Herzogenbuchsee in the Canton of Berne. The regional climate is humid with average temperature of 0.1 °C in January and 18.1 °C in July and with average yearly precipitation of 1140 mm (both averages over the years 1997–2003). The soils were Eutric Cambisols. The typical land use of the region is intensive agriculture with crop rotation of maize, sugar beet, potato, wheat, barley and grassland.

The region was affected by an open-cast tunnel construction for a high-speed railway line in the years 2000–2005. The topsoil and the subsoil (A- and B-horizon) were removed and stored on-site in separate dumps of 2.5 m (topsoil) and 4.5 m height (subsoil). After the termination of the tunnel construction, the land was restored in different stages from 2002 to 2005. The restoration was accomplished with shovel excavators and advanced in stripes of ca. 10 m width, according to the reach of the shovels. First the subsoil was poured and immediately afterwards the topsoil was distributed over the subsoil. Work was only done under dry weather conditions, the daily progress varied between 1000 and 4000 m^2. After the fill, a mixture of grasses and legumes (red clover, orchard grass, alfa alfa, timothy) was sawn on the restored soils.

Our test site had had two treatments on adjacent lots: one lot was restored in 2002 and the other lot was restored in 2004. The subsoil had been poured on the construction plane and was ca. 80 cm profound; the topsoil was ca. 35 cm thick. As the original soil material

Table 1
Particle size distribution of the two restored soils, where the experiments took place

	Sand (%)	Silt (%)	Clay (%)	Org. material (%)
Restoration 2002	50	31	16	3
Restoration 2004	45	36	16	3

had been used for restoration, we found very similar soils for both treatments. Our investigations focused on the topsoil, hence we only analysed the topsoil. On both lots, we found a sandy loam with many stones also in the topsoil (Table 1). Since the restorations had been accomplished, the farmer had not ploughed the lots, only harvested the grass four times per year under dry weather and soil conditions.

2.3. Test design

We carried out a wheeling test on 25 November 2005, and continued our observations until 28 February 2006. For the wheeling, we used a Steyr 8075 tractor (75 hp) with a one-axis manure trailer, which were typical of the local farmers' machinery. The vehicles had radial tyres. The tractor had single wheels in the front and double wheels in the rear. The trailer had twin-tyres on two single wheels. We ascertained the tyres' contact areas right before the wheelings by pouring chalk around the tyres of the vehicles and measuring the side lengths of the rectangles within the chalk lines with a folding rule after removing the vehicles. The wheel loads were measured with a balance of the traffic police. The contact pressure under the tractor's front and rear wheels as well as under the trailer's wheel was ca. 100 kPa (Table 2). The same tracks were wheeled four times at ca. 1.4 ms^{-1} without stopping.

The wheelings were carried out one directly after the other. The tracks had been laid over both restorations (Fig. 3). One of the tracks lead over the probes of the HSDM to assess soil displacement within the profile, the other track contained the marks for the observation of the soil surface's vertical movements.

For the assessment of soil displacement within the soil profile, we distributed the HSDM-probes in four different groups of three probes each (Fig. 3). Two groups of the probes were placed in a track of the wheelings, one in the restoration of 2002 and one in the restoration of 2004. Two additional groups of probes, on each restoration, were put in lines that were not wheeled during our experiment. We placed all probes at the same geodetic height level to avoid that the liquid levels of the probes drifted beyond the range of the pressure sensor. As our test site was on a small knoll, the different groups of the HSDM-probes were placed at different soil depths. On the restoration of 2002, the probes lay at ca. 25 cm (beside the track) and ca. 28 cm (track), respectively. On the restoration of 2004, we placed them at depths of ca. 29 cm (beside the track) and ca. 33 cm (track). All probes were put in the topsoil (A-horizon). The central unit of the HSDM, with the pressure sensor and the valves of the probes, was placed in a soil pit with its bottom on the plane of the restoration. We dug narrow horizontal channels from the soil pit to the points in the foreseen track, where the HSDM-probes were to be placed. The channels had the width of the probes and the depth at which the probes were put in the soil. Thus the tubes connecting the probes with the central unit ran horizontally from the probes to the soil pit. We placed the probes in the channels at their ends in the track in the way that the probe bottom lines were horizontal. After, we filled up the channels again with the material that had been

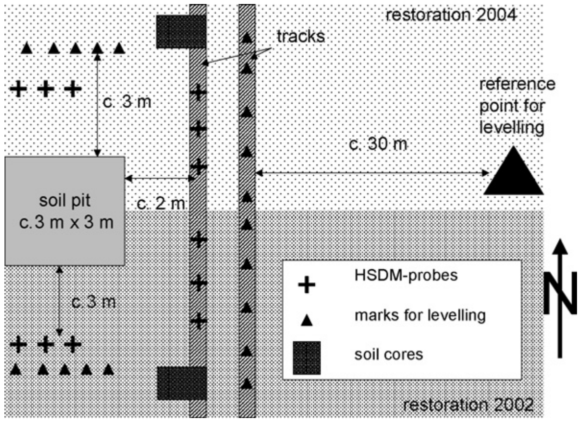

Fig. 3. Test design for the field experiments.

Table 2
Load parameters of the test vehicles

Wheel	Contact area (m^2)	Wheel load (kN)	Contact pressure (kPa)
Tractor front	0.042	4.4	105
Tractor rear	0.135	13.7	102
Trailer	0.209	21.6	103

dug out. The reference probes were placed on a rack that was fixed to the restoration plane at the bottom of the soil pit. As the restoration plane had strongly been compacted, it did not follow the vertical movement of the restored soil above, induced by swelling and shrinking. Hence, we could assume that the reference probes kept their height position and only the probes within the soil profile moved up and down.

The measurements were executed and controlled with a steering interface running with a special programme of LabView-software. In the first weeks of the observations, we initiated the measurements by hand, from 23 December 2005, to 28 February 2006, the measurements were automatically initiated by the control device. During the wheelings, we connected the pressure sensor to one single probe in the restoration of 2002, in order to get continuous measurements. The relay-card of the HSDM had a limited memory capacity of max. 16 kB, what forced us to stop the data records after each wheeling and download the data. Before and after the wheelings, we accomplished a complete cycle of measurements with all the 12 probes in the soil and the two reference probes. In the following time, we always executed one complete measuring cycle per measuring day. The automatic measurements in the second half of the observation period ran daily before sunrise at 5 a.m. to avoid temperature differences between the probes in the soil and the reference probes in the pit because of sunshine on the coverage of the soil pit. The manual measurements had a frequency of 3–10 days with an interruption in the first 3 weeks because of problems with the data transfer.

We assessed the vertical movements of the soil surface with digital levelling. We used nails of 10 cm length with a flat top of 10 cm in diameter as marks on the soil surface. The marks were placed in correspondence to the HSDM-probes in the soil (Fig. 3). We arranged 10 marks in the other track of the wheelings, 5 on the restoration of 2002 and 5 on the restoration of 2004, respectively. Beside the lines with the HSDM-probes that were not wheeled in our experiment, we placed additional five marks on the soil surface on each restoration. We fixed a bolt on a rock about 30 m away from our test sites as height fix-point for the digital levelling. The rock was placed at a passing place of a reinforced agricultural gravel road; hence with constant height position independent from swelling and shrinking processes of the restored soil. We started the digital levelling on the day of the experiment's installation (3 November 2005). Before the wheelings, we measured the heights of all the marks. After each wheeling, we assessed the height changes of the wheeled marks in the track. At the end of the wheeling experiment, we ascertained the geodetic levels of all the marks again. In the following, we repeated the digital levelling every 7–10 days with one turn over all the 20 marks. We estimated a standard deviation (s_{lev}) of the digital levelling of 3 mm according to the cumulated errors of the marks at the soil surface, of the bolt on the rock and the standard deviation of the instrument.

We took soil cores in the tracks and beside the tracks at the same depth like the HSDM-probes right after the wheelings and at the end of the observation period on 28 February 2006 (Fig. 3). Since the vertical movement of the HSDM-probes is induced by the deformation of the soil right under the bottom of the probes, the top line of the soil cores corresponded to the bottom line of the HSDM-probes on the particular test area; with one exception on the restoration of 2002. Beside the track, the pit for the soil cores was dug a bit deeper on 28 February 2006, so that the bottom level of the HSDM-probes was higher than the top line of the soil cores. Consequently, the soil cores partly contained subsoil material (as this was the highest point of the knoll, the topsoil was shallower than on the other plots). The soil cores contained 100 cm^3 and were 5 cm high and ca. 5 cm in diameter. Because of the many stones in the restored soil, we took 10–12 soil cores per test area. The soil parameters determined in the laboratory represent averages of at least seven soil cores without stones.

In the laboratory, we ascertained the coarse pores with an equivalent diameter of $\geq 5 \times 10^{-5}$ m by applying a hanging water column to the soil cores to reduce the soil water potential from saturation to -6 kPa. We measured the weight reduction from the saturated to the conditioned state of the samples, which corresponded to the volume of the eliminated water. After, the soil cores were dried for 24 h at 105 °C and weighed to determine dry bulk density. Material from the soil cores was taken to ascertain particle size distribution (clay, silt, sand, organic material) of the topsoils of the two restorations. We used the pipet method after eliminating particles >2 mm in diameter by wet-sieving.

We accomplished a statistical comparison of means to assess the differences between the tracks and the unwheeled test plots concerning bulk density and coarse pore content. As the sample size was rather small, we chose a non-parametric test (Mann–Whitney test) to check the significance of the differences of means. We used the software SPSS for this data analysis.

Soil temperature was measured in the depth of the soil cores on the day of the wheelings with a common thermometer. In the following, we used the data from an official weather-observation station at a distance of 35 km. The intention of observing the soil temperature was only to check if the soil temperature dropped below 0 °C and frost might enhance the regeneration of the soil structure after wheeling. For this purpose, the information of the weather-observation station was useful enough, as the climate in the region is moderate with little chance of frost in 25–30 cm soil depth.

For the day of the wheelings, we ascertained the water content of the soil cores and calculated the degree of saturation. For this reason, we assessed the weight of the fresh soil cores right after their transport to the laboratory. The difference between the weight of the fresh cores and their weight after they had been oven-dried corresponded to the weight of water at the day of the wheelings. We calculated the degree of saturation by dividing the water weight of the fresh soil cores through the water weight at saturation.

3. Results

3.1. Wheelings

Fig. 4 shows the soil displacement caused by the wheelings, recorded continuously with one HSDM-probe in the restoration of 2002. The arrows indicate the approximate starting points of the wheelings.

At the soil surface, we ascertained a final soil displacement of ca. 11 mm on the restoration of 2002 and ca. 10 mm on the restoration of 2004 after the last wheeling. With the HSDM, we determined a final soil displacement of 6.2 mm after the last wheeling (Fig. 4). This result stems from continuous measurements with one single measuring line. Before the first and after the last wheeling, we ran a whole measuring cycle with all the measuring lines of the HSDM. The difference between these two cycles for the measuring line shown in Fig. 4 amounted to 4.2 mm of soil displacement. The difference in soil displacement between the continuous measurements in one single line and the ones from two measurement cycles are due to the fact that we had only single measurements for the single line, while for the complete measurement cycles, we calculated the average of 120 single measurements for each probe (cf. Section 2.1).

3.2. Development after the wheelings

Fig. 5 shows the records with the HSDM in the restoration of 2002 at a depth of 28 cm (track) and 25 cm (no track), respectively, from the day of the wheelings to the end of the experiment. Each data point in the figure corresponds to the average of all records with the three probes in each test plot. For this reason, the effect of the wheelings is smaller than in Fig. 4 showing the records of one single probe. In Fig. 5, we defined the origin of the *y*-axis in the way that it corresponded approximately to the starting level of the

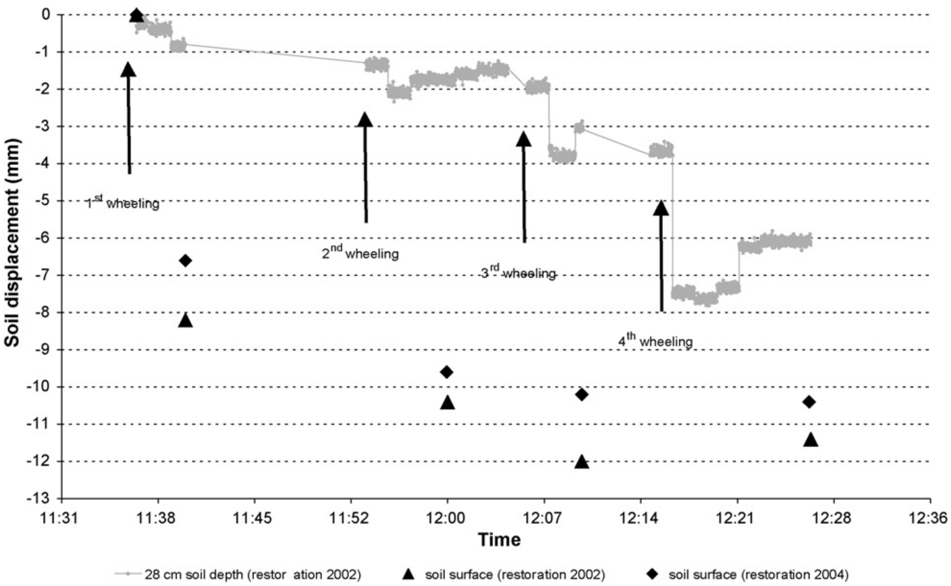

Fig. 4. Soil displacement caused by the four wheelings. The measurements at the soil surface show the plastic deformations only, while the measurements in 28 cm soil depth also represent elastic deformations under surcharge. The arrows show the approximate starting points of the wheelings.

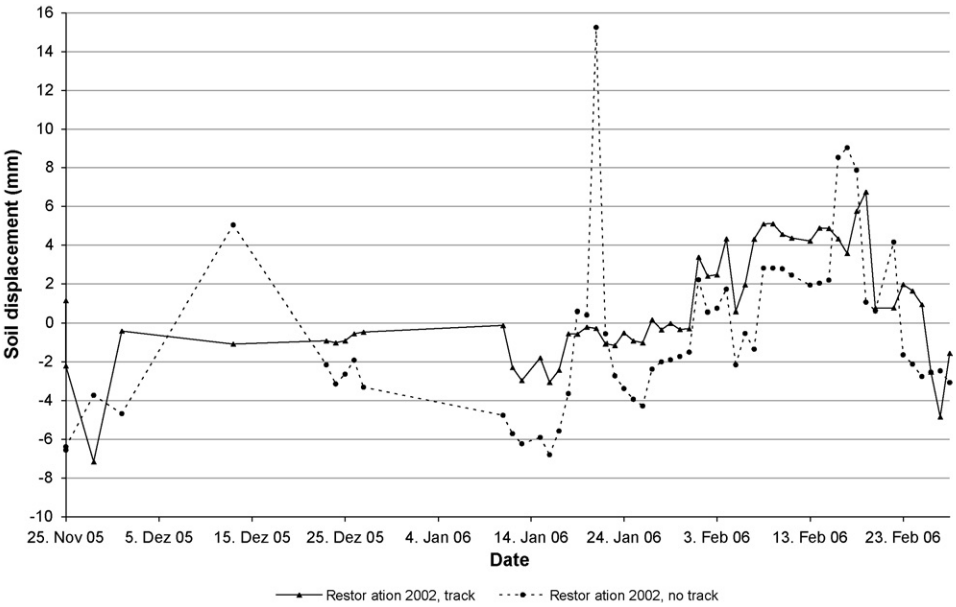

Fig. 5. Soil displacement assessed with the HSDM on the restoration 2002 in 28 cm depth (track) and 25 cm depth (no track), respectively. The measurement period lasted from the day of the wheelings (25 November 2005) to the end of the experiments (28 February 2006).

track before the wheelings. In the first weeks, the data were less frequent because of the problems with the data transfer (cf. Section 2.3). Fig. 5 shows two outliers for the no-track test plot that we cannot explain (13 December 2005 and 21 January 2006). The data records in the restoration of 2004 scattered with an amplitude of far more than 10 mm, what we accredit to technical problems with the tubes or the valves of these probes. We therefore excluded the HSDM-results from the restoration of 2004 from our interpretations.

Soil displacement at the soil surface is shown in Fig. 6 for all four test plots from the day of the installation (3 November 2005) to the end of the experiment (28 February 2006). Each data point in the figure corresponds

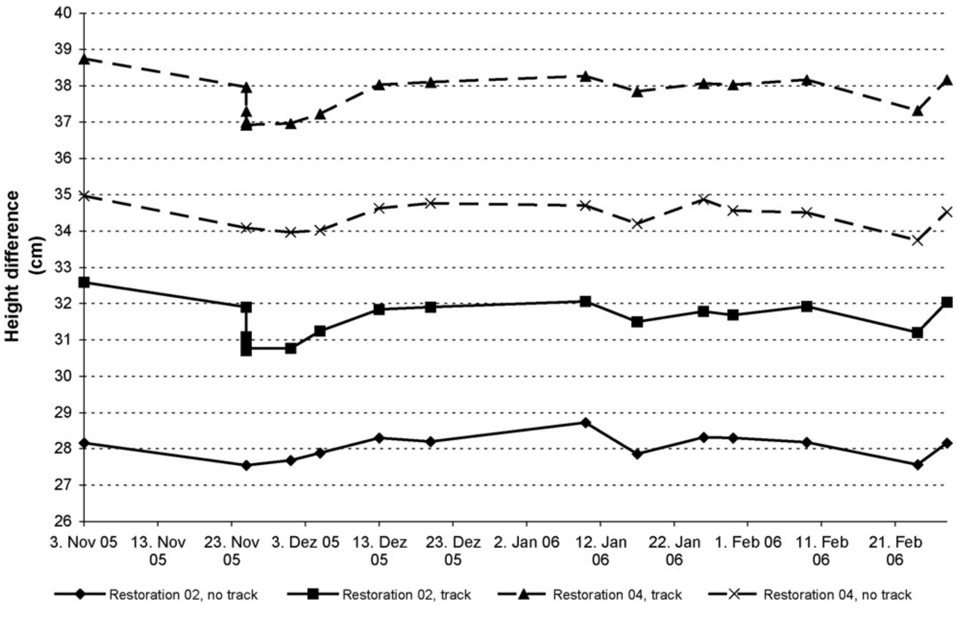

Fig. 6. Soil displacement at the soil surface assessed with digital levelling on both restorations from the day of the experiment's installation (3 November 2005) to its end (28 February 2006). The diagram shows the absolute height differences between the measuring marks and the height fix-point on the rock.

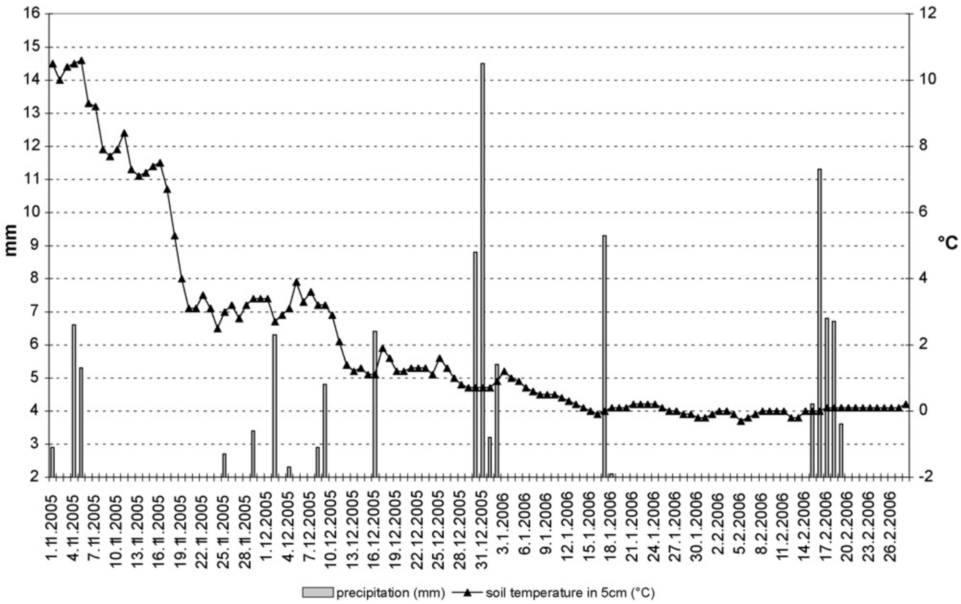

Fig. 7. Precipitation and soil temperature in 5 cm depth during the observation period. Data from the meteo-station Liebefeld (BE) at a distance of ca. 35 km.

to the average of the measurements with the five marks on each test plot. The figure shows the absolute height differences between the measuring marks and the height fix-point on the rock at the edge of the experimental site.

On the day of the wheelings, we measured a soil temperature of 3 °C in an open pit for soil core extraction. Precipitation and soil temperature in 5 cm depth are given in Fig. 7 for the whole time of the experiment. Two stronger precipitation events were recorded during the measuring period, one between 30 December 2005 and 2 January 2006; and one between 15 February 2006 and 18 February 2006. We have no data for the displacement at the soil surface for both precipitation periods. For the displacement within the soil profile, the data lack for the first precipitation event, but are available for the second one.

3.3. Soil parameters

On the restoration of 2002 and in the depth of the HSDM-probes, we ascertained a mean bulk density of 1.41 g/cm^3 beside the track and one of 1.63 g/cm^3 in the track, for the day of the wheelings (25 November 2005). On the same day, the mean coarse pore content was 14.9% beside the track and 7.2% in the track (Figs. 8 and 9). Both soil parameters showed significant differences (Mann–Whitney test) between the track and beside the track. The degree of water saturation was

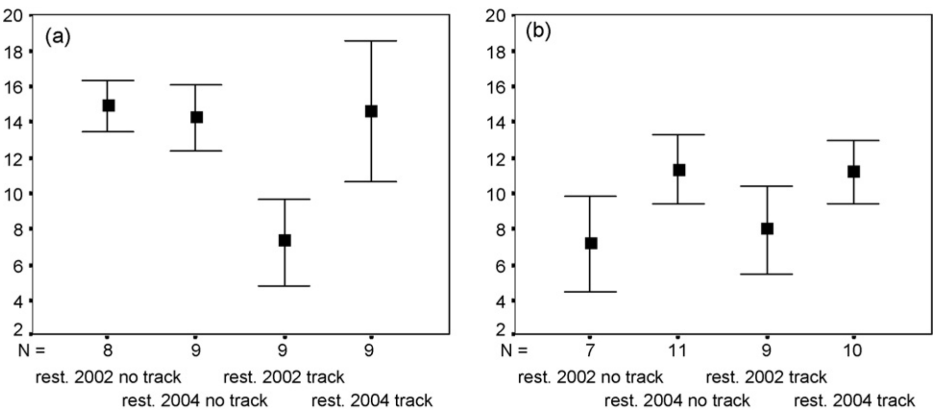

Fig. 8. Coarse pore content: means and standard deviation for the single test plots; (a) soil cores taken immediately after the wheelings (25 November 2005) and (b) soil cores taken at the end of the experiment (28 February 2006).

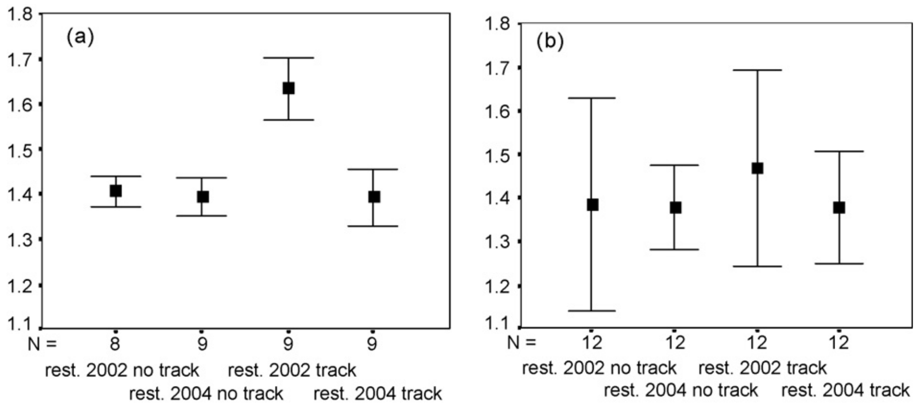

Fig. 9. Bulk density: means and standard deviation for the single test plots; (a) soil cores taken immediately after the wheelings (25 November 2005) and (b) soil cores taken at the end of the experiment (28 February 2006).

78% in the track and 61% beside the track. At the end of the experiment (28 February 2006), we determined a mean bulk density of 1.38 g/cm^3 beside the track and 1.47 g/cm^3 in the track, respectively, in approximately the same depths. The mean coarse pore content beside the track was 7.1 and 7.9% within the track. These values did not show a significant difference neither for bulk density nor for coarse pore content.

On the restoration of 2004 and in the depth of the HSDM-probes, we determined an average bulk density of 1.39 g/cm^3 beside the track and also 1.39 g/cm^3 within the track at the day of the wheelings. The average coarse pore content was 14.2% beside the track and 14.6% in the track (Figs. 8 and 9). The degree of water saturation was 67% in the track and 64% beside the track. At the end of the experiment, we measured a mean bulk density of 1.38 g/cm^3 beside the track and the same value of 1.38 g/cm^3 in the track. Coarse pore content was in average 11.3% beside the track and 9.7% within the track. There were no significant differences of the parameters beside the track and within the track, neither for the day of the wheelings nor for the day of the experiment's end.

4. Discussion

We ascertained only small soil displacements after the wheelings, although the soil was near water saturation. The reason for the small soil deformation may be the smaller wheel loads and contact pressures of the test vehicles than those of construction machines or combine harvesters, which most other authors used as test vehicles. In addition, both restored soils have a high sand content (cf. Table 1), which makes them less susceptible to compaction than soils with smaller particle sizes. As mentioned in Section 2.3, we had to stop the data records after each wheeling and download the data because of the limited memory capacity of our relay-card. When we started the data records again, the pressure difference gauge did not show exactly the same value as before stopping the data records. The interrupt of the data records is discernible with the straight lines that are not vertical in Fig. 4. These straight lines are not horizontal either because of the fluctuations of the pressure difference gauge. As these problems with the pressure difference gauge did not show up in the laboratory, we accredit them to the special supply with electric power in the field.

Fig. 4 shows the same soil displacements at the soil surface for both restorations independent of their age. For the displacements within the soil profile, we have only data for the restoration of 2002. After the last wheeling, they are approximately half of the displacement at the soil surface (Fig. 4).

At the soil surface, we could use the digital telescope level only after removing the surcharge; therefore the measuring values show the plastic deformation, only. With the HSDM, we measured continuously, while the wheels passed over the probe. In Fig. 4, the partial reduction of soil displacement after removal of the surcharge (i.e. elastic deformation) is discernible for the second, third and fourth wheeling. At the first wheeling, data recording was stopped before the surcharge was removed. The passing of the single wheels of the vehicles cannot be distinguished in Fig. 4, although the wheel loads differed strongly (Table 2). However, they had almost equal contact pressures, what may have had a stronger influence on soil displacement.

Each wheeling adds to the soil displacement, what corresponds to the findings of Horn et al. (2003). After the digital levelling at the soil surface, the first wheeling caused the strongest soil displacement, which is again in agreement of the other authors' experiments. According to the HSDM-measurements in Fig. 4, the fourth wheeling had the strongest influence on soil displacement. We cannot say, if this phenomenon is due to measuring errors or a possible shear failure of the soil beneath the HSDM-probe of this measuring line.

Fig. 6 shows a recovering from the displacements at the soil surface after 18 days (on 13 December 2005). Afterwards, the measuring marks in the tracks show the same movements of the soil surface as the ones beside the tracks. Hence, we can state a recovering of the soil from the displacements caused by our experimental wheelings. Surprisingly, the amount and time of this recovery did not depend on the age of the restoration. The soil displacements shown in Fig. 6 for the period of December 2005 and February 2006 are probably due to swelling and shrinking of the soil.

Our HSDM-device revealed a great progress towards the model used by Tobias et al. (2001) avoiding the drift of the measuring values after a couple of days. This was mainly a result of the separate control valves for each probe. Hence, we could show that the displacements within the soil profile reformed as well (Fig. 5). Contrary to the soil surface, they have not reached the original level after 18 days, but it was almost reached on 1 December 2005. However, the data before 23 December 2005 are afflicted with strong uncertainties. In January and February 2006, the soil was swelling within the whole profile, what affected the soil surface too (cf. above). The strong elevations around 20 February 2006 can be interpreted as a consequence of the second intensive precipitation period. The measurements within and beside the track show similar developings that correspond to the movements of the soil surface, particularly in January and February 2006. The strong elevations around 20 February 2006 are not retraceable with the movements of the soil surface; however, there is a lack of data of the soil surface for this period. The absolute values of the HSDM-measurements are almost the same as the ones of the levelling at the soil surface. This means that the HSDM-probes and the levelling marks had moved parallel, while the HSDM-reference probes that were fixed to the plane of the restoration did not change their heights. It remains an open question, to which parts this effect is due to measurement errors, or if smaller deformations occurred only in deeper soil layers than those, where our HSDM-probes had been placed. The second case could be explained by the fact that the soil water infiltrated quickly into deeper soil layers because of the high amount of coarse pores (Fig. 8), and the swelling process took place in deeper layers. Conversely, the effect of frost can probably be excluded. Fig. 7 shows that soil temperature in 5 cm depth reached the freezing point only on 15 January 2006 and hardly sank below it in the remaining observation time. We do not assume that a high amount of water would have frozen at this temperature, particularly because the freezing process generates condensation energy. Since the soil cools down from the surface to deeper layers, we do not assume that in the depth of the HSDM-probes (28 cm) soil temperature was lower than in 5 cm depth and, hence, did not sink below freezing point during the whole observation period.

The soil parameters show clear differences between the track and beside the track for the restoration of 2002, which indicate compression within the track (Figs. 8 and 9). On the other side, we cannot state relevant differences between the track and beside the track for the restoration of 2004. These differences between the two restorations cannot be followed with the deformation measurements in Figs. 5 and 6. At the end of the experiment, no differences in the soil parameters between the track and beside the track can be stated on either restoration. The restoration of 2004 shows approximately the same values as right after the wheelings. Hence, bulk density and coarse pore content did not change during the observation period in this restoration. However, for the restoration of 2002 Fig. 8 does not indicate a recovery of the track from the compaction, but the coarse pore content beside the track assimilated to the one of the track. Fig. 9 shows a reduction of bulk density within the track at the end of the experiment, while bulk density beside the track stayed almost constant. However, the measuring values of bulk density scatter strongly for the restoration of 2002 (Fig. 9). We accredit these effects, particularly the reduction of coarse pores beside the track, to the fact that the soil cores taken at the end of the experiment partly contained material from the top layer of the subsoil. This top layer may slightly had been compacted during the restoration process, when the topsoil was poured on it.

We can evaluate the degree of compaction by comparing the measured values to recently published expert opinions (Tobias and Tietje, 2007) and former experimental results (Flühler, 1973; Kremer, 1998). The authors determined a critical value of 7% coarse pore content, below which the soil's oxygen supply is insufficient, and which soil science experts use to state a critical degree of compaction. This critical value is approximately reached on the restoration of 2002 in the track right after the wheelings and on both test sides at the end of the experiment.

The second well-used parameter to evaluate the degree of compaction is packing density defined after Renger (1970) and the German soil-mapping manual (Finnern et al., 1996) as

$$PD\,(-) = BD\,(g/cm^3) + 0.009\ \ clay\,(\%)$$

where PD means packing density, which is a unitless parameter, BD means bulk density in (g/cm^3) and clay means clay content in (%). Experts state a value of 1.7 as critical, above which the soil's ecological functions are impeded by compaction in the long-term (see Tobias and Tietje, 2007, and the literature cited by them). On the restoration of 2002, we calculate a packing density of 1.77 in the track right after the wheelings, which indicates soil compaction that affects the ecological functions. At the end of the experiment, the track on the restoration of 2002 still showed the highest bulk density out of all test plots (Fig. 9). Packing density is 1.61, just below the critical value of 1.7. Beside the track, we calculate a packing density of 1.52 on the restoration of 2002 at the end of the experiment.

5. Conclusions

The results of our field tests are quite arbitrary, considering the resistance of restored soils against compaction in relation to their age after heaping. The deformation measurements show a decline of the displacements caused by the wheelings within a short time period, for both restorations. Interpreting these results, we have to consider that both soils had high sand content and were thus less susceptible to compaction than more fine-grained soils. In addition, the wheel loads and contact pressures were rather low, because we wanted to simulate usual management practices. The test vehicles were representative of the farming equipment in the region.

According to the soil parameters, the restoration of 2004 seems to be less susceptible to compaction than the restoration of 2002, although it is younger and supposed to have consolidated less. On the restoration of 2002, the wheelings caused a compaction that is assumed to affect soil fertility in the long-term, despite the low wheel loads and contact pressures. In addition, the analyses of the soil cores containing subsoil material (soil cores from beside the track on the restoration of 2002 at the end of the experiment) indicate critical compaction for this subsoil layer. The reason for these differences between the two restorations may lie in different soil moisture conditions at the time of heaping.

As our test results do not give a definite answer to the question of the development of mechanical resistance with increasing age of a restored soil, we recommend not shortening the period of extensive management after heaping in the sense of precautionary soil protection. We strongly recommend continuing research in this field. In particular, the relation between the soil conditions at restoration and the subsequent susceptibility to compaction needs deeper investigation. Further, the relations between soil displacement and soil physical parameters should be studied in depth. This may also serve to develop easy methods for farmers to evaluate the sustainability of their management practices (e.g. rut depth measurement). The progressing construction activity increasingly affects precious agricultural soils. The restoration of agricultural land will gain importance in the future, in order to maintain the resource for the production of food and renewable primary products.

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