*__ORAL PRESENTATION__*

# Soil moisture suction in no-till and tilled soils: analyzing long-term tensiometer measurements in the Swiss Central Plateau

D.S. Lehmann[1], A. Chervet[2], H. Liniger[1,3], V. Prasuhn[4], C. Ifejika Speranza[1,3], W.G. Sturny[2]

1. Institute of Geography, University of Bern, Hallerstrasse 12, 3012 Bern
2. Soil Conservation Office of the Canton Bern, Rütti 5, 3052 Zollikofen
3. Center for Development and Environment, University of Bern, Mittelstrasse 43, 3012 Bern
4. Agroscope, Reckenholzstrasse 191, 8046 Zürich

Corresponding author: daria.lehmann@outlook.de

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## ABSTRACT

Fertile soils are crucial for human well-being, yet the intensification of agriculture and use of heavy machines increasingly threatens their quality. Agricultural practices with heavy machines expose soils to a high risk of irreversible subsoil compaction. Research has shown that from a sustainable land management perspective, soils should not be trafficked with heavy machines when soil conditions are wet (soil moisture suction <6 cbar at a soil depth of 35 cm). However, there is a lack of knowledge about the frequencies of wet soil conditions in Swiss agricultural soils and about potential influences of soil management systems on soil moisture. This study aims at closing these research gaps by analyzing the long-term (1996–2019) dataset of the Canton Bern including 13 different locations on six sites in the Swiss Central Plateau. Soil moisture suction data measured with five tensiometers per location at a soil depth of 35 cm and precipitation sums per site for three measurement days (md) per week are used. On every site, at least one permanent grassland and one crop rotation location are present. Furthermore, two tillage systems (no-till and mouldboard plough) and 11 different crops occur in the dataset. After data correction and validation, 22'947 md with available soil moisture suction data are analyzed. To put the results into a larger context, spade tests are performed at every location, and a climate and weather characterization of the years 1996–2019 is undertaken. Periods with wet soil conditions (<6 cbar at 35 cm soil depth) during the vegetation period from April to October range from 41 to 48% of the md for different locations (average over all sites), while site-specific differences range from 31 to 76% on permanent grassland locations. The duration of wet soil conditions can exceed three months in extreme cases. Furthermore, a seasonal curve in soil moisture suction is found and influences of the longer-term (≥3 months) weather conditions, as well as of single precipitation events on soil moisture suction fluxes are apparent. Differences in soil moisture suction fluxes are big between different sites and years: comparing a specific md over different sites and years shows that soil moisture suction values can cover the whole measurable range between 0 and 80 cbar. While the seasonal curve and the annual fluctuations likely originate from climate and weather influences, the differences between the sites can not be attributed to a specific influence factor. Differences between permanent grassland and crop rotation locations can mostly be attributed to different crops' seasonal evapotranspiration rates. Other systematic differences which hold for all sites and years can not be identified. Differences between no-till and mouldboard plough are present, but non-systematic based on the analysis on one site. The spade tests show that tillage systems impact physical soil properties. In conclusion, the results point to a highly complex human-climate-soil-system. This study lays a valuable basis for future research, among others, by providing concrete recommendations for future study designs. Further research about soil moisture suction is needed to promote sustainable land management in Switzerland.

## 1. INTRODUCTION

Soil moisture data is of great interest in various fields of research. In agronomy, it influences plant growth and is also crucial for predicting soil trafficability and workability (Bell, K. R.; Hamza, M. A.; Batey, T.; Dobriyal, P.; Obour, P. B.). To prevent subsoil compaction, heavy machines should not be used if the so-called "wheel load carrying capacity" (WLCC) of the soil is exceeded by the real wheel load of a machine. As the WLCC decreases with the increase of water-filled pores in the soil, soil moisture is directly linked to the risk of subsoil compaction (Soane, B. D.; Kondo, M.; Batey, T.; Stettler, M.; Gut, S.).

Various measurement technologies are available for soil moisture. Using tensiometers has a long tradition (Richards, L. A.; Or, D.) and multiple advantages (cf. Lekshmi, S. U.), while the measuring range is restricted by the saturation vapor pressure (limits are 0 to about -80 kPa). Tensiometers measure soil moisture suction (SMS) which characterizes the binding of soil moisture to the soil matric (Schmugge, T. J.; Seneviratne, S. I.) and is defined as the absolute value of the soil matric potential. It is impacted by soil properties, vegetation, land management, topography and weather conditions (Quiroga, A. R.; Chervet, A.; Mittelbach, H.; Zhu, Q.; Gut, S.; Prasuhn, V.; Durner, W.; Dong, J.), hence it shows a hardly predictable spatio-temporal variability (Dobriyal, P.; Mittelbach, H.; Zhu, Q.; Hu, W.; Vereecken, H.). Long-term measurements allow to address this challenge (Bell, K. R.; Mittelbach, H.).

From 1996-2019, the Soil Conservation Office of the Canton Bern (SCOB) collected SMS data measured with tensiometers on agricultural fields, resulting in a unique dataset. By analyzing it, this study aims to compare SMS in Swiss agricultural soils (a) under different farming practices (permanent grassland (PG) vs. crop rotation (CR)), (b) under different tillage systems (no-till (NT) vs. mouldboard plough (MP)) and (c) under different crops. It provides insights into the frequency and seasonality of wet soil conditions (and the associated risk of irreversible subsoil compaction) in dependence on soil management.

## 2. MATERIALS AND METHODS

The six sites Grasswil, Langnau, Oberacker, Rubigen, Schlosswil and Treiten are all situated in the Swiss Central Plateau. This region is in a transition zone between humid oceanic climate and continental temperate climate. Table 1 provides an overview of sites' properties and years with available SMS data. At least one PG and one CR location are present per site. The tillage system NT was applied only in Rubigen and Oberacker, while MP was applied on all sites except Rubigen. Oberacker is the only site with two CR locations. Mean annual precipitation is highest in Langnau (1438 mm) and lowest in Treiten (1023 mm) (SCOB).

Table 1 The six sites' locations, general properties and years with available data (T = temperature) (own analyses and SCOB; Chervet, A.; Cantons Solothurn Aargau, and Basel-Landschaft; FOMC).

| **Site** | **Locations** | **Soil Type** | **Water Influence** | **Slope, Exposition** | **Altitude [m a.s.l.]** | **1981–2010 March to Oct T [ °C]** | **Years with Data** |
|---|---|---|---|---|---|---|---|
| Grasswil | PG, CR-MP | Cambisol | slope water | PG: 3% E<br>CR: 6% E | 522 | 12.6 | 1997–2017 |
| Langnau | PG, CR-MP | Cambisol | ground-water | PG: 0%, flat<br>CR: 0%, flat | 654 | 11.5 | 1996–2017 |
| Ober-acker | PG, CR-MP, CR-NT | Cambisol | none | PG and CR: mostly 0% and flat | 555 | 12.6 | 1996–2019 |
| Rubigen | PG, CR-NT | Cambisol | none | PG: 4% SW<br>CR: 6% SW | 554 | 12.6 | 1996–2017 |
| Schloss-wil | PG, CR-MP | Cambisol | slope water | PG: 4% NW<br>CR: 4% SW | 742 | 11.5 | 1996–2016 |
| Treiten | PG, CR-MP | Fluvisol | ground-water | PG: 0%, flat<br>CR: 0%, flat | 434 | 13.8 | 1996–2006<br>2011–2017 |

SMS was measured with 5 "standard tensiometers" (Eijkelkamp Soil and Water) per location at a soil depth of 35 cm. Measurements were performed trice a week (Mon, Wed, Fri); in the same temporal resolution, precipitation sums per site were assessed using a Hellman rain gauge. Documentation about farming practices, agricultural activities (ploughing, seeding, harvesting, mowing, mulching and cattle pasture), tillage systems and crops is available. All locations were managed according to standards for proof of ecological performance (FOAG). In Oberacker, collaborators of the SCOB collected the data; on all other sites, farmers were responsible therefor. In Oberacker, the tensiometers were moved on the CR so that they were always placed where winter wheat was cultivated. This made it possible to measure SMS over multiple years for the same crop (on all other sites, this is not the case). In total, 11 different crops are present in the dataset (unequally distributed in the dataset).

The dataset was reduced to the vegetation period from 1st April to 31st October to focus on crops' growing seasons and on periods of agricultural activities. Tensiometer measurements were qualitatively validated with intersubjective validation; implausible values were deleted.

To provide a framework for the correct interpretation of SMS data, site- and soil-specific properties, as well as climate and weather conditions were assessed. A spade test (spade length: 45 cm) was taken per location (Hasinger, G.). Climate and weather conditions were characterized using the homogenized precipitation and temperature data series at the meteo station "Bern/Zollikofen" (FOMC).

Only the median SMS per measurement day (md) was considered. This "median" can consist of either 1, 2, 3, 4, or 5 single tensiometer measurements, whereas the occurrence of medians based on only one or two measurement(s) is rare (0.1% and 1.2%

of all md). These medians are referred to as “SMS values” and were divided into four categories (FOEN):

- <6 cbar: wet soil conditions; high risk of irreversible subsoil compaction (Wyler, R.)
- 6–10 cbar: very moist soil conditions; malleable soil
- 11–25 cbar: moist soil conditions; brittle soil
- >25 cbar: dry soil conditions; firm soil; low risk of irreversible subsoil compaction

In total, the dataset consists of 24’310 md, of which 1’363 (or 5.6%) are data gaps. Thus, there is a total of 22’947 md with an available SMS value. A frequently used data subset for analysis consists only of the years 2001–2006 and 2011–2016, in which data is available on all sites (“common years”). The common years have 12’475 md with an available SMS value.

# 3. RESULTS

## 3.1.Site- and soil-specific properties

The spade tests (cf. Fig. 1 for Oberacker) reveal big differences between the sites and the locations on one site. In Oberacker, the soil under MP shows iron concretions (ca. 30-45 cm soil depth). Very few iron concretions are visible at this depth in the soil under NT, and none in the PG. Soil color and other physical soil properties differ between the three locations, too.

Fig. 1 Spade tests for CR-NT (left), CR-MP (center) and PG (right) in Oberacker.

## 3.2. Climate and weather characterization

Fig. 2 shows the precipitation and temperature anomalies for March to October for all analyzed 24 years compared to the norm 1981-2010. Comparing the two halves in common years (2001-2006 vs. 2011-2016) reveals that a precipitation surplus of +308.8 mm was reached in the first half, while precipitation was deficient with -556.1 mm in the second half as compared to the long-term average 1981-2010.

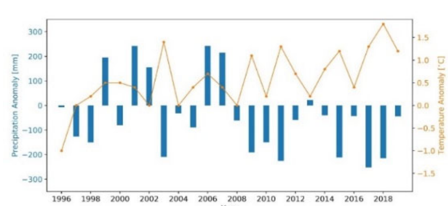


Fig. 2 March to October precipitation and temperature anomalies relative to the norm 1981-2010 for the meteo station "Bern/Zollikofen” of the FOMC. Norm values: 12.6 °C and 793.8 mm.

## 3.3. Wet soil conditions

Wet soil conditions occur on 41% to 48% of the md for different locations (average over all sites), while site-specific differences range from 31% to 76% on PG locations and from 34% to 69% on CR locations with Schlosswil being the wettest and Oberacker the driest site (see Table 2). Wet soil conditions are less frequent (45% compared to 49%) in the first than in the second half of common years (average over all sites on PG locations).

Table 2 Relative frequencies of soil moisture suction values in the defined categories for different data subsets (n: number of measurement days with an available soil moisture suction value) in common years.

| Data Subset | Sites | n | Wet (<6 cbar) | Very Moist (6-10 cbar) | Moist (11-25 cbar) | Dry (>25 cbar) |
|---|---|---|---|---|---|---|
| PG | Grasswil | 1’035 | 41% | 23% | 15% | 21% |
| | Langnau | 1’052 | 55% | 17% | 16% | 12% |
| | Oberacker | 1’087 | 31% | 18% | 11% | 40% |
| | Rubigen | 1’077 | 39% | 21% | 17% | 24% |
| | Schlosswil | 983 | 76% | 9% | 9% | 6% |
| | Treiten | 1’061 | 43% | 11% | 11% | 35% |
| | All Sites | 6’295 | 47% | 17% | 13% | 23% |
| CR-MP | Grasswil | 1’001 | 43% | 13% | 12% | 33% |
| | Langnau | 1’007 | 54% | 20% | 16% | 10% |
| | Oberacker | 1’082 | 35% | 14% | 14% | 37% |
| | Schlosswil | 948 | 69% | 10% | 9% | 13% |
| | Treiten | 989 | 42% | 9% | 11% | 38% |
| | All Sites | 5’027 | 48% | 13% | 12% | 27% |
| CR-NT | Oberacker | 1’084 | 34% | 18% | 14% | 35% |
| | Rubigen | 1’069 | 48% | 17% | 15% | 21% |
| | All Sites | 2’153 | 41% | 17% | 14% | 28% |

The maximum duration of wet soil conditions is 44 md (= ca. 102 days) (PG location in Grasswil 2007). In common years on PG locations, the average duration of periods with wet soil conditions is 5.4 md (= between 12 and 13 days). Relative frequencies of SMS values in the category “wet” (for PG locations in common years) show a seasonal curve: Soils are wet more often in April, May and October than in June, July, and August.

### 3.3.1. Influence of farming practices

The SMS fluxes and precipitation sums presented in Fig. 3, as well as similar plots for other years, suggest that differences between farming practices on one site are mostly smaller than between different sites.

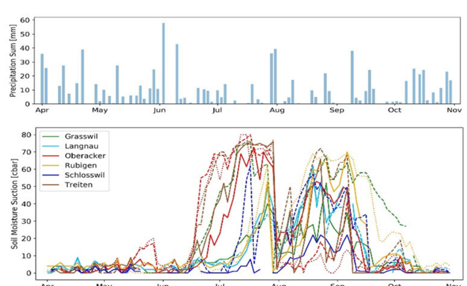


Fig. 3 Average precipitation sums and SMS fluxes 2013. Line: PG, dashed line: CR-MP, dotted line: CR-NT.

There is a difference in SMS fluxes between PG and CR in Oberacker (cf. Fig. 4): the PG location is wetter from June to mid-July, while it is drier from August to November.

Yearly SMS fluxes show that absolute differences between the farming practices mostly lie between 0 and ca. 30 cbar; in extreme cases, differences of up to 70 cbar are possible.

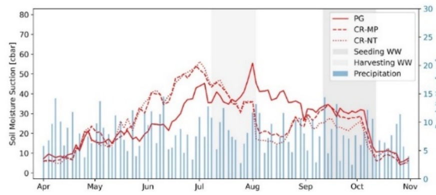


Fig. 4 Average SMS fluxes and precipitation sums for Oberacker in common years (WW= winter wheat).

### 3.3.2. Influence of tillage systems

The only possibility for a comparison of MP and NT on the same site is Oberacker. Fig. 4 shows that the average absolute difference between MP and NT is smaller than between PG and CR. From April to July, almost no difference between MP and NT is visible, while small (<10 cbar) absolute differences become apparent in August and September. Meanwhile, Fig. 3 reveals that absolute differences in SMS between MP and NT can be >10 cbar for single years. They occur in both directions, meaning that MP is sometimes wetter and sometimes drier than NT. However, a systematic pattern is lacking.

### 3.3.3. Influence of crops

Due to the big differences in SMS fluxes between sites and years, comparing different crops on the same site and in the same year would be advantageous. However, the dataset does not allow therefor. Comparing SMS of a specific crop (on different sites and in different years) with SMS of the PG on the same site in the same year reveals systematic patterns, like, e.g., a change in the direction of differences around mid-June or in the beginning of July for 4/5 examples of sugar beets in common years (higher SMS of sugar beets before the changing point, but lower SMS of sugar beets after the changing point compared to PG).

## 4. DISCUSSION

### 4.1. Wet and dry soil conditions

SMS values in the category “wet” (<6 cbar at a soil depth of 35 cm) occur on 31%-76% of the md on PG locations and on 34%-69% of the md on CR locations in common years. They are also frequent in years with precipitation sums below the average of 1981-2010. This could be challenging in agricultural production. However, SMS is not the only factor determining the WLCC of soils. Further physical soil properties (e.g., bulk density or further physical soil structure attributes) are also expected to be crucial (HAFL; Marbot, B.; Stettler, M.).

SMS at 35 cm soil depth follows a seasonal curve – a result which is in line with other studies (e.g. Wu, W.; Wyler, R.; Gut, S.; Lee, E.). The analysis of yearly SMS fluxes shows a direct impact of precipitation sums ≥30 mm on SMS, as well as of longer-term (≥ 3 months) weather conditions. Comparing a specific md over different sites and years shows that SMS values can cover the whole measurable range between 0 and 80 cbar. The big annual differences in SMS are in line with results from similar research (Wyler, R.; Gut, S.; Prasuhn, V.).

The differences between sites could be caused by local climatic and weather influences. However, based on the temperature and precipitation data per site (cf. chapter 2), one would expect Treiten to be the site with lowest frequencies of wet soil conditions, while the opposite would be true for Langnau – neither of these expectations were confirmed. A possible reason could be the influence of slope water on the PG location in Schlosswil leading to more frequent wet soil conditions than in Langnau. Topography and microrelief also influence soil moisture (Seibert, J.; Lee, E.), and the analysis of annual SMS fluxes in Treiten hints at such influence of microrelief: SMS rises very fast in dry periods in Treiten compared to the other sites, while at the same time, it stays at 0 cbar longer in rainy periods. A small soil volume with plant available water above a layer with low permeability could explain these properties and why Treiten is not the site with the lowest frequency of wet soil conditions, as suggested by precipitation and temperature data. Differing physical soil properties can be another reason for differences in SMS fluxes between the sites (e.g., English, N. B.; Chervet, A.; Dong, J.; Martínez-Fernández, J.).

#### 4.1.1. Influence of farming practices

Relative frequencies of wet and dry soil conditions in common years do not reveal a farming-practice-specific pattern valid for all sites. SMS fluxes in Oberacker (cf. Fig. 4) reveal seasonal differences between CR and PG, while similar plots for other sites show distinct patterns. In Oberacker, the seasonal pattern of differences in SMS fluxes can be explained by higher ET rates of winter wheat compared to PG from May to mid-July (Gut, S.). The point at which the CR locations in Oberacker are no longer drier than the PG location coincides with the harvesting dates of winter wheat. A similar pattern can also be seen in annual SMS fluxes in Oberacker and on other sites: in 12/14 years in common years with cereals on the CR location, a systematic difference between PG and CR can be identified.

In general, if SMS fluxes are analyzed for every year and site separately, most of them can be explained considering various interacting factors: precipitation distribution, applied farming practices and tillage systems, cultivated crops and/or site-specific characteristics.

#### 4.1.2. Influence of tillage systems

The relative frequency of wet soil conditions in Oberacker is almost equal (difference of 1%) on the NT and on the MP soil. Also, the average SMS fluxes in Oberacker show almost no difference between the tillage systems from April to July. SMS is slightly (around 5 cbar) lower on the NT than on the MP soil, only after harvesting winter wheat. This could be explained by higher evaporation on the MP soil through the partly uncovered soil after ploughing. However, this pattern is not visible in annual SMS fluxes. Generally, tensiometers were removed from the fields during the harvest of winter wheat and reinserted thereafter, whereby wet soil was applied around the measurement instrument to ensure a good contact to the soil. This process could explain the non-existence of systematic patterns, as the applied wet soil was not standardized for all locations.

Yearly SMS fluxes show partly big differences (up to ca. 60 cbar in extreme cases) between the tillage systems. However, no systematic pattern can be found over all the years. In general, differences in SMS between the tillage systems often lie between 0 and 5 cbar.

The spade tests show a clear difference between NT and MP. Rooting density is higher in NT than in MP. This is likely caused by soil compaction due to ploughing in MP. Iron concretions are present in MP from a soil depth of ca. 30-45 cm, which points to more frequent anoxic conditions, although wet soil conditions were found to be almost equally frequent under both tillage systems. Perhaps, the selected category for “wet soil conditions” (<6 cbar) is not sufficiently detailed: 0 cbar points to anoxic conditions, while 1-5 cbar do not necessarily indicate anoxic conditions. Thus, while NT and MP might both be categorized as “wet”, anoxic conditions could only occur on the MP soil. As this study proves that physical soil properties differ between the tillage systems, the WLCC of the two compared soils is expected to be different, too (cf. chapter 4.1.).

#### 4.1.3. Influence of crops

SMS is influenced by ET (Eagleson, P. S.). ET rates are crop-specific and change during the different stages of seasonal plant growth (e.g., Allan, R. G.; Prasuhn, V.), hence, crop-specific differences in SMS could be expected. From an agronomic perspective, it makes sense that sugar beets have lower ET rates than the PG until ca. mid-June, but then gradually increase their ET until September (Prasuhn, V.). For other crops, systematic patterns are visible, too, but some uncertainties in interpretation remain. Three main problems complicate the interpretation of annual SMS fluxes: (a) it is unclear if animals grazed directly around the tensiometers or only further away, (b) it is unclear if mowing was performed directly around the tensiometers or only further away and (c) it is unclear during which agricultural activities tensiometers were removed.

### 4.2. Limitations

There are limitations to this study’s findings. First, only SMS at a soil depth of 35 cm was analyzed. Second, the six analyzed sites in the Swiss Central Plateau are not sufficient to fully represent agricultural soils in Switzerland. Third, all analyzed locations were managed according to standards for proof of ecological performance (cf. FOAG). Results might differ for locations managed according to different agronomic standards such as organic production. Finally, the analyses only include the vegetation period from April to October.

## 5. CONCLUSIONS AND OUTLOOK

The analysis of the long-term dataset of the SCOB reveals that md with SMS values <6 cbar at 35 cm soil depth are frequent. However, the WLCC of soils is not only dependent on SMS. Thus, this study’s results do not suffice for an assessment of the WLCC of soils. A seasonal curve in SMS values is visible, which can be attributed to monthly norm precipitations and temperatures. In general, differences in seasonal SMS are big between different sites and years: comparing a specific md over different sites and years shows that SMS values can cover the whole measurable range between 0 and 80 cbar. Differences between farming practices are small and can mostly be attributed to different crops' ET rates. While seasonal SMS fluxes and physical soil properties differ between the two tillage systems in Oberacker, no reliable systematic pattern could be found. It is possible that additional data on the removal and reinsertion of the tensiometers might reveal further insights. Comparing crops' seasonal soil moisture fluxes to the PG location at the same site in the same year shows crop-specific patterns, but some uncertainties in interpretation remain.

The results based on the analysis of the dataset of the SCOB allow to give general recommendations for future studies: long term-research should be fostered, temperature and precipitation data should be collected at every site, crops' SMS should be compared in the same year on the same site and details about tensiometers' maintenance should be provided. Three especially interesting approaches for future research going beyond the performed analyses can be highlighted: Model water balances in agricultural soils along the profile, model crop water use, improve calculation of the WLCC.

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