

Original Research

Variability of Selected Physical and Mechanical Properties of Soil in Alfalfa Crop Production

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Abstract

In recent years, studies have focused on monitoring soil compaction caused by agriculture. The aim of the research presented in this article was to examine the impact of forage cultivation (organic farming) on soil properties. Field measurements focused on monitoring the variability of soil moisture content (SMC) and penetrometric resistance (PR) during alfalfa cultivation across 3 soil horizons. The study area was a 47.64-hectare plot (Oponice, Slovak Republic) with a total of 21 monitoring points (MP). Standardized methodologies and measurement techniques were used to monitor soil properties (WET sensor with HH2 logger, Eikelkamp penetrometer). Statistical evaluation of the results was performed using descriptive statistics, one-way ANOVA, deterministic spline interpolation (ArcGIS 10.0), and cluster analysis (Orange). The results for soil moisture content indicate significant changes in variability (horizons, dates). The coefficient of variation (CV) values for soil moisture content ranged from 8.47% to 23.12%. A significant depth dependence of the measurements was observed (pilot measurements: $P < 0.05$, $F = 7.51$). An examination of the relationship between individual measurement periods showed that in selected horizons they were dependent (SMC01→SMC02, 0-20 cm, 21-40 cm; SMC02→SMC03, all horizons) and in the others they were independent (SMC01→SMC02, 41-60 cm). The average PR values showed the lowest heterogeneity in the deep soil horizon (CV: PR01, 59.81→16.52%; PR02, 41.97→31.25%; PR03, 38.86→21.22%). Comparisons of measured penetrometer resistance values between irrigated and non-irrigated areas or between different measurement dates showed weak to strong correlations (0.02-0.87; 1.68 to 2.72 MPa). The obtained results were also subjected to deterministic and cluster analyses of penetrometric resistance, with the results indicating significance among the measurements. The results obtained from soil moisture monitoring indicate that soil moisture levels are balanced, but there are negative effects on soil compaction.

Keywords: alfalfa, soil moisture content, penetrometric resistance, deterministic analyses

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Introduction

Agricultural land is a type of land used for the production of various crops and is considered very important in terms of environmental decontamination [1]. The basic property of soil is its productive function. In the agricultural sector, it is the most important basis for production, and increasing yields for the growing world population can be achieved through its proper use (harmonizing soil efficiency and sustainability – the modern perception of agriculture [2]). Higher productivity can be achieved on the one hand through proper agricultural techniques and on the other hand by applying agrochemicals to control, reduce, and eliminate various pests and diseases. However, their excessive application has negative consequences for crop production and food security [3]. Intensive crop cultivation has spread worldwide in recent years, primarily involving heavier machinery and shorter crop rotations. Soils consist of minerals (sand, silt, and clay particles), organic matter, and pore spaces that contain water and air [4]. Heavy machinery and the factors mentioned above ultimately cause soil compaction [5]. Soil compaction is a process in which soil particles are rearranged. Soil compaction can be considered the most serious environmental problem, which has been and continues to be caused mainly by conventional agriculture. It is the most difficult type of degradation to identify and rationalise (e.g., without obvious signs on the soil surface [6]). The result is a subsequent disruption of the soil structure, which ultimately affects its compaction, changing the bulk density and reducing porosity [7]. However, this soil degradation reduces the pore space in the soil matrix, where crops grown in such soil often have a limited root system (lower nutrient uptake, slowed growth, overall lack of energy, and reduced yields [8]). Soil compaction is therefore one of the main problems facing modern agriculture. Excessive use of machinery, intensive crop cultivation, short crop rotation, intensive grazing, and inappropriate soil management lead to compaction. Soil compaction increases soil strength and reduces soil physical fertility due to reduced water and nutrient supply and storage, leading to additional fertilizer requirements and increased production costs [9]. To improve this phenomenon, various methods have been designed to estimate soil compaction intensity, soil water content, bulk density, and penetrometric resistance [10]. Subsoil compaction can be considered long-term degradation due to its persistence, even though this phenomenon also occurs in surface layers in some places. The result is not only monitored compaction, but also a negative impact on the structure of arable land and crop production in both the short and long term [11]. This fact has also been monitored by other authors, who have noted weak crop growth. However, this may also be due to incorrect farming practices [12]. The effects of soil compaction on crops and soil properties are complex because compaction is an important structural

attribute of soil. The defined property, soil strength, can be used as a measure of soil compaction (reflecting the soil's resistance to root penetration [9, 13]). Compaction can be reduced, for example, by controlled driving (or by controlling the mechanical impact of agricultural machinery – not only tractors, but also other machines such as combine harvesters, cutters, irrigators, trailers [14]). A moderately increased soil strength may be advantageous in some practical cases (moving machinery), but on the other hand, an excessive increase is mostly disadvantageous (e.g., during processing, higher resistance, more difficult to achieve a suitable soil structure [15]). Compacted soil has poorer properties related to water movement in the soil (capillary action, infiltration, and moisture [16]). The tillage practices applied and the crops grown are also important aspects of soil compaction. In practical terms, it is not only about operations, but also about spatial and temporal variability. On the one hand, individual operations can effectively loosen the surface soil and create larger pores, while on the other hand, they can lead to a compacted layer below the tilled horizon [17]. Bio-tillage is a principle that uses plant roots as a tool (great potential for improving soil quality, a method for alleviating soil compaction stress [18]). In bio-tillage, root systems are key to improving the structure of compacted soil by rearranging particles during elongation [19]. The introduction of forage crops reduces soil compaction through so-called bio-tilling, where deep-rooted crops such as alfalfa, chicory, and radish penetrate compacted layers and improve soil structure. These crops increase porosity and organic matter while reducing compaction compared to continuous cultivation on arable land [20, 21]. Bio-tillage improves soil physical properties, including pore geometry, aggregate stability, air permeability, and resistance to root system penetration [22].

Based on the above considerations, we decided to investigate selected soil properties (penetrometric resistance, soil moisture) that affect zonal or deep compaction when growing fodder under irrigation. To evaluate the implementation of the selected forage crop cultivation and improve its properties, we established the following hypotheses:

- The initial phase of forage cultivation without mechanical tillage results in uniform soil moisture across the entire area.
- Soil moisture will show significant differences not only between horizons but also between sampling dates.
- In the first few years of cultivation, forage crop cultivation did not prove effective in reducing soil compaction in the specified soil horizons.

Materials and Methods

The research focused on evaluating soil moisture in 3 soil horizons and the soil compaction rate and

its changes during the specified monitoring period. In addition to statistical evaluation, the results of the work were also subjected to an evaluation of soil moisture variability (gravimetric, moisture meter) and soil penetrometric resistance variability based on field measurements with a penetrometer. Measuring selected soil properties at several dozen points across a plot of land covering 47 ha would not only be difficult but also expensive. We therefore decided to carry out the measurements at strategically distributed sampling points, with the predicted values being assigned to all other locations. From the available methodologies, it is clear that the input values can be randomly or regularly distributed, or based on a sampling scheme. For this reason, the number of monitoring points was set at 20 and then 21 in irrigated and non-irrigated areas.

Characteristics of the Location

The selected site was subjected to research activities, focusing on monitoring selected soil properties throughout the observation period. Details about the agricultural enterprise were provided in the published article [23]. However, the essential information can be highlighted in this article. The total area is 47.64 ha and is located outside the urban area of Oponice (48.464524 N, 18.137509 E, at an altitude ranging from 149.3 to 160 m a.s.l., Fig. 1). The company decided to grow alfalfa on the selected land. According to BPEJ 0127003, the land is classified as a warm, very dry, lowland climatic region [24]. In terms of predominant grain size, the soils are classified as heavy, deep, and non-skeletal, and in terms of soil type, they are black soils. Irrigation was carried out using a Valley Pivot irrigator (Valley Pivot Irrigation, Valmont S.A.U., Spain, 28521 Rivas Vaciamadrid Madrid, Spain). The average monthly precipitation in 2024 was 23.08 mm (the total

annual precipitation for the whole year was 277 mm) and the average temperature was 13°C, ranging from -11°C in winter to 37°C in summer [25, 26]. Relative humidity ranged from 45 to 85% (depending on the month).

Characteristics of Measuring Equipment

Soil Moisture

Soil moisture was determined using 2 methods: the gravimetric method and the WET measuring device with an HH2 logger (WetSensor, Royal Eijkelkamp, EN Giesbeek, Netherlands, Fig. 1 [27]). Samples were taken at individual monitoring points to determine soil moisture, or an electronic device was used. For each selected passage, 3 samples were taken using a professional Eijkelkamp hand drill (Royal Eijkelkamp, EN Giesbeek, Netherlands [28]), or the average moisture value was calculated from the 3 measured values. All samples were stored in standardised aluminium sealable cups, which were numbered on site and assigned to monitoring points. After sampling, the samples were weighed individually on a certified KERN scale (Kern Microtechnik GmbH, Eschenlohe, Germany [29]) with a sensitivity of 0.01 g. Later, all samples were placed in a Venticell 50 soil sample dryer (MMM Medcenter Einrichtungen GmbH, Semmelweisstrasse 6, D-82152 Planegg, Munich [30]) set to a temperature of 105°C and dried at this temperature for 26 hours. The resulting values were converted to percentages. Mass moisture is the ratio of the weight of water to the weight of dry matter. Volume moisture is the ratio of the volume of water to the total volume of the sample. The conversion is performed according to the relevant standard and relations (the conversion includes: soil bulk density, water density) [31-33]. Soil moisture is calculated using the following formula:



Fig. 1. Location of measurements, monitoring points, measuring device.

% Soil Water

$$= \frac{\text{weight of wet soil (g)} - \text{weight of dry soil (g)}}{\text{weight of dry soil (g)}} \times 100 \quad (1)$$

Penetrometric Resistance

A hand-held cone penetrometer (Royal Eijkelkamp, P.O. Box 4, 6987 ZG Giesbeek, the Netherlands; Fig. 1 [34]), equipped with a Penetrologger digital recorder, was used for the measurement. The Penetrologger consists of a dust- and water-resistant cover, a shock absorber, a cone needle (in our case with a diameter of 1 cm and a 60° bevel), communication ports, a GPS antenna, an LCD screen, a control panel, and a spirit level. During the measurement, it was necessary to ensure that the cone needle was pressed evenly into the soil (approx. 4 m.s⁻¹). The measuring range of the penetrometer used is from 0 to 10 MPa with a working depth of up to 0.8 m (the depth is measured by an internal ultrasonic sensor). The device has a resolution of 1 N. Communication between the penetrometer and external devices is provided by communication ports [34]. In the experiments, the measurement locations corresponded to the model soil compaction. Measurements at a single point represented the average value from 10 repetitions to a depth of 75 cm of the soil profile.

Field Measurements, Statistical Evaluation

Measurements in field conditions were carried out on predetermined dates at individual monitoring points. A Topcon GRS-1 handheld satellite navigation device (RTK accuracy, signal correction: SKPOS, Topcon, 7400 National Drive, Livermore, CA 94550 United States [35]) was used to determine the boundaries of the land. The strategic change of the cultivated crop to a fodder crop, alfalfa, should bring about favorable changes in soil compaction conditions. Sowing was carried out on the targeted land in 2024 (the soil had previously been plowed, harrowed, and tilled with a compactor). After sowing, an irrigation dose of 20 mm was applied in June, and harvesting was carried out in June and July. At the end of July, another irrigation dose (20 mm) was applied, and in September and October, another harvest was carried out.

Spatial variability was evaluated using ArcGIS software (ArcGIS, 2010) [36]. The analysis of the results was also performed using the ArcGIS Spatial Analyst extension. A continuous surface representation of a raster data file is a graphical representation of a specific value or range being studied (e.g., soil moisture, penetrometry, etc.). It can be said that surface interpolation tools generate predictions from sample measurements for all locations in the output raster data file (even where no measurements were taken – predictions). The application in the GIS environment offers several ways (models) to derive a prediction for

each location. These models make assumptions using various calculations. In our evaluations, deterministic interpolation methods were applied, which assign values to locations based on surrounding measured values and specified mathematical formulas that determine the smoothness of the resulting surface. The output values were processed using the Spline model, where the analysis included calculations, model application, and the resulting mapping (Spatial Analyst extension).

For a high-quality and sufficient evaluation of the results, statistical analyses were proposed, with a hypothesis of the significance of the influence of input factors (monitoring date, plot zone). Statistical evaluation of the results, in other words, testing the significance of differences between the measurements taken (between individual measurement dates, between irrigated and non-irrigated areas), was performed using one-way ANOVA analysis or correlation, depending on the application possibilities [37]. We believe that the results obtained will show changes in the impact of the irrigated area of the plot. When evaluating the results achieved between individual locations, we also focused on the possibilities of obtaining and assessing analytical similarities or differences (Distance Matrix and Hierarchical Clustering; Orange software; Orange [38]). The output is a distance matrix, with distances calculated using Euclidean metrics (the direct distance between 2 points in Euclidean space).

Results and Discussion

At the Department of Machines and Production Biosystems (currently the Institute of Agricultural Engineering, Transport and Bioenergy, Faculty of Engineering, Slovak University of Agriculture in Nitra, Slovakia), a number of researchers have long been involved in monitoring selected soil properties, mainly in various agricultural conditions. Properties such as soil infiltration capacity, soil moisture, and mechanical properties such as shear strength and penetrometric resistance of soil are monitored. On a selected plot of land, we have managed to introduce a new direction of experiments, where we decided to monitor changes in soil moisture (referred to as SMC) and penetrometric resistance (referred to as PR) when introducing fodder cultivation (alfalfa).

Soil Moisture

Pilot soil moisture measurements (SMC01, measurement date – April 2024) at individual monitoring points (MP01 to MP20) were performed using the gravimetric method at 3 depth horizons. The results show higher values of average soil moisture in the medium-deep (40 cm; 13.81±2.37 %-weight, CV = 17.19 %) and deep horizons (60 cm; 15.27±3.53 %-weight, CV = 23.12%). A significantly lower average value was observed in the shallow horizon

(20 cm; 12.57 ± 2.66 %-weight, CV = 21.16 %). The results show increased moisture mainly at monitoring point MP01 in all horizons examined, and at a depth of 60 cm also at point MP15. Secondary soil moisture measurements were also performed in conjunction with penetrometric resistance measurements in September (SMC02, measurement date – September 2024), but with the difference that the monitoring was performed with a WET sensor with an HH2 logger (also in individual horizons – 20 cm, 40 cm, and 60 cm). Based on the evaluated results, it can be said that the soil moisture between the individual monitoring points has evened out. The difference compared to the pilot measurements was that we added point MP21 (in the part of the plot where we only estimated the moisture during the first measurement) for a better and more reliable representation of the variability. In these measurements, the average soil moisture value in the shallow horizon was lower than in the first measurement (20 cm; 11.33 ± 1.43 % vol., CV=12.64%), as well as in the medium-deep horizon (40 cm; 12.38 ± 1.24 %-vol., CV = 10.04%) and in the deep horizon (60 cm; 13.23 ± 1.12 %-vol, CV = 8.47%). The values can be statistically compared with each other because the originally measured soil moisture values were converted to soil moisture results in %-weight. The third group of soil moisture measurements (SMC03) was again performed by collecting and drying samples and determining soil moisture in %-weight. The average soil moisture values were lower in the shallow horizon compared to the first measurement (20 cm; 10.93 ± 1.07 %-weight, CV = 9.82%), as well as in the medium-deep horizon (40 cm; 12.54 ± 1.24 %-weight, CV = 9.87%) and deep horizon (60 cm; 13.46 ± 1.17 %-weight, CV = 8.71%). Compared to the second measurement (SMC02), there were slight deviations (shallow horizon – lower moisture value, medium-deep and deep – higher moisture value). The above values can also be compared with the pilot and secondary measurements at corresponding monitoring points. A positive result of the data obtained is the fact that the value of the coefficient of variation decreased significantly already in the second group of measurements in all measured horizons, and another advantage is that the decrease is also visible in the third group of measurements. There was a slight difference at a depth of 60 cm, where there was an increase of 0.24 percentage points in CV. However, this can be considered insignificant from a statistical point of view.

When examining the dependence of sampling depth (pilot measurements, SMC01) on the surveyed plot at individual monitoring points, we did not find a significant dependence in 2 cases (horizons 20 cm and 40 cm, 40 cm and 60 cm, $F < F_{crit}$), while the results were significant ($P < 0.05$) when evaluating the horizons (20 cm and 60 cm). However, the second group of soil moisture measurements (SMC02) at monitoring points (the number increased by one) yielded interesting observations when monitoring significance. A demonstrable dependence ($P < 0.05$, $F = 6.4$) was observed between

the 20 cm and 40 cm depth horizons during one year of alfalfa cultivation. Further comparison and evaluation by one-factor analysis focused on the 40 cm and 60 cm depth horizons. To our surprise, a positive dependence was also observed in this measurement ($P < 0.05$, $F = 5.4$). The last observations focused on depth horizons of 20 cm and 60 cm. The result was confirmed, as in the first group of measurements (observed dependence of horizons, $P < 0.05$, $F = 22.87$). When comparing individual horizons (20 cm, 40 cm, and 60 cm) between individual measurement groups (i.e., SMC01, SMC02), it can be said that no dependence was demonstrated in the shallow horizon ($P > 0.05$, $F = 2.97$), but dependence was demonstrated in the medium-deep and deep horizons (40 cm: $P < 0.05$, $F = 5.59$; 60 cm: $P > 0.05$, $F = 6.12$). The third group of measurements (SMC03) was not carried out until November, when the external humidity and temperature were clearly different compared to the measurements in September or April. We again focused on evaluating the individual depth horizons in relation to each other, and found that when comparing the depth horizons (20 cm and 40 cm), the dependence was sufficiently demonstrated ($P < 0.05$, $F = 20.14$). An even greater significance was observed when comparing the 20 cm and 60 cm horizons ($P < 0.05$, $F = 53.13$, $F_{crit} = 4.08$). The weakest dependence was found between the 40 cm and 60 cm horizons ($P < 0.05$, $F = 6.16$). A comparison of the results of measurements taken in November (SMC03) with those taken in September (SMC02) showed the expected equalization of soil moisture. When observing individual horizons, we confirmed significant results in all of them, with the highest manifestation in the 60 cm horizon ($F = 55.22$, $P < 0.05$). A lower level of dependence, although still sufficiently evident, was observed in the 20 cm horizon ($F = 47.57$, $P < 0.05$), and the lowest level was observed in the 40 cm horizon ($F = 42.66$, $P < 0.05$).

The results observed during the research period showed that, based on the input values, after the winter period and based on the length of the crop growing season, the variability of soil moisture was balanced. The results are demonstrated not only by a graphical evaluation of variability, but also by a statistical evaluation. No significant differences ($P > 0.05$) were demonstrated even when evaluating soil moisture variability from the perspective of the entire plot (Fig. 2) in the irrigated and non-irrigated parts of the parcel. The results are, of course, also related to the timing of the measurement, when irrigation had not yet been implemented on the plot. Irrigation was applied several times during the growing season, with the moisture itself being distributed more evenly throughout the soil horizon during monitoring. The cultivated crop therefore contributes to the distribution of moisture in the soil.

A graphical evaluation of variability in individual soil horizons and measurement dates is shown in Fig. 2, Fig. 3, and Fig. 4. The color representation of

variability in specific horizons with accompanying histograms provides a perfect overview of moisture conditions. The histogram offers a visual representation of the distribution of quantitative data, which is divided into a series of intervals (in our case, 5 classes). The spatial intervals are non-overlapping, neighbouring and specified as consecutive intervals of the variable. The results provide an idea of the density of the underlying distribution of soil moisture data at individual depth horizons. The histogram curves clearly show that extreme values appeared in relation to the rest of the distribution at some monitoring dates and horizons. When monitoring at a depth of 20 cm (SMC01), it can be observed that the majority of the

land reaches soil moisture of only up to 13.45% weight. The rest of the plot reaches soil moisture levels above 13.45% weight and up to 16.73% weight, and last but not least, a narrowly specified area is supplied with moisture above 21.49% weight. At the monitored horizon of 40 cm (SMC01), soil moisture shifted to higher values, where, based on the histogram, soil moisture was predominantly between 10.21 and 16.36% by weight. Moisture values above this level were only recorded at around 3 monitoring points. At a depth of 60 cm, there was a significant change in the spatial zonal distribution of moisture, and the histogram shows that more than 70% of the area has soil moisture ranging from 12.44 to 16.99% by weight. From the overall assessment,

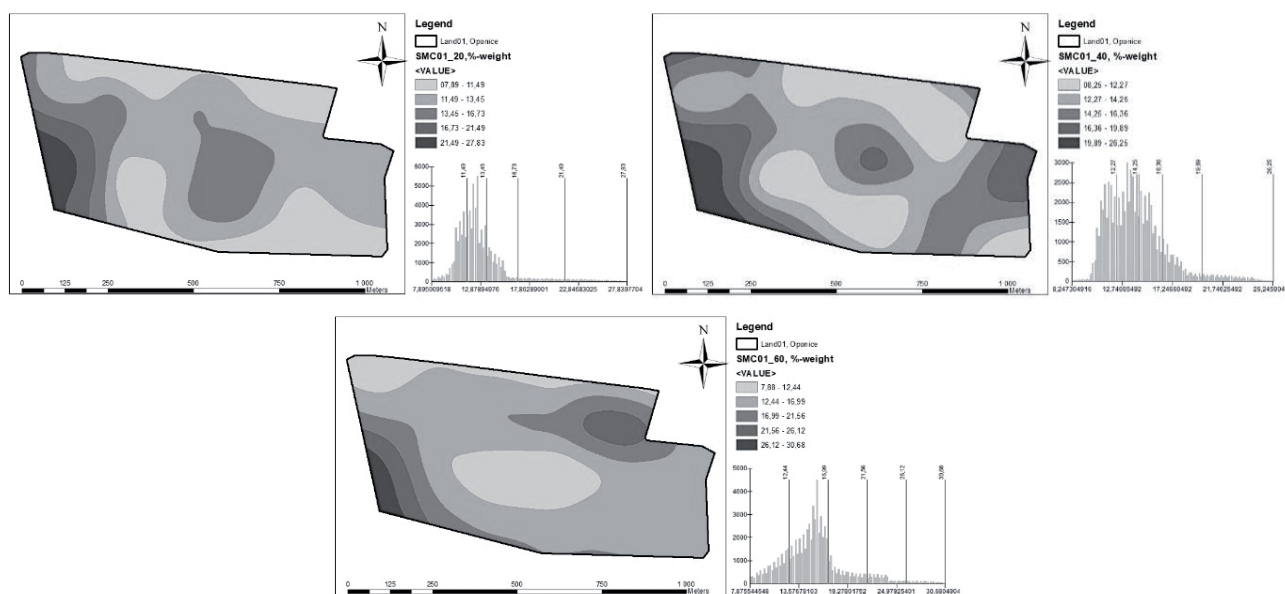


Fig. 2. Spatial variability of the SMC, SMC01, depth horizons, a) 0-20 cm, b) 21-40 cm, c) 41-60 cm.

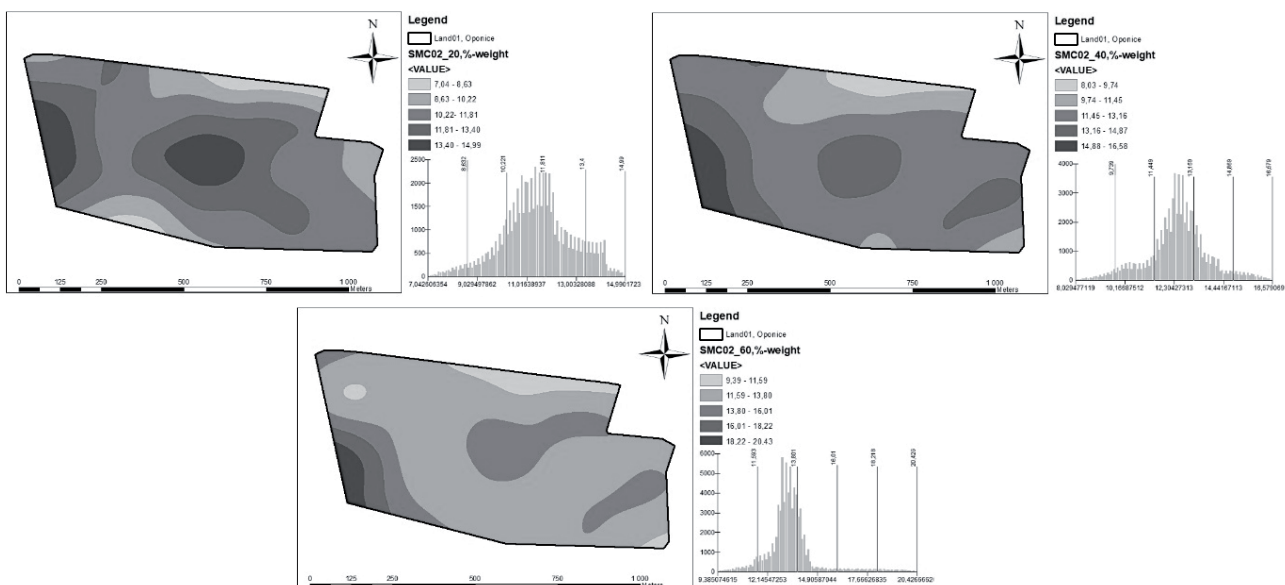


Fig. 3. Spatial variability of the SMC, SMC02, depth horizons, a) 0-20 cm, b) 21-40 cm, c) 41-60 cm.

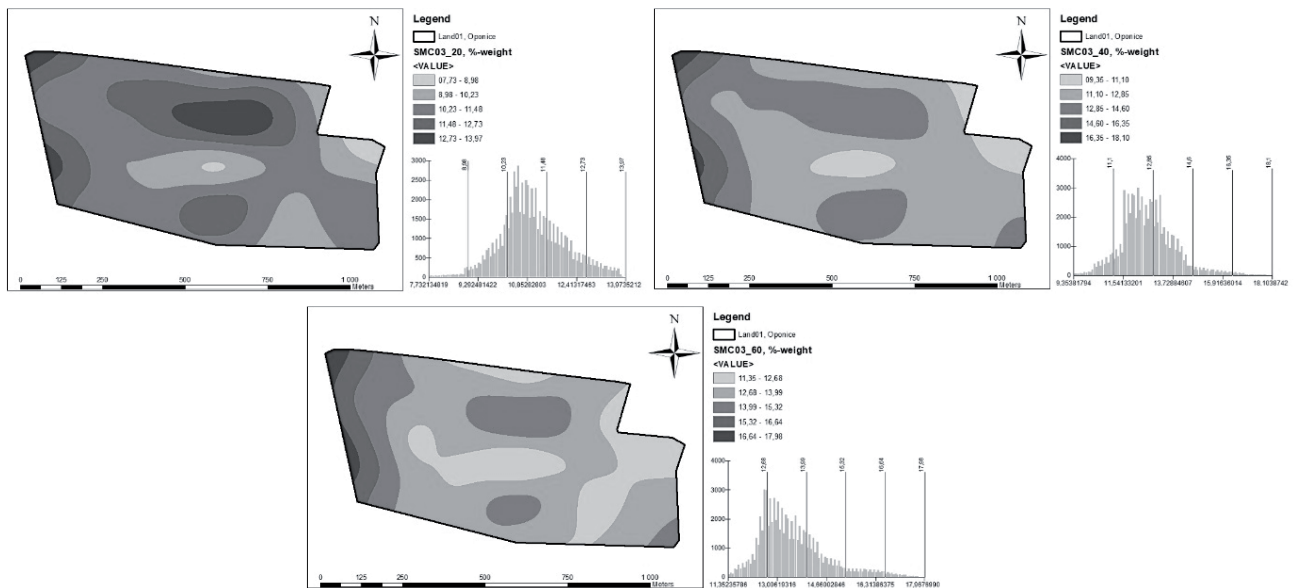


Fig. 4. Spatial variability of the SMC, SMC03, depth horizons, a) 0-20 cm, b) 21-40 cm, c) 41-60 cm.

it can be concluded that soil moisture ranged from 11 to 16% weight in all 3 horizons. The secondary group of measurements (SMC02) took place in September, when we decided to reassess soil moisture variability. In terms of spatial distribution, a positive correlation can be observed, which we also confirmed statistically with a one-factor analysis. Most of the plot (shallow horizon) showed soil moisture ranging from 10.22 to 13.40% weight. In contrast to the 20 cm horizon, the average moisture supply increased in the deeper horizon to a range of 11.45-13.16 %-weight. In the deepest horizon examined (60 cm, SMC02), in terms of the variability of the entire plot, it can be said that soil moisture ranging from 11.59 to 16.01% by weight is found on an area of more than 72%.

The tertiary measurement group (SMC03) was carried out in November, with maximum soil moisture levels of 14% by weight reached across the entire plot at a depth of 20 cm. The histogram shows a normal distribution (8.98÷13.71% weight) with a mean value of 10.93% weight. At a depth of 40 cm, the average moisture content shifted to higher values by an average of 1.61% weight, with a predominant spatial concentration (more than 90%) in the moisture range of 11.1-14.6% weight (histogram SMC03, 40 cm). At the last horizon examined (60 cm), moisture in the range of 11.35-15.32 %-weight was achieved on more than 90% of the land area.

The results of the variability of dynamic soil properties related to water movement in the soil (examined soil moisture, but also, for example, electrical conductivity, hydraulic conductivity of the soil, movement of soluble substances) predominantly show a lognormal distribution. The distribution is characterized by asymmetry and is defined only for positive values and is applied in modeling selected physical quantities. In our case, it is also a continuous probability

distribution of a one-dimensional but real quantity. As can be seen from the results, the variability and its distribution (histogram) indicate changes in each horizon and sampling date (defined by the mean value and standard deviation in each case – sampling date, depth horizon).

Penetrometric Resistance

Penetrometric resistance (PR) measurements were performed, as well as soil moisture measurements, at 3 staggered intervals at a total of 20 (21) monitoring points. The result of the penetrometer measurement is a graphical representation of the dependence up to a depth of 75 cm. The graphical representation of the results is shown in Fig. 5 (pilot measurements, PR01), Fig. 6 (secondary measurements, PR02), and Fig. 7 (tertiary measurements, PR03). As already mentioned, the first group of measurements was carried out in April. The total number of monitoring points at this stage was only 20. Scientific research shows that soil penetrometric resistance exhibits high spatial variability, which is usually influenced by the characteristic parameters of the site of interest (e.g., soil moisture, bulk density, type and forms of tillage). PR and its dependence are highly sensitive to soil moisture. Even under our conditions, we tried to highlight soil compaction at precisely determined soil moisture levels in individual horizons. Our goal was also to monitor resistance values in relation to moisture in a given area (zone), assuming that the value would be higher in drier and more compacted areas.

We assessed our measurements and evaluations according to practical monitoring needs. From an economic point of view, areas with a penetrometric resistance value above 2.0 MPa are considered compacted areas. From the point of view of subsequent management, it is more advantageous to apply localized

management. Graphical representations of resistance curves in pilot measurements (PR01) and in cultivated alfalfa crops show favorable results at individual points, where the penetrometric resistance value of 2 MPa was exceeded at 12 monitoring points at a depth of up to 20 cm (at 5 points, the increase was only up to a maximum of 2.16 MPa; MP2, MP3, MP7, MP12, MP16). Values higher than 2.5 MPa occurred in the specified depth horizon (0-20 cm) at only 4 points (MP5, MP14, MP17, MP19) and above 3 MPa at only one point (MP14). Unlike the shallow investigation, we also focused our attention on the middle horizon (21-40 cm). A resistance value above 2 MPa was found at eight monitoring points, with a maximum value of 2.36 MPa. The deep horizon (41 to 61 cm) may not be important for the cultivation of some crops in some places, but we decided to investigate this fact for our cultivated crop. Values above the threshold level of 2 MPa were found at 9 monitoring points (values above 2.5 MPa only at monitoring point MP5, with a maximum value of 2.65 MPa).

The secondary group of penetrometric resistance measurements (PR02) was not carried out until September. In the shallow depth horizon (up to 20 cm), the penetrometric resistance value exceeded the limit of 2.0 MPa at 11 points examined (MP2, MP5, MP7, MP9, MP13, MP15-18, MP20, MP21), with an increase above 2.5 MPa occurring in only 3 of them (MP2, MP7, and MP9) and the limit of 3.0 MPa only at monitoring point MP9. The difference compared to the first group of measurements showed a decrease in the number of points where the penetrometric resistance was above 2.5 MPa. In the middle horizon (21-40 cm), however, we observed compaction compared to the pilot measurements when monitoring the resistance limit values. Penetrometric resistance above 2 MPa appeared at several points (up to 16 points) and above 2.5 MPa at 4 points (MP9, MP14, MP16, MP19). At 2 points, the resistance value was even above 3.5 MPa (MP14, MP16). In the deep horizon (41-60 cm), the compaction was even more significant, with resistance values above 2 MPa occurring at almost all points except MP12. The difference compared to the

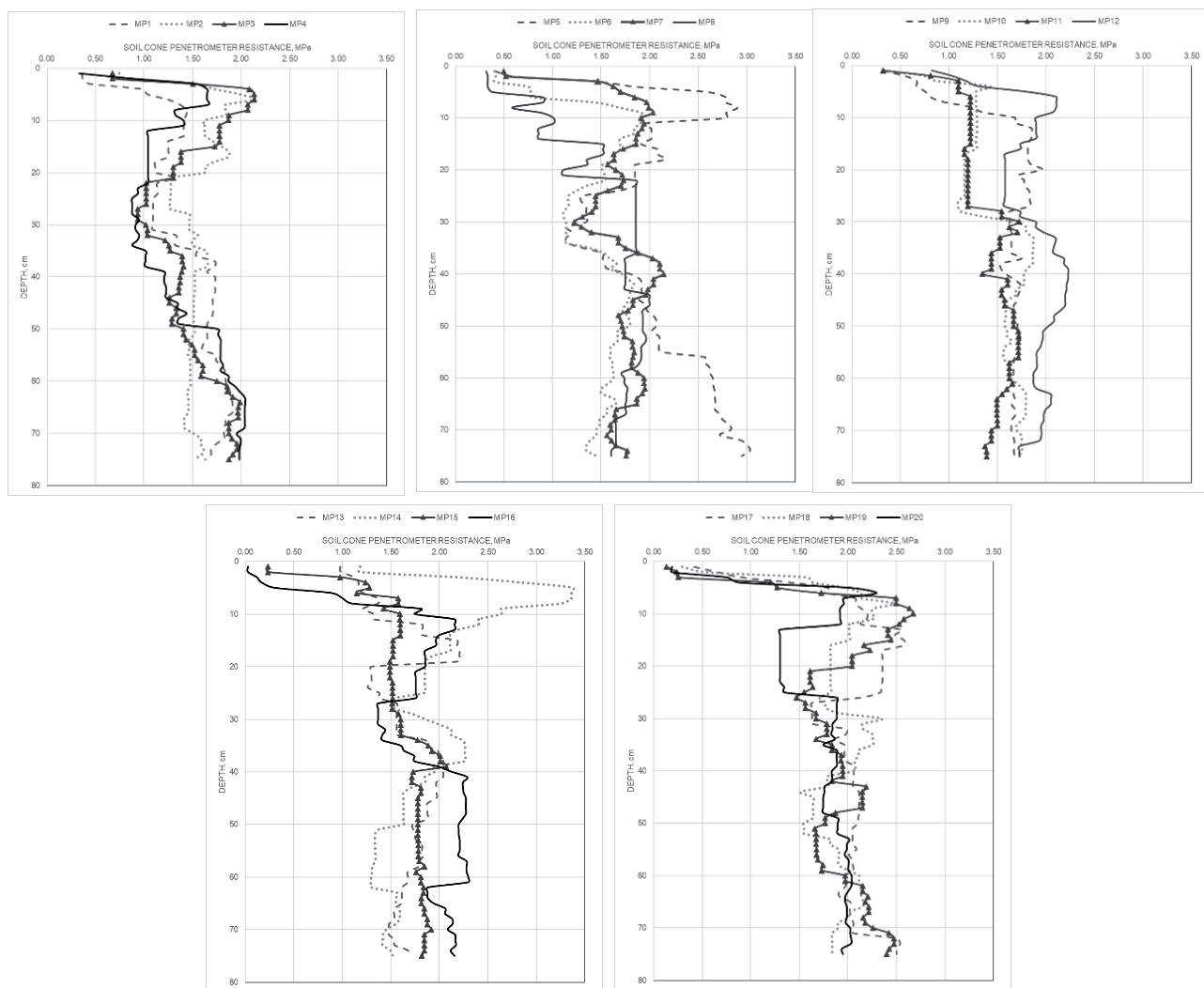


Fig. 5. Soil penetrometric resistance, PR01, MP1 to MP20, pilot measurements, a) MP1-MP4, b) MP5-MP8, c) MP9-MP12, d) MP13-MP16, e) MP17-MP20.

pilot measurements is clearly evident, as can be seen from the graphical curves of the soil's penetrometric resistance. Resistance values above 2.5 MPa were observed at 13 monitoring points, and above 3 MPa at 4 points (MP3, MP14, MP16, MP19). The tertiary group of measurements (PR03) was carried out in November, when, due to the impact of precipitation and the later measurement date, we expected increased resistance values, mainly in the shallow horizon. In the shallow horizon (0-20), our hypotheses of increased compaction were clearly confirmed, with resistance values above 2 MPa found at almost all points except one (MP6). In the aforementioned horizon, an increase above 2.5 MPa was still significantly evident (i.e., above 50% of the number of points), with resistance values above 3 MPa evident at 9 monitoring points. However, in the middle horizon examined, we assumed that the increase in compaction would not be as significant. The resistance limit value of 2 MPa was exceeded at all monitoring points, 2.5 MPa at 16 points, and 3 MPa at 6 points. This means that 2 horizons

showed significant compaction across the board at the specified measurement date. Based on the examination of the first two, we assumed that the third depth horizon (41-60 cm) would show only higher compaction. Resistance above 2 MPa was observed at all points, 2.5 MPa at 16 points, and above 3.0 MPa at seven points. The result is significant compaction in the third horizon as well, compared to the measurements taken in September.

The main statistical evaluations of the penetrometric resistance results (Mean, Standard Deviation, Sample Variance, Kurtosis, Skewness, Minimum, Maximum and CV) in the 3 horizons are presented in Table 1. The average values in the pilot measurements ranged from 0.9 to 2.35 MPa (average values in individual MP) with a CV value of up to 59.81%, which reflects the high heterogeneity in places in the shallow subsoil under investigation. In the middle horizon, the average penetrometric resistance values ranged from 0.98 to 2.01 MPa with CV values up to 22.49%. The results clearly show that the heterogeneity in the middle horizon is significantly lower than in the shallow horizon. In the

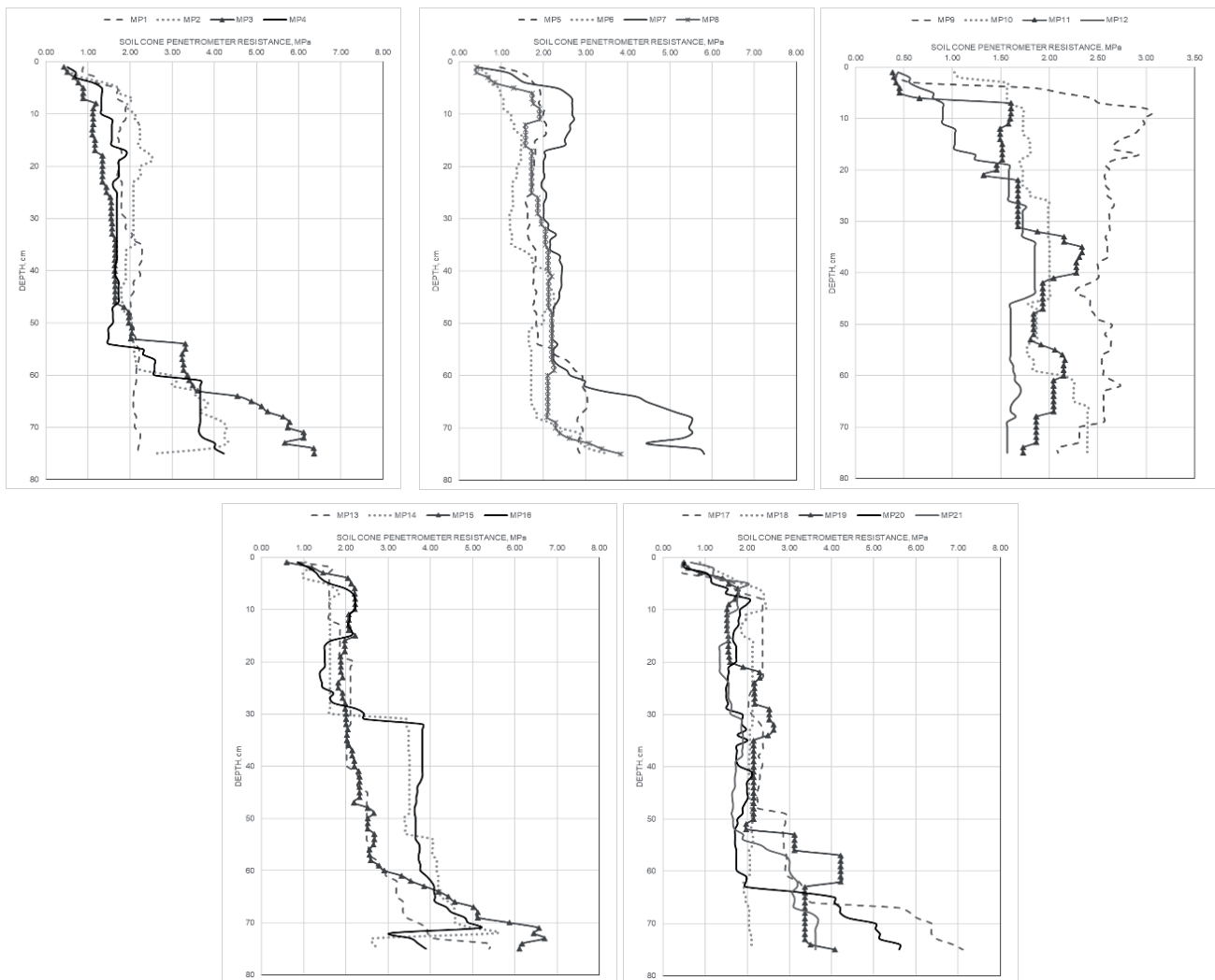


Fig. 6. Soil penetrometric resistance, PR02, MP1 to MP21, secondary measurements, a) MP1-MP4, b) MP5-MP8, c) MP9-MP12, d) MP13-MP16, e) MP17-MP21.

deepest horizon examined, the average penetrometric resistance values ranged from 1.44 to 2.25 MPa with a CV value of less than 20% (CV = 16.52%). The results indicate the highest level of homogeneity in the horizon examined. The second group of measurements was also subjected to an evaluation of the heterogeneity of the determined average penetrometric resistance in the individual horizons examined. The results of monitoring the researched parameter (PR) show that the level of heterogeneity in the shallow horizon was at CV = 41.97% (average PR value from 0.95 to 2.35 MPa). In the medium-deep horizon (21-40 cm), homogeneity improved slightly to CV = 40.61% (average penetrometric resistance values ranged from 1.39 to 2.68 MPa). The lowest heterogeneity was observed in the deepest horizon, at a level of CV = 31.25% (average PR = 1.49-4.22 MPa).

The main statistical evaluations of the penetrometric resistance results (Mean, Standard Deviation, Sample Variance, Kurtosis, Skewness, Minimum, Maximum and CV) in the 3 horizons are presented in Table 1. The average values in the pilot measurements ranged from 0.9 to 2.35 MPa (average values at individual MPs) with a CV value of up to 59.81%, which reflects the high heterogeneity in places in the shallow subsoil under investigation. In the middle horizon, the average penetrometric resistance values ranged from 0.98 to 2.01 MPa with CV values up to 22.49%. The results clearly show that the heterogeneity in the middle horizon is significantly lower than in the shallow horizon. In the deepest horizon examined, the average penetrometric resistance values ranged from 1.44 to 2.25 MPa with a CV value of less than 20% (CV = 16.52%). The results indicate the highest level of homogeneity in the horizon examined. The second group of measurements was also subjected to an evaluation of the heterogeneity of the determined average penetrometric resistance in the individual horizons examined. The results of monitoring the researched parameter (PR) show that the level of heterogeneity in the shallow horizon

was at CV = 41.97% (average PR value from 0.95 to 2.35 MPa). In the medium-deep horizon (21-40 cm), homogeneity improved slightly to CV = 40.61% (average penetrometric resistance values ranged from 1.39 to 2.68 MPa). The lowest heterogeneity was observed in the deepest horizon, at a level of CV = 31.25% (average PR = 1.49-4.22 MPa).

The third group of measurements was carried out in November, showing a similar scenario to the pilot measurements. In the shallow horizon, the highest level of heterogeneity was demonstrated (CV = 38.86%) with average penetrometric resistance values ranging from 1.5 to 3.18 MPa (average values at individual MP). Lower heterogeneity was also demonstrated in the middle horizon (CV = 28.27%) with slightly increased average PR values (1.78-3.34 MPa). The highest homogeneity was observed in the examined deep horizon (41-60 cm) with a CV of 21.22% and significantly increased average PR values of up to 65.1% (PR = 2.03-5.52 MPa).

The results were also subjected to one-factor ANOVA and correlation analysis, while we also monitored the dependence of the irrigation area on the rest of the area at 2 selected monitoring points (MP03→MP05, MP11→MP19). In the pilot measurements, when irrigation had not yet been started, significant differences were found in both cases. The correlation results showed a strong dependence between MP03 and MP05 and a moderate dependence between MP11 and MP19. Secondary measurements showed differences from the pilot measurements (dependence confirmed between MP11 and MP19), but the dependence between MP03 and MP05 was not confirmed. However, the correlation in the first case (MP03, MP05) indicated a strong dependence, and in the second case (MP11, MP19) a moderately strong dependence. When comparing the correlation between pilot and secondary measurements at the 4 selected monitoring points, it can be said that in the irrigated area there was a strong dependence of values in both cases, but in the non-irrigated area the dependence was weak to moderate. Tertiary measurements showed significance in both cases, with

Table 1. Main statistical results of the analyzed penetrometric resistance (in MPa), PR01-PR03 (SD – standard deviation, SV – sample variance, CV – coefficient of variation).

Variable	Mean	SD	SV	Kurtosis	Skewness	Minimum	Maximum	CV, %
PR01, 0-20 cm	1.534	0.619	0.383	0.110	-0.099	0.030	3.377	40.34
PR01, MP1, 20-40 cm	1.597	0.344	0.119	-0.657	-0.084	0.880	2.353	21.56
PR01, MP1, 40-60 cm	1.788	0.250	0.063	0.540	0.369	1.210	2.650	13.99
PR02, MP1, 0-20 cm	1.615	0.561	0.314	-0.092	-0.139	0.383	3.057	34.71
PR02, MP1, 20-40 cm	1.994	0.478	0.228	4.375	1.738	1.193	3.810	23.96
PR02, MP1, 40-60 cm	2.313	0.622	0.387	1.035	1.277	1.487	4.217	26.91
PR03, MP1, 0-20 cm	2.341	0.707	0.500	0.532	-0.335	0.407	4.450	30.21
PR03, MP1, 20-40 cm	2.463	0.480	0.230	4.347	1.457	1.543	4.503	19.50
PR03, MP1, 40-60 cm	2.810	0.903	0.815	4.781	2.033	1.850	6.927	32.12

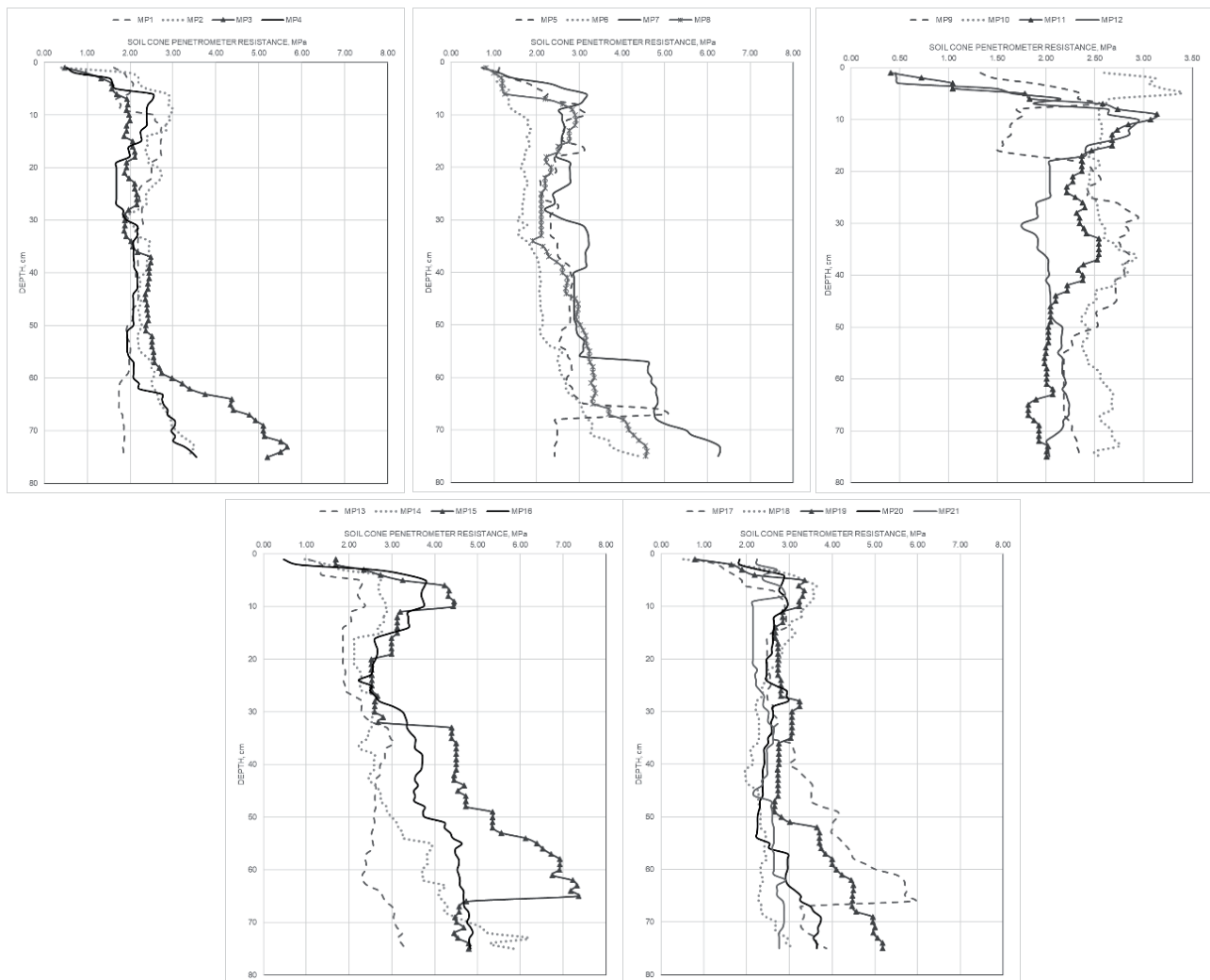


Fig. 7. Soil penetrometric resistance, PR03, MP1 to MP21, tertiary measurements, a) MP1-MP4, b) MP5-MP8, c) MP9-MP12, d) MP13-MP16, e) MP17-MP21.

the correlation between points MP11 and MP19 being several times more pronounced. The correlation results showed moderate dependence for the first pair of monitoring points, but insignificant dependence for the second pair (MP11, MP19).

In addition to the basic statistics mentioned above, interpolation tools were also applied to evaluate the results, creating a continuous (or predictive) surface from the input sampled point values. When evaluating the results, we chose deterministic methods that indicate variability dependencies. Variability displays using these methods help identify the condition of the subsoil. Map displays of minimum, maximum, and average resistance variability were applied for a total depth of 60 cm (0-60 cm). From a strategic point of view, it can be said that the variability of the monitored values ranges from meters to tens of meters (horizontally), which may require several systematic measurements for a more detailed examination in order to achieve a more accurate characterization of the zones of a given location.

Unlike the monitoring of spatial variability of soil moisture (which is a dynamic property), the spatial variability of static physical properties of soil (e.g., soil mechanical composition, density, etc.) is commonly adjusted to normal probability distributions. The variability is also normally distributed in our measurements, but extreme deviations were identified in some places. Graphical representations of the spatial variability of the average penetrometric resistance at individual measurement dates are shown in Fig. 8. Pilot measurements pointed to a missing monitoring point 21, where the graphical deterministic results of spatial variability of the maximum and average PR values would show zero resistance values for a certain area (selected class). The value at point 21 was therefore approximated so that no zero value extremes would arise in the spatial variability (assigned resistance values AVG MP20→MP21). The histogram of pilot measurements of the average value of penetrometric resistance showed a normal distribution of values around the mean value of 1.68 ± 0.37 MPa with a CV value of 22.19% (minimum

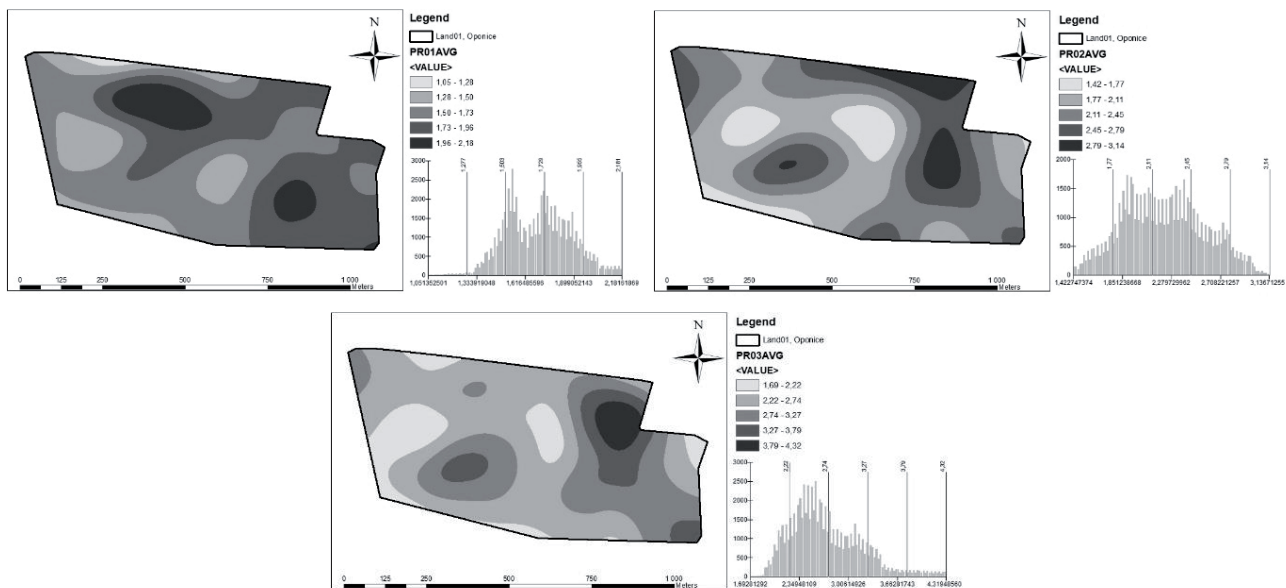


Fig. 8. Spatial variability of the soil cone penetrometric resistance (in MPa), a) PR01, b) PR02, c) PR03.

value 0.03 MPa). For this reason, 21 monitoring points were added for further measurements to more accurately reflect the variability of the results.

Secondary PR measurements, which included monitoring point 21, showed that the distribution of measured data was also closer to the so-called normal distribution in all cases examined. The histogram of secondary measurements of the average penetrometric resistance value showed variations around the mean value of 2.25 ± 0.80 MPa, but with a significantly higher CV value than in the pilot measurements ($CV = 34.42\%$, minimum value 0.38 MPa). The tertiary measurements were more or less similar to the secondary measurements, especially in terms of the distribution of the measured data. Once again, a normal distribution was observed, with the obtained values of average penetrometric resistance PR approximating 2.72 ± 0.67 MPa. The minimum value for these measurements was 0.41 MPa, and the coefficient of variation CV reached 23.77%. When evaluating the variability of the average PR, it can be said that the dependence was demonstrated mainly between the second and third measurements. The zone locations indicate significantly consistent minimum, maximum, and average PR values ($P < 0.05$).

The measured PR results were also subjected to

Distance Matrix and Hierarchical Clustering analysis. The evaluation of the input data required setting the Distance widget (Compare – Columns, Distance Metric – Euclidean). The program application is a tool used to visualize and examine the calculated distances (differences) between data instances or variables. The results obtained show the distances in a grid format, where the color tones represent how similar or different the data points are. The created map of penetrometric resistance distances obtained from field measurements and data processing presents in color the largest (lightest) and smallest (darkest) distances between individual measurement dates of the examined characteristic (at zero distance, same value, black color). The results show the variability of penetrometric resistance depending on the measurement date (PR01, PR02, and PR03). The greatest distances were observed when evaluating the clustering of penetrometric resistance results (Max, AVG) between measurement dates PR01 and PR02 (Max, 3.922; AVG, 3.684), with higher similarities shown between measurements PR01 and PR03 (Max, 3.436; AVG, 3.565) and the highest similarities between measurements PR02 and PR03 (i.e., the smallest distances, Max, 2.315; AVG, 2.146). The change was observed when evaluating

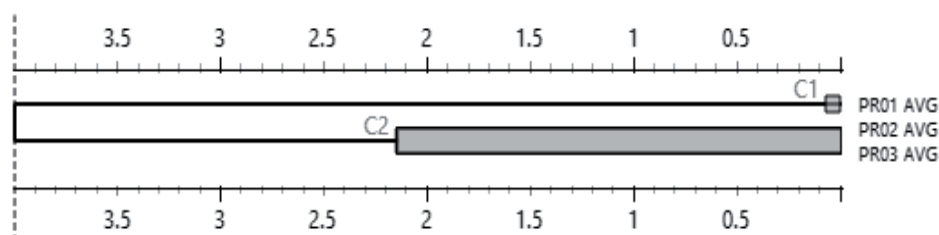


Fig. 9. Hierarchical Clustering for soil penetrometric resistance (AVG), for all measurement dates.

the minimum average values of penetrometric resistance (the greatest difference between PR01 and PR03, 4.970; the average difference between PR01 and PR02, 4.222; and the smallest difference of 3.571 between PR02 and PR03). The results obtained point to relationships between the individual measurement dates, with the smallest differences being more significantly related to each other (most similar, statistically most significant). However, the clustering results are more clearly presented graphically by applying dendrograms (Fig. 9). We applied Hierarchical Clustering in all 3 cases of monitoring PR results (Min, Max, AVG), using Linkage (Ward). The results confirmed the same results as those obtained from the individual Distance Matrix. The measurements taken in September and November (PR02, PR03) are the most similar. PR01 showed the greatest distance from the 2 measurement dates mentioned above.

With the development of agricultural technologies to meet the growing demands of a rapidly growing population and economic development, intensive agricultural practices are widely adopted around the world [39]. Soil compaction can be assessed by measuring penetrometric resistance using penetrometers. Similar topics have been addressed by researchers around the world who have assessed soil compaction by measuring penetrometric resistance. Their work focused on a rapid method of monitoring differences in soil compaction using cone penetrometer resistance measurements [15, 40]. According to Warrick and Nielsen [41], the spatial variability of static physical properties of soil, such as soil mechanical composition, density, and others, commonly follows normal probability distributions, while dynamic properties (i.e., those related to the movement of water or dissolved substances), such as soil hydraulic or electrical conductivity, are typically lognormally distributed. The results of the study indicate normal distributions before irrigation and 24 hours after irrigation. The spatial distribution of PR before irrigation and 24 hours after irrigation is related to normally distributed physical properties of soil, such as soil mechanical composition, rather than soil hydraulic conductivity. As reported by Long et al., soil compaction is particularly concerning as it leads to the degradation of the physical, chemical, and biological properties of the soil. Soil compaction negatively affects crop growth, reduces yields, and poses a significant threat to food security and the overall sustainability of agricultural systems. The progress of agricultural mechanization has caused, in other words, mechanical compaction, which can represent soil degradation [39]. As Sidhu and Duiker point out, soil compaction affects not only yields but also crop height. The effects of compaction on yield are greatest when the crop is under stress (e.g., drought or excessively wet growing season) [42]. Since soil compaction mainly reduces soil porosity (or increases soil bulk density), increasing soil porosity (or reducing bulk density) is an obvious way to reduce or eliminate soil compaction.

Soil compaction management, especially in arid and semi-arid areas, can be achieved through the appropriate use of some or all of the following technologies, such as adding organic matter, controlled traffic, mechanical loosening such as deep loosening, and selecting crop rotations that include crops and pasture plants with strong roots capable of penetrating and breaking up compacted soil. Improved soil management techniques are essential to ensure that the physical conditions of the soil are not compromised and to promote practices that increase organic matter content, reduce tillage, and maintain agricultural land use [43]. The use of irrigation and intensive crop production results in increased yields on the one hand, but on the other hand, it changes soil properties (moisture, penetrometric resistance, etc.) [40]. A potentially effective method for alleviating compaction stress is bio-tillage, which utilizes crop root systems as a modern tillage tool [44]. An example of this method of tillage is the application of deep-rooted cover crops that penetrate compacted soils and thus improve soil structure [45]. Unlike traditional tillage, bio-tillage is based on the function of roots, the creation of pores, and the change in soil structure for crop growth [46]. The root system of the cultivated crop is limited to existing structural pores if the penetrometric resistance increases with measurement depth [47]. An advantage for crops is also increased access to nutrients and water [48]. In the early stages of research and application, cover crops were considered beneficial in terms of reducing soil erosion, while at a later stage, the concept of using roots gained application for bio-tillage with cover crops [49]. Bio-tillage improves the physical properties of the soil, with the positive result of reducing resistance and improving root penetration through the soil structure [50, 51]. Practical examples also point to improvements in soil physical properties under no-till conditions, where, in a 5-year no-till system, planting a selected crop led to a reduction in soil bulk density and penetration resistance (the available water content in the soil increased) [52]. The cultivation of millet and hemp did not yield positive results regarding the monitoring of soil physical properties, root development, and yield during the first year of the long-term experiment. An interesting finding was that higher penetration resistance was maintained in the surface layers (without tillage, the surface layer became more compacted – as indicated by parameters of porosity, soil density, and penetration resistance), but resistance decreased in the deeper layers (0.20-0.40 m). Results similar to those in our study were also observed, i.e., critical levels of compaction that limit root penetration and crop yields vary depending on the crop and soil texture class (penetration resistance values >2 MPa in coarse-textured soils and >3 MPa in fine-textured soils may be critical limits). These cover crops also improved root growth, soil microporosity, and overall porosity. Cultivation of millet and hemp in a long-term production system can therefore improve soil physical properties (e.g., soil water availability for plants) [53]. Greater root development

promotes better utilization of water and nutrients from the soil, which provides greater production stability, especially during periods of prolonged drought. In addition to the above, these studies also confirm improvements in soil properties even after a longer period of cultivation [54, 55]. Greater root development of crops in the soil is facilitated by root channels (so-called biopores) formed during decomposition, which guide deep root growth. Continuous biopores act as pathways connecting the soil surface to deeper layers, thereby ensuring soil aeration, alleviating compaction, and improving water infiltration into the soil. During the growth process, root expansion should bring soil particles closer together, which promotes the development of soil structure and porosity [56]. Another study focused on the cultivation of another crop (*Raphanus sativus*) in sandy loam soil, where the results pointed to more favorable soil properties (reduction in compaction and penetrometric resistance and improvement in water movement in the soil) [50]. Bio-tillage has proven to be an effective strategy for mitigating adverse soil compaction, improving soil structure, increasing crop yields, and ultimately enhancing the sustainability of agricultural practices [39]. In addition to the above-mentioned positive properties, bio-tillage also indirectly increases the organic matter content [57]. Several years of studies have also pointed to the fact that the biological pores created promote the growth of subsequent crops [58]. Biological pores, which are created, for example, by the decomposition of roots from previous crops, provide more transitional porosity and lower monitored soil resistance [59]. Other studies agree with this finding [60].

Based on the results, it can be concluded that root growth and development within the soil profile contribute to an improvement in the soil's physical and hydraulic properties, although this effect likely becomes apparent only after a longer study period.

Conclusions

The article focused on evaluating the zonal variability of soil moisture content (SMC) and penetrometric resistance (PR) during the cultivation of alfalfa under irrigation. The research was conducted at monitoring points, and the results were subjected to statistical and deterministic analysis. The variability of the examined properties at individual measurement dates was expressed by map displays of variability using the deterministic Spline method. The results were also subjected to Distance Matrix and Hierarchical Clustering analysis. Based on the established hypotheses, the research measurements and analyses performed, and the results achieved, the following conclusions can be stated:

- Our hypothesis regarding the monitoring of changes in soil moisture variability has been supported by the more consistent results from our most recent

studies. Given the low number of irrigation applications, we did not observe a significant effect of irrigation on soil properties during the monitoring period.

- The soil moisture examined at individual sampling dates and horizons showed demonstrable differences in dependence. When observing individual horizons, we found significant results with the highest F parameter values between tertiary and secondary measurements (60 cm horizon → $F = 55.22$, 20 cm horizon → $F = 47.57$, 40 cm horizon → $F = 42.66$).

- Our third hypothesis was also confirmed: within a single growing season, alfalfa cultivation did not significantly reduce soil compaction and, under certain conditions, actually worsened deep soil compaction. The increase in compaction during the first growing season may also have been caused by the fact that no agricultural machinery was used for tillage and the crop had not yet had time to spread its roots sufficiently. We believe that further years of cultivation and subsequent research will demonstrate a reduction in soil compaction resulting from the introduction of forage crop cultivation. A comparison of irrigated and non-irrigated areas using the correlation method between pilot and secondary measurements at selected monitoring points showed a strong dependence of values in the irrigated part, but in the non-irrigated area, the dependence was weak to moderate. Tertiary measurements also showed significance.

Abbreviations

BPEJ	- Bonified Soil-Ecological Units
PR	- Penetrometric Resistance
SMC	- Soil Moisture Content
MP	- Monitoring point

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AI Usage Disclosure Statement

DeepL Translator (deepl.com/cs/translator#en/sk/collector%20ring%0A) was used only for translating parts of the text and for language editing. The AI tool was not involved in generation of data and outputs. The authors, who assume full and exclusive responsibility for the final content, scientific integrity, and originality of this work.

Conflict of Interest

The authors declare no conflict of interest.

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