

LONG-TERM EFFECTS OF DIFFERENT TILLAGE AND FIELD OPERATION REGIMES ON SOIL STRUCTURE.

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Abstract

Only little is known about the rate and extent of structural evolution under the combined influence of tillage and wheeling. Whereas some quantitative information on the regeneration of compacted soils is available, the course and potential of structure formation and recovery under the absence of wheel traffic – as made possible by Controlled Traffic Farming (CTF) systems using permanent traffic lanes – are not well investigated and understood. Therefore the effects of tillage practices and field traffic organization on soil structure were studied in a crop sequence under practical soil management conditions on a loamy orthic luvisol at Tänikon, Switzerland (1187 mm mean annual precipitation, 8.0 °C mean annual temperature).

From 2000 to 2008 the effect of no-till on soil structure evolution was studied on a formerly ploughed field and compared to continuously ploughed plots. Since 2008 the previous random field traffic organization was maintained in the ploughed and no-till plots, but changed to controlled traffic in plots formerly under shallow tillage and consecutively managed by no-till.

Soil structure evolution was described by repeated samplings of undisturbed soil cores in the top- (10-15 cm) and subsoil (35-40 cm) and subsequent analysis of porosity, permeability and strength characteristics in the lab. In situ measurements of parameters characterizing soil water regime (volumetric water content, matric potential) and the soil environment (O₂- and CO₂-concentrations in soil air, oxygen diffusion rate, redox potential) under field conditions were done quasi continuously at several soil depths.

Results show a slow evolution of structural properties in the subsoil and a limited structure formation in the absence of tillage measures in the topsoil. Soil structure evolution can be followed up in short-term cycles covering individual vegetation periods as well as in medium-term cycles covering crop rotation periods. In situ measurements of water retention characteristics and properties of soil environment revealed consistent but minor effects of field traffic organisation on processes depending on soil structure as well as on weather conditions.

Keywords

soil compaction, soil structure, soil tillage, field traffic, structure regeneration

Introduction

Soil structure is considered one of the key elements of soil quality, controlling many soil processes - thereby influencing many other soil properties - and defining exchange processes between soils and atmosphere, hydrosphere or biosphere. Direct effects of soil structure on processes mostly depend on the pore system characteristics and are affecting the water and air regime of a soil, changing transport and storage processes for water and air (1). Modified transport characteristics as a consequence of changes in soil structure influence the

availability of oxygen in the soil. Because soils are the habitat of an extreme diversity of organisms, reduced oxygen availability affects the environmental conditions for soil organisms: wherever metabolically possible, reduced oxygen availability leads to a replacement of aerobic respiration by anaerobic metabolic pathways based on alternative oxidizing substances like NO₃⁻, Mn(III, IV) or Fe(III) (2). The consequences are impaired soil processes (e.g. mineralization) and chemically reduced metabolites such as N₂, N₂O, Mn(II) or Fe(II) (3). These adaptations of metabolic pathways change the redox status of the soil environment, thereby for instance altering the chemical properties of nutrients and pollutants, which has consequences for their mobility, availability and toxicity (4,5).

The strength characteristics of a soil are on the one hand influencing the development of crop root systems, on the other hand they contribute to the preservation of favourable pore system properties against mechanical impacts. The latter is all the more important because - considering the degree of mechanisation of today's agriculture - mechanical impacts on soil structure ("soil compaction") may have serious consequences (6).

Soil structure characteristics are not constant over years, but are modified in different time scales. Whereas the compaction processes as a consequence of wheeling happens in very short time intervals (seconds; 7), regeneration and improvement of a soil structure take much more time: depending on the nature of these processes, the time scales may range from seconds (mechanical loosening) over months to years or even decades (natural alleviation processes, either climate-driven or biotic; 8). In agriculture, changes in soil structure are often discussed in conjunction with the process of soil compaction. The extent of soil structure deformation as the result of soil compaction by vehicle traffic or tillage measures was often analyzed (9), but only few studies address the rate and extent of the regeneration of compacted soil layers (1). Improving the sustainability of soil management by reducing compaction risks and systematically supporting natural regeneration processes for soil structure will facilitate the recovery of repeated soil structure degradations typical for highly mechanised soil management systems in humid regions. At the same time this strategy may give the opportunity

to really improve soil structure quality to an optimum state for given site and management conditions. Attempts to describe optimum values or threshold values for structural soil properties or soil functions depending on soil structure are rare, probably because this topic is conceptually not well developed and corresponding data are difficult to get in the required quality (10,11,12).

The aims of this study were (i) to describe the effects of soil tillage on long-term evolution of soil structure by comparing plough tillage to no-till, (ii) to test the effects of field traffic organisation on soil structure by comparing random with controlled traffic, and (iii) to assess these effects on soil structure by comparing different structural properties.

Materials and Methods

Study site and experimental design

In the autumn of 1999 the field experiment STABIO-T was installed at the Swiss Federal Research Station Tänikon, which is situated in the Northeastern part of Switzerland, 540 m above sea level (13). The soil of the experimental site is a deep orthic luvisol with a loamy texture and a considerable stone content (approx. 10 vol.% in the 0-90 cm depth range). Table 1 characterises the soil parameters, while Figure 1 shows annual mean temperatures and annual precipitations for the years 2000 to 2011 together with the long-term means for the period 1970-1991.

Table 1. Soil characteristics of the experimental site at Tänikon, Switzerland.

Depth	Clay % [w/w]	Silt % [w/w]	Sand % [w/w]	org. C. % [w/w]	pH [H ₂ O]
0 - 20 cm	22	35	43	1.6	6.6
30 - 50 cm	25	34	41	-	6.8

In the STABIO-T experiment the effects of several tillage systems on agronomic parameters were investigated during an experimental period of nine years in a randomized block design with three field repetitions ("blocks") as random factors. The experimental plots were 12 m wide and 30 m long. For the present study a closer look was taken at the effects of the two extreme

tillage systems "ploughing"(PL) and "no-till" (NT) on structural soil properties. The STABIO-T experiment started in 1999 on a field which had formerly been tilled in a conventional way by ploughing, therefore the no-till system had to be newly established on this soil as NT treatment. Ploughing was done to a depth of ca. 25 cm.

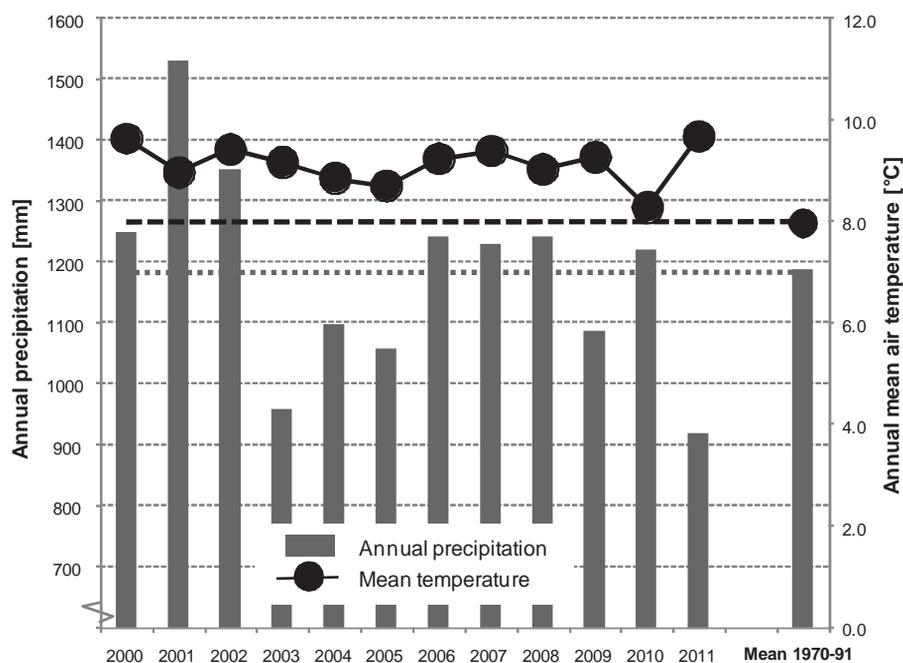


Figure 1. Annual precipitations and annual mean temperatures of the experimental site at Tänikon, Switzerland, for the period 2000 to 2011 and means for 1970-91.

In 2008 the CTF experiment (“Controlled Traffic Farming”) was established on the same experimental field as STABIO-T, making use of the existing experimental design of the STABIO-T experiment. The aim of the CTF experiment was to test the feasibility of a CTF version adapted to Swiss site and management conditions (14). The adaptation of the CTF treatment to Swiss conditions consisted in two aspects:

A working width typical for Swiss farms was chosen (4.5 m). This led to a traffic pattern with three typical traffic zones (Figure 2): the unwheeled zone (n), the moderately wheeled zone (m) and the intensively wheeled zone (i). According to the Swiss ordinance on impacts on soil all traffic lanes of a CTF design must be part of the productive soil surface and are therefore subject to soil protection measures. Because of that, the vehicles have to meet the requirements of physical soil protection and must e.g. be equipped with appropriate tyres.

Altogether, these two adaptations of the CTF treatment lead to a higher proportion of wheeled zones, especially moderately wheeled zones, as compared to conventional CTF solutions in Australia: intensive traffic is concentrated on less than 10% of the cultivated area, whereas more than approx. 60% of the cultivated area remains totally

unwheeled. The moderately wheeled traffic zone is owed to the concessions to (a) smaller working widths for tillage/seeding and harvesting operations and to (b) low pressure tyre equipment respecting the requirements of physical soil protection.

This adapted controlled traffic scheme was combined with no-till to the CTF treatment C and compared to random traffic combined with either ploughing (Pr) or no-till (Dr). In the CTF treatment, the three traffic zones were monitored separately as shown in Figure 2: unwheeled (Cn), moderately wheeled (Cm) and intensively wheeled (Ci). The definition of the soil management treatments in the new CTF experiment was adapted to the existing tillage treatments in the STABIO-T experiment, which offered the possibility to benefit from the established experimental layout: Pr followed the former PL treatment, Dr followed the former NT treatment. The CTF no-till treatment C, however, followed the shallow (10 cm) mulch seeding treatment of the STABIO-T experiment. Therefore, at least in the first few years of establishing the C treatments of the CTF experiment, direct comparisons between the no-till treatments Cn, Cm, Ci vs. Dr have to be interpreted with care.

The crop sequence from the beginning of the STABIO-T experiment in 2000 until the CTF experiment in 2011 is given in Table 2. Apart from tillage and field traffic organisation, management operations were done for all treatments in the same way and at the same time.

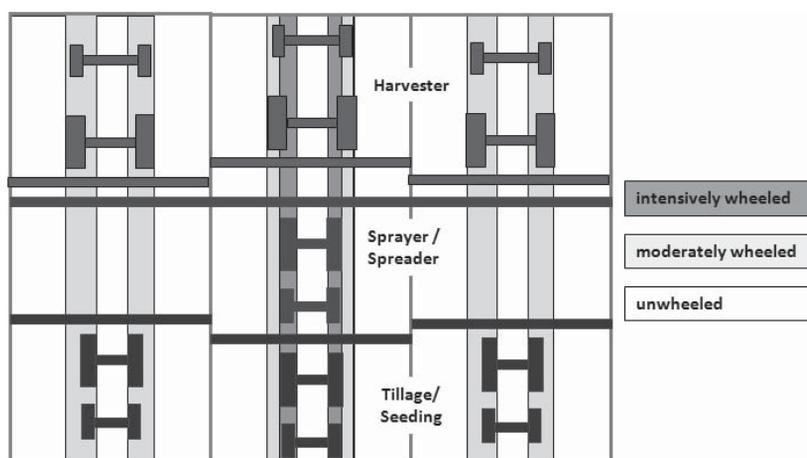


Figure 2. Traffic zones of the CTF main treatment C with different wheeling intensities: unwheeled (Cn), moderately wheeled (Cm: wheel tracks of tillage, seeding and harvesting) and intensively wheeled (Ci: wheel tracks of tillage, seeding, fertilizing, spraying and harvesting).

Table 2. Crop sequence from 2000 to 2011 in the STABIO-T and the following CTF experiment.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Crop ¹	WW+	SM	WW	WB	L	L	SM	WW	P	WW	WB	L

¹ WW = winter wheat; + = mustard as catch crop; SM = silage maize; WB = winter barley; L = ley; P = protein peas

In the PL and in the Pr treatment a two-furrow plough of 0.70 m working width and a 3 m rotary harrow seeding combination was used. In the NT treatment a 2.25 m and in the C treatment a 4.50 m no-till seed drill, respectively, was used. A combine harvester with a working width of 4.50 m and a tractor-driven mowing combination for forage harvest were used in all treatments (Table 3). The

vehicles used in these two experiments for the remaining field operations were the same for all treatments - only the field traffic *organisation* differed in the CTF treatment. In agreement with best practice in physical soil protection, all self-propelled vehicles were equipped with appropriate tyres, which were operated at the rated inflation pressure (Table 3).

Table 3. Vehicles, tyre equipment and tyre inflation pressures used in the CTF experiment.

Vehicle	Empty weight [kg]	Front axle		Rear axle	
		Tyre	Inflation pressure [kPa]	Tyre	Inflation pressure [kPa]
Same Dorado 75 (plough, cultivator)	3'950	360/70R20	80	420/70R30	80
John Deere 6920S (no-till seeder)	7'320	540/65R28	80	650/65R38	80
Fendt 411 (plough/seed drill)	5'770	420/70R24	80	460/85R34	80
John Deere 2254 (combine harvester)	12'900	800/65R32	100	540/65R24	120

Parameters and methods

During the STABIO-T experiment, undisturbed soil samples were taken in only one of the three field repetitions, and in the CTF experiment in two of them. In the first three experimental years (2000-02) structural properties were investigated every 3 to 4 months, and thereafter (from 2003 to 2011) only once a year in spring. This particular sampling period was chosen because in April and May soil structure has normally been equilibrated during winter. Provided soil moisture conditions were appropriate, 8 undisturbed cylindrical soil samples were taken at these sampling dates from the top- and the subsoil, (sample centre at 13 and 37 cm respectively), with sample dimensions (height x diameter) of 100 mm x 30 mm (from 2000 to 2008) and 100 mm x 60 mm (from 2009 to 2011), respectively.

Soil structure was characterized by parameters describing porosity (bulk density, total porosity, macropore volume), transport properties (air permeability) and stress-strain behaviour (loss of total pore volume at a given stress level). Bulk density was determined by weighing and measuring the height of the samples after saturation at maximum swelling, total pore volume was calculated based on bulk density and analyzed particle density. Macropore volume is defined here as air-filled pore volume at -60 hPa matric potential (pF 1.8). Air permeability was determined at -60 hPa matric potential by measuring the mass flow of air passing the sample vertically with an overpressure of 2 hPa.

Soil moisture of the sub-treatments Cn (unwheeled traffic zone) and Cm (moderately wheeled traffic zone) was characterized in situ by water content and matric potential at 10, 20 and 35 cm depth. Volumetric water content was measured since 2009, using two EnviroScan FDR sensors (Sentek; Stepney, Australia) per sub-treatment and field block. The EnviroScan FDR sensors belonging to one measuring site were installed in a vertical PVC tube and consisted of three modules, each of them measuring the volumetric water content at one soil depth. Matric potential was also measured since 2009, using three pF-Meter sensors (ecoTech; Bonn, Germany) per sub-treatment, depth and field block. These maintenance-free sensors have a measuring range from pF 0 to pF 7. Both sensor types for soil moisture measurements were attached to an automated logger network consisting of CR800 and CR1000 loggers (Campbell Scientific; Logan, USA), which was operated with a measuring frequency of 30 minutes.

In the sub-treatments Cn and Cm O₂- and CO₂- concentrations of soil air were measured 2009 in two, and from 2010 on in all three field repetitions ("blocks"). For this purpose, semi-permeable polypropylene tubes of 5.5 mm diameter and 50 cm length were permanently installed horizontally at 10, 20 and 35 cm soil depth in 4 repetitions perpendicular to the driving direction. Soil air was analysed directly in the field by pumping a small air sample out of a membrane tube and analysing it by using a Checkmate 9900 (PBI Dansensor; Ringsted, Denmark). These manually operated measurements were normally done once per week during the whole vegetation period.

Results and Discussion

The more intensive monitoring at the beginning of the STABIO-T experiment revealed typical short-term cycles of structural evolution during a vegetation period, which was best observable in the PL treatment (Figure 3). The macropore volume was always highest at the beginning of the crop growth periods immediately after intensive tillage, thereafter it decreased during the vegetation periods, and reached its lowest values after crop harvests and the associated mechanical impacts (cf. silage maize harvest in 2001). In these short-term cycles the amplitude of topsoil macropore volume was particularly pronounced in the PL treatment and considerably smaller in the newly adopted NT treatment. In contrast to PL which increased regularly the macropore volume by mechanical loosening, the abandoning of mechanical tillage measures and the exclusive relying on natural processes for structural recovery in NT reduced amplitude and magnitude of the macropore volume considerably.

The yearly samplings of soil structure in an equilibrated state in spring, typical for the main growing period of the crops, made a medium-term cycle of structural evolution observable. This equilibrated state of soil structure is assumed to be the characteristic result of the structure forming processes of mainly the preceding vegetation period, thus integrating the effects of mechanical loosening, compaction by wheeling and natural regeneration processes during the vegetation period of the preceding crop.

Based on macropore volume data the evolution of soil structure could not clearly be assigned to the cultivation of specific crops: Although maize in 2001 and winter

barley in 2010 resulted in losses of macropore volume in the topsoils of both tillage systems, macropore volume increased in the same crops in 2006 and 2003, respectively. These observations may suggest that the interactions between soil moisture (or weather conditions) and soil management practices are deciding for all structure forming processes. The evolution of macropore volume in ley was in both tillage systems favourable if considering the effect of the second ley year only. During the establishment of ley in the first year,

however, macropore volume deteriorated considerably, especially in the plough treatment.

Looking at the course of macropore volume in the medium-term cycle, the direction of macropore volume evolution (increase or decrease) was principally the same in both tillage systems, suggesting that natural regeneration processes are determining the general direction of structural evolution, whereas mechanic loosening and compaction by wheeling are modulating the general trend.

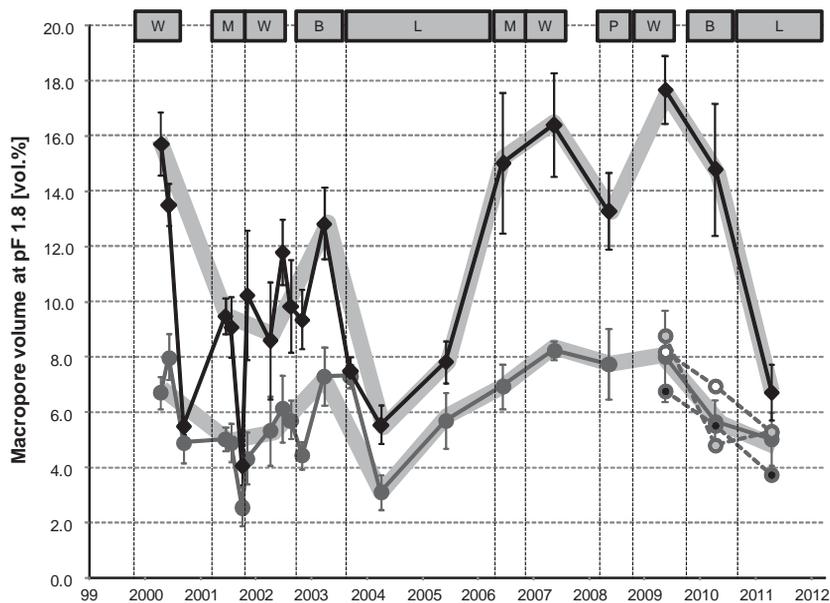


Figure 3. Macropore volume of topsoil (13 cm depth) in the experimental period 2000 to 2011, indicated as median values of 8 or 16 single values (STABIO-T or CTF experiment, respectively) with quartile ranges.

Thin lines: short-term cycle ("vegetation period cycle"; 2000-2002), thick lines: medium-term cycle ("crop sequence cycle"; 2000-2011). Abbreviations for crop sequence: see Table 2.

In the CTF experiment the course of macropore volume in the two tillage treatments with random traffic fell in line with the previous evolution in the STABIO-T experiment. This was not surprising, since both treatments were managed as before and on the same plots. However, as soon as ploughing was replaced by non-inverting tillage in the first year of ley in 2011, the macropore volume of the plough treatment Pr dropped and approached that of the no-till treatment Dr. This effect was similar to that in 2004, suggesting that the structural stability of the soil was rather low.

The newly introduced field traffic organisation in the CTF no-till treatment C appeared to have only a small effect

on the structural evolution during the first three years of the CTF experiment: whereas the sub-treatments Cm and Dr did not differ at all, only slight indications of an improved macropore volume in Cn (unwheeled) and of a deterioration in Ci (intensively wheeled) could be observed (Figure 3).

Using field data of soil moisture measurements in the CTF experiment, small differences in macropore volume between the CTF sub-treatments Cn and Cm could be demonstrated by plotting a water retention curve using the measured volumetric water content and matric potential data (Figure 4). The estimated values for macropore volume confirm the results of the desorption measurements using undisturbed samples and suggest that the differences in macropore volume between the two differently wheeled zones can mainly be attributed to differences in large macropores.

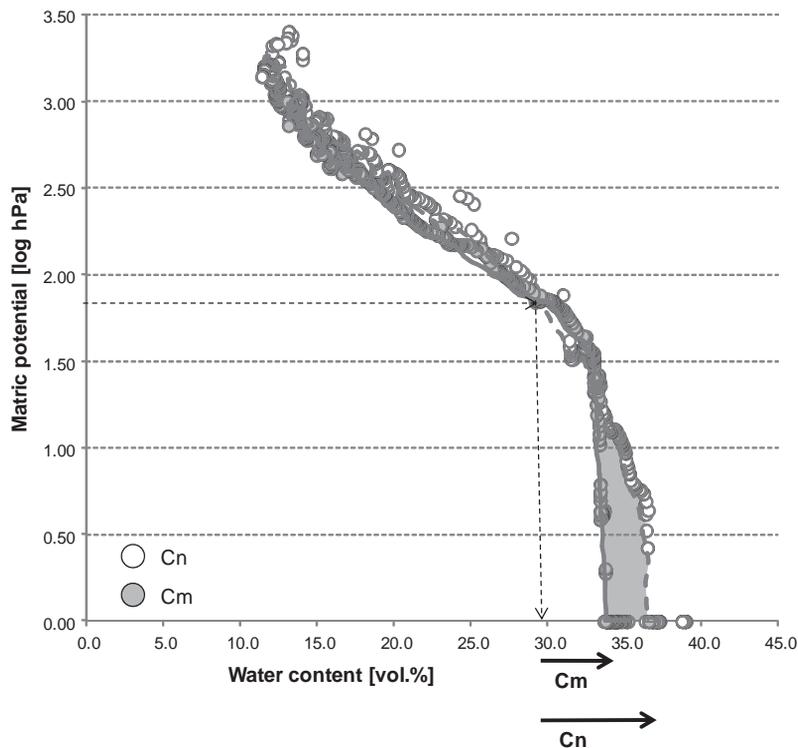


Figure 4. Water retention curves of the CTF sub-treatments Cn and Cm using field data for volumetric water content and matric potential measured at 10 cm depth in winter barley 2010. Time interval was from June 19 to July 6 2010. Values correspond to medians of 6 (volumetric water content) and 9 (matric potential) single values, measured in all of the three field repetitions. Curves are moving averages based on 10 data points. Black arrows are representing estimates for macropore volume at pF 1.8 based on the water retention curves for the two sub-treatments Cn and Cm.

Air permeability at -60 hPa of the topsoil generally confirmed the results of treatment effects on macropore volume (Figure 5). In the short-term cycle during one vegetation period, air permeability values especially indicated losses in permeability due to mechanical impacts (e.g. during harvest operations). In both the short-term and the medium-term cycles, the air permeability values of the two tillage treatments showed clearly different magnitudes. The sub-treatments Cn, Cm and Ci of the controlled traffic treatment C did not differ significantly with reference to air permeability, but median values were arranged according to the expected order of impact on soil structure in these traffic zones, with lowest values in the intensively wheeled Ci traffic zone.

In the CTF experiment soil aeration was investigated in the sub-treatments Cn and Cm using O_2 -concentration in soil air as indicator. The O_2 -concentrations in Cm tended to be lower than in Cn. The differences in O_2 -concentrations between Cn and Cm during the vegetation period 2010 (Figure 6) demonstrate, that in the first half of the vegetation period (under winter barley) the O_2 -concentrations were only temporarily lower in Cm than in Cn. However, in the second half of the vegetation period (under the growing ley) the O_2 -concentrations were generally lower in Cm than in Cn, predominantly in the top 20 cm. This difference between the traffic zones Cn and Cm was even more pronounced in the last weeks of the vegetation period.

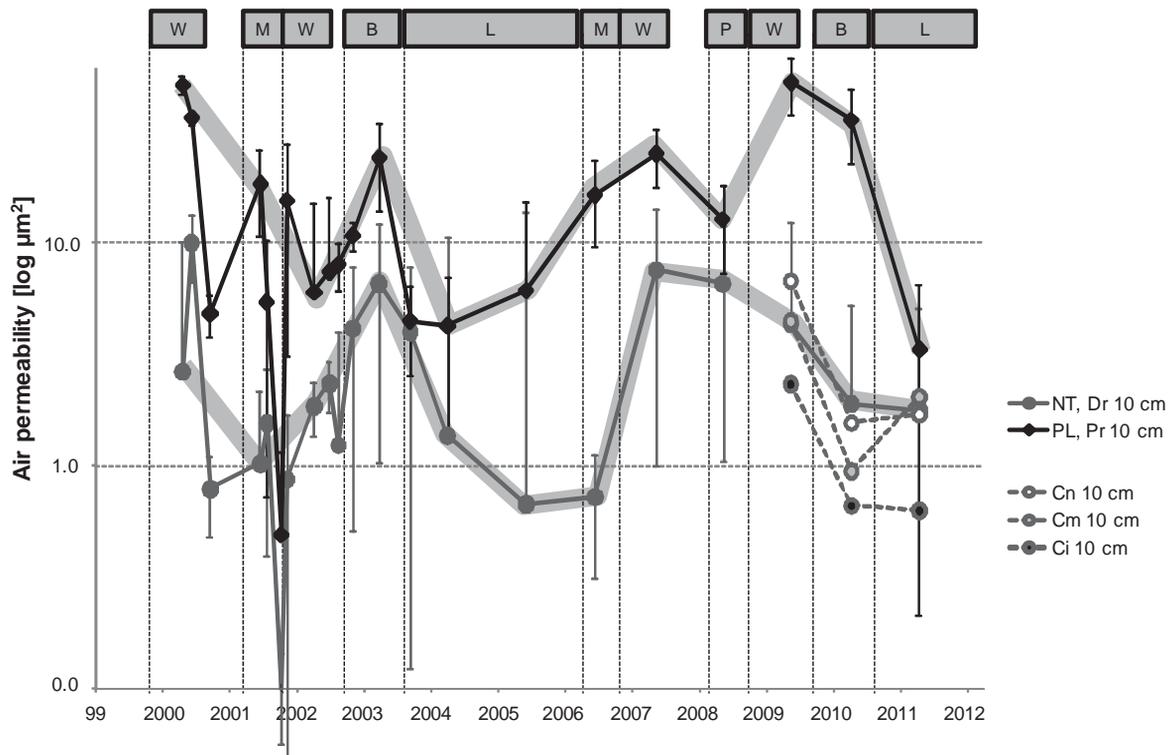


Figure 5. Air permeability of the topsoil (13 cm depth) at pF 1.8 in the experimental period 2000 to 2011, indicated as median values of 8 or 16 single values (STABIO-T or CTF experiment, respectively) with quartile ranges.

Thin lines: short-term cycle ("vegetation period cycle"; 2000-2002), thick lines: medium-term cycle ("crop sequence cycle"; 2000-2011). Abbreviations for crop sequence: see Table 2.

Conclusions

The monitoring of structural properties demonstrated that soil structure evolved in at least two different cycles: The short-term cycle over one vegetation period was particularly reflecting immediate impacts of mechanical loosening and wheeling on soil structure and is substantially depending on the prevailing weather conditions.

The medium-term cycle over a crop sequence of several years is integrating the effects of all the mechanical and natural processes shaping structure formation during a vegetation period and characterizes the mid-term evolution of soil structure.

In the plough tillage system compacted topsoil zones can be loosened mechanically as long as soil moisture is in a favourable range. The mechanical loosening of compacted soil structures and the compaction of the loosened soil by the impact of heavy vehicles is leading to high amplitudes and magnitudes of structural

topsoil parameters in both the short- and medium-term cycles of structure evolution. Maintaining a generally loose soil structure during the main crop growth period necessitates high tillage efforts after compaction events. The no-till system on the other hand relies on natural regenerative processes and a higher topsoil resistance against mechanical impacts through increased structural stability. These characteristics are resulting in a narrow bandwidth of structural topsoil parameters and in a generally more compact soil structure, which may be functionally comparable to a more loose soil structure, but perhaps is associated with higher risks for crop development in extreme (wet) weather situations.

Considering the limitations of structural evolution in a no-till system with missing possibilities for mechanical loosening after heavy compaction events, the question was raised whether it would be possible to sustainably increase the quality of soil structure by introducing a controlled field traffic organisation. It was hypothesized

that the totally unwheeled traffic zone of a CTF scheme should offer the best conditions for structural improvement. The results of the CTF experiment after three years showed, that (a) the hypothesized differing effects of the three CTF traffic zones Cn (unwheeled), Cm (moderately wheeled) and Ci (intensively wheeled) on soil structure could be measured in the topsoil and were principally meeting the expectations, but (b) that the differences between the effects of the traffic zones were small and of minor importance compared to the differences induced by the different tillage systems.

The reasons for this are not fully clear yet. One reason is probably the chosen adaptation of the CTF treatment to Swiss site and management conditions: because vehicles driving on the traffic lanes have to meet the requirements of physical soil protection, they have been equipped with wide tyres. As a consequence their impact on the soil structure of the moderately wheeled traffic zone Cm was much less pronounced as it would have been with small tyres typically used in CTF traffic lanes. Another reason could be the structure forming potential of the soil at the experimental site, which may be unusually restricted. Further work is necessary to methodologically describe the structure forming potential of a soil and to characterize typical agricultural soils accordingly.

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