J. Hydrol. Hydromech., 70, 2022, 3, X–X
https://doi.org/10.2478/johh-2022-0015

sciendo Journal of Hydrology and Hydromechanics Institute of Hydrology SAS

Long-term soil water content dynamics under different land uses in a small agricultural catchment

Ágota Horel, Tibor Zsigmond, Sándor Molnár*, Imre Zagyva, Zsófia Bakacsi

Centre for Agricultural Research, Institute for Soil Sciences, Herman O. St. 15, 1022 Budapest, Hungary.
* Corresponding author. Tel.:+36-30-564-1384. E-mail: molnar.sandor@atk.hu

Abstract: Longer term monitoring of soil water content at a catchment scale is a key to understanding its dynamics, which can assist stakeholders in decision making processes, such as land use change or irrigation programs. Soil water monitoring in agriculturally dominated catchments can help in developing soil water retention measurements, for assessment of land use change, or adaptation of specific land management systems to climate change. The present study was carried out in the Pannonian region (Upper-Balaton, Hungary) on Cambisols and Calcisols between 2015 and 2021. Soil water content (SWC) dynamics were investigated under different land use types (vineyard, grassland, and forest) at three depths (15, 40, and 70 cm). The meteorological data show a continuous decrease in cumulative precipitation over time during the study with an average of 26% decrease observed between 2016 and 2020, while average air temperatures were similar for all the studied years. Corresponding to the lower precipitation amounts, a clear decrease in the average SWC was observed at all the land use sites, with 13.4%, 37.7%, and 29.3% lower average SWC for the grassland, forest, and vineyard sites, respectively, from 2016 to 2020 (measured at the 15 cm depth of the soil). Significant differences in SWC were observed between the annual and seasonal numbers within a given land use ($p < 0.05$). The lowest average SWC was observed at the grassland (11.7%) and the highest at the vineyard (28.3%). The data showed an increasing average soil temperature, with an average 6.3% higher value in 2020 compared to 2016. The grassland showed the highest (11.3 °C) and the forest soil the lowest (9.7 °C) average soil temperatures during the monitoring period. The grassland had the highest number of days with the SWC below the wilting point, while the forest had the highest number of days with the SWC optimal for the plants.

Keywords: Forest; Grassland; Soil water regime; Vineyard; Climate change.

INTRODUCTION

Adequate moisture content in soils is a vital key for a healthy ecosystem, where the soil-plant-water system needs to be in balance to avoid ecological adversities. Longer term monitoring of soil water content on a catchment scale, where different land use types or vegetation conditions are present, is the key to understanding its dynamics. This, in turn, can assist stakeholders in decision making processes, such as land use change or irrigation programs. Moreover, long-term monitoring also helps scientists to better estimate future scenarios of climatic changes and their impacts on agricultural lands (Horel et al., 2022), or to expand water retention measurements from farm to catchment scale.

Soil water contents can differ greatly at different land use sites due to different site characteristics and/or management, including vegetation type and soil physical properties (Abdelkadir and Yimer, 2011; Fu et al., 2003; Jakab et al., 2017). At the same time, no significant differences in SWC between land use types were reported as a result of many field based studies or sometimes the differences were found only for some specific land use types (Gao et al., 2014; Niu et al., 2015). However, SWC databases differ greatly between researches. Some studies use small number of measurements or short monitoring periods over large areas, while others focus on long monitoring periods in smaller study areas (Brocca et al., 2012). Although studies on SWC are well-presented in scientific literature, data on continuous SWC measurements on plots with different land use over several years where the yearly differences within a land use can be analyzed are still limited.

Plant available water is the water content between field capacity and wilting point. Outside this range plants experience water related stress affecting plant development or crop production. Water deficiency coupled with high air temperatures also can cause a decrease in crop production (Ihsan et al., 2016; Nicolas et al., 1984) or grassland productivity (e.g. forage supply for livestock) (Craine et al., 2012; De Boeck et al., 2016). The drought of 2018 in most Central-European countries resulted in early-wilting of trees (Brun et al., 2020; Schuldt et al., 2020), causing high tree mortality that can considerably change ecosystem functions and composition of ecological communities in forests (Anderegg et al., 2013). Drought resilient vegetation species in areas with increasing air temperature and precipitation deficiency are outcompeting other species in natural vegetation such as grasslands, and being more frequently sown in arable lands. The drought-tolerant species further influence ecological changes in arid or semi-arid lands as found by Móricz et al. (2021) in forest ecosystems.

Soil parameters that greatly influence SWC, and water movement in the soils are: particle size distribution, organic matter content, and bulk density (Gupta and Larson, 1979). Particle size distribution, and consequently the pore size distribution and soil hydraulic characteristics, is one of the main inherent factors affecting water infiltration to the soil (Cosby et al., 1984). Soils with high sand content have faster infiltration rates than clayey soils depending on the amount and type of clay minerals. Similarly, the ability of soils to retain water changes with soil texture, clayey soils tend to hold more water than soils with dominantly coarser soil texture such as sand. Soil organic carbon is another important factor influencing soil water movement through the unsaturated subsurface, as soil particles can become aggregated by organic and inorganic materials present in soils. As such, SWC has been shown to be directly related to the soil organic matter content (Gupta et al., 1977). Moreover, the relationship between soil particle sizes, organic matter content, and bulk density was the focus of many studies. Chaudhari et al. (2013) found that soil organic matter and clay contents of soils adversely affect soil bulk density. Increasing soil bulk density can increase soil matric potentials (Box and Taylor, 1962) and consequently can influence plant available water.

Besides soil physical and chemical parameters, the types of vegetation can greatly influence the amount of precipitation that can reach the soil surface. A dense vegetation canopy intercepts raindrops, which might not reach the ground, especially for smaller precipitation events, or, the non-evenly distributed, rainwater might result in heterogeneous soil water content. Canopy storage capacity is a major part of the water balance. Ochoa-Sánchez et al. (2018) found that canopy storage of an Andean grassland can be around 2 mm, which is similar to tree canopy water storage determined by Hadiwijaya et al. (2021). Most studies in current literature show that the greatest relative throughfall among land use types can be obtained in forests while the greatest stemflow, when the rainwater drips from the stems, occurs in grasslands (Sadeghi et al., 2020). In a forest environment, besides rainfall intensity, forest litter also influences the amount of rainwater entering the soil matrix (Du et al., 2019). Root water uptake, which depends on the vegetation succession stages (Šurda et al., 2015), is another important factor influencing soil water content. Tree and grapevine roots can go deep into the soil enabling soil water uptake from lower soil layers.

Another important factor driving changes in SWC is the air and soil temperature. It affects evaporation rates from bare soil surfaces, plant canopy surfaces, and also the overall transpiration values at vegetated areas. Evapotranspiration is one of the important components of the water balance equation. Changes in water budget at catchment scale vary by land use dominancy, as forested areas might have higher evapotranspiration compared to grassland-dominated catchments (Zhang et al., 2001). Grassland evaporation rates might vary between 4.1 and 6.2 mm d^{-1} (Kelliher et al., 1993), while for areas with denser vegetation, such as forests, higher transpiration and rainfall interception are being forecasted (Zhang et al., 2016), consequently further influencing the trend in current soil water regime.

The aim of the present paper is SWC assessment for different land use types over five consecutive years. The two farthest land use sites were less than 0.7 km apart. Our main focus was on studying the changes in soil water dynamics over the time within a given land use; therefore, comparisons between land use types are mainly presented for general catchment information. We also explored some of the plants' abilities to adapt to the changing environmental conditions (i.e. lower precipitation and increased average air temperatures), which might determine future agricultural sites on a catchment scale. The collected long-term data provided us with information on wide spectra of precipitation and air temperature variances, compared to the median values. As climatic changes affect soil water budgets at different land use and vegetation sites, a more complete understanding of current soil water response to changing environmental conditions on a field scale is necessary. After analyzing the soil water regime differences at different land use sites, resulting from differences in soil physical properties and vegetation cover, it was hypothesized that the annual and seasonal variances in precipitation and air temperature greatly affect plant available water in soils.

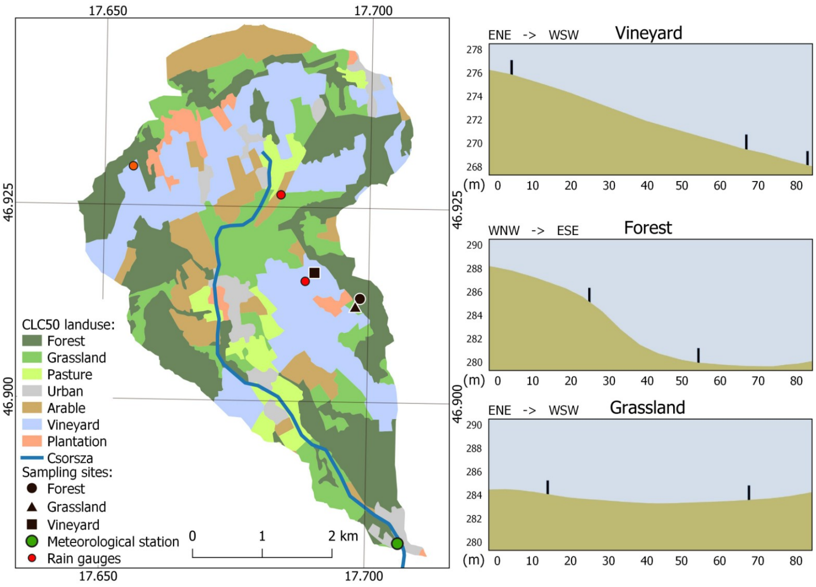
MATERIALS AND METHODS

Site information

The present study is a part of a more complex project set up at a small agricultural catchment (called Csorsza catchment; with Csorsza stream being a part of the water network feeding Lake Balaton, Hungary; Figure 1). The catchment has a total area of 21 km^2 and is located in the Upper-Balaton region. Continental climate with oceanic and Mediterranean influences is dominant in this region. It is usually hot and dry in the summer season, and cold in the winter season with most precipitation events occurring during the spring and fall months. The region is described as moderately rain deficient, with the mean annual precipitation being around 600 mm and the average wind speed 3 m s^{-1} (Dövényi, 2010). Annual sunlight is between 1970 and 2000 hours and mean annual air temperature is about 9.2–10.0 °C. During the growing season (from around early May to late October), the mean air temperatures are between 15.5 at higher elevation points and 16.5 °C at the lower elevation points (Dövényi, 2010).

Within the catchment, for the purpose of the present paper, three land use sites (vineyard, grassland, and forest) were selected to monitor SWC and soil temperature (Figure 1). The cultivated variety of grape was Furmint (*Vitis vinifera* L.). The vineyard currently has grass-strips between rows, with no tillage soil management. There is normally one light grapevine topping carried out in every spring. Regular weed control with herbicide is being performed when necessary. Harvest time is usually between late September and late October, depending on the ripeness of the grapes. The study site is part of the Balaton Upland wine-growing area, with vines being grown in all the suitable areas. At the forest site, a mix of sessile oak (*Quercus petraea* L.) and black locust (*Robinia pseudoacacia* L.) trees are present. The grassland site has tall grass along with some drought-tolerant plant species. The grass is being cut once a year if the precipitation amount is sufficient for plant growth. The distance between the vineyard and the forest is approximately 650 m, between the vineyard and the grassland is 690 m, and between the forest and the grassland is 80 m (Figure 1). For the land use sites no land use changes were occurring during the last several decades; however, it is a common land use change process to convert forests to grasslands and grasslands to vineyards in this region. There is no irrigation at this catchment, all the farmlands are rain-fed. Topographic elevations at the site are 268 (vineyard), 281 (grassland) and 285 m (forest) above the sea level (Figure 1).

The study area is part of a small basin on the NW side of Balaton uplands. The soils of the studied sites are Cambisols and Calcisols, according to WRB (2015). Part of the soils was formed on loess material, in which the original carbonates were washed into the deeper layers of the profiles. From the lithological point of view, the structure of the area above the Palaeozoic basement is typically two-layered: the solid Triassic limestone is overlain by young Tertiary sediments (mainly loess and slope-formed debris). At the highest elevations, where limestone outcrops, Leptosols are the most common soils (WRB, 2015). Down the Csorsza-stream valley, the loose, loessy sediment cover gradually increases in thickness. Where it is less than half a meter thick Epileptic Cambisols are found, covered with grassy vegetation. Where the loose sediment is more than half a meter thick Endoleptic Cambisols are being formed and they are most suitable for the establishment of woody plants.



a) b)

Fig. 1. Area of the Csorsza study catchment showing (a) locations of sensors for continuous monitoring of soil water content and soil temperature, rain gauges, and the main meteorological station; (b) slope inclination and positions for the studied land use types, including discrete soil sampling/measuring points (small black lines).

Where the topsoil is poorly developed, Calcisols are predominant. The valley bottom is characterized by alluvial sediment mixed with loess, with arable lands in the drier areas and pastures in the periodically waterlogged areas.

Soil profiles were excavated at three land use sites (Figure 1) to better understand SWC and soil water infiltration through the soils. One of the soil profiles was excavated in the vineyard, in the lower third part of the slope, where there was an evidence of former deep cultivation and the soil profile development was poor. The soil was classified as Cambic Calcisol (Anoclayic, Endoloamic). These soils cover approximately 29% of the total catchment area. In the topographically exposed parts of the catchment, the loess cover is thinning, partially or completely eroded. Where the loess cover is absent, the mountain-forming, mesozoic limestone appears near the surface in dense debris or as the continuous solid rock at 0.5–1 m depth in the soil profile. The weathering residue of the limestone mixed with loess material forms the fine earth part of the soils. The soil under the grassland was classified as Epileptic Cambisols (Loamic). It covers approximately 23% of the total catchment area. The soil under the forest was classified as Endoleptic Cambisols (Anoloamic). Forests cover 29% of the total catchment area. At the bottom of slopes or in the river valley, the clay content of accumulated sediments is generally higher.

Soil sampling

To study the basic physical parameters of bulk density and pF values, undisturbed soil samples (100 cm^3 in volume) were collected in triplicates at all the land use site locations from the soil depth of 15 cm. Disturbed soil samples were also collected to determine particle size distribution and soil chemical parameters.

Soil physical properties

Particle size distribution was determined using the sieve-pipette method. The soil:water suspension was mixed in a sedimentation cylinder, then sampled with a pipette to collect particles of a given size (Buzás, 1993).

The soil water retention data (saturated and residual water contents (θ_{sat} and θ_{res}, respectively) as well as the field capacity (θ_{FC})) were determined according to the standard methods in sand, kaolinite boxes, and pressure membrane extractor (Cresswell et al., 2008). Soil bulk density was determined by a standard gravimetric method. All the physical soil parameters were measured in triplicates.

Soil chemical properties

Soil samples for chemical analyses were collected from the upper 0–20 cm layer in three replicates from each sampling site. In total there were 36 samples per site collected over 12 sampling days during the period of study, therefore, the average values of 36 samples for chemical characteristics and electrical conductivity of the soils were used in the discussion. Samples were homogenized, sieved (< 2 mm), and analyzed for total nitrogen (N_{Tot}), NH_4^+-N, NO_3^--N, K_2O (Al soluble), P_2O_5 (Al soluble), soil organic carbon (SOC) content, and pH_{H2O}. The amount of N_{Tot} was determined using the modified Kjeldahl method (ISO 11261, 1995) and the SOC content was measured by wet digestion using the Tyurin method. K_2O and P_2O_5 content in the soils were measured using an inductively coupled plasma optical emission spectrometry (Quotation ICP-OES, Ultima 2, Thermo Fischer Scientific, Waltham, MA, USA) after ammonium lactate extraction (Al). The soil pH was measured in 1:2.5 soil:water suspensions. Soil element concentrations are reported as mg kg^{-1} of dry weight soil.

Meteorological data

In 2016 a meteorological station was installed at the outlet of the Csorsza catchment, which is approximately 2.5 km from the farthest sampling site (Figure 1). This main station collects data on air temperature, atmospheric pressure, precipitation, wind speed and direction, relative humidity, and radiation. Before the meteorological station was installed, all necessary information we collected from nearby stations. To further monitor precipitation patterns several rain gauges (ECRN-100, Decagon Devices) with 0.2 mm resolution were placed at different locations within the catchment for minimizing discrepancies in local rain events.

Soil water and temperature

Volumetric soil water content (SWC) and soil temperature monitoring was conducted from November 2015 at 15, 40, and 70 cm below the soil surface at the studied land use sites using 5TM soil water and temperature sensors (Decagon Devices Inc., Pullman, WA, USA). The data were collected every 10 minutes, resulting in 144 SWC data per day. In the case of grassland, due to the highly eroded topsoil, sensors could be placed only at 15 and 40 cm below the soil surface. One sensor set per site, with one sensor per depth was used. Data before 2016 and after 2021 were used only for winter periods.

Gaps in the data occurred due to instrument failure or connection problems with the data loggers.

Statistical analysis

The effects of seasonal air temperature and precipitation variations on soil water content at different land use sites (vineyard, grassland, or forest) were analyzed using nonparametric statistical analyses of the Wilcoxon signed rank test or the Wilcoxon rank sum test and Kruskal–Wallis ANOVA for the non-normally distributed datasets. Prior to statistical analyses, to compare the land use sites (when sites were not individually analyzed), the data on soil water and temperature were filtered: all days where one of the treatments had missing data were omitted from the datasets. All statistical calculations were performed using the software package R (R Core Team, Version 4.0.2). Statistical significance of differences between the data sets was determined at $p < 0.05$. Same small letters in Figures and Tables indicate no significant differences, while different letters indicate significant differences between the investigated parameters at $p < 0.05$.

RESULTS

Soil physical and chemical characteristics

There were significant differences between the soil physical parameters at the studied land use sites. The soil texture, particle size distribution, and water content of the soils are presented in Table 1. The three studied soils significantly differed in both clay and sand contents: the vineyard soil had the highest clay and sand contents while the forest soil had the lowest clay and vineyard had the lowest sand contents. The forest soil had significantly higher silt content compared to the vineyard or grassland. The saturated water content of the soils was the highest at the vineyard site ($p < 0.05$) and the lowest at the forest site. The field capacity and residual water contents of the soils were similar between the vineyard and grassland sites, while significantly lower values were observed for the soils at the forest site (Table 1).

The basic soil chemical characteristics for the investigated land use types are summarized in Table 2. Most of the investigated soil chemical parameters were significantly different among land use types. The highest SOC content was measured in the forest soils, while the lowest in the vineyard soils. Due to annual fertilizer treatments, helping plant growth and fruit production, the vineyard had significantly higher K_2O and P_2O_5 contents than for grassland or forest.

Table 1. Soil physical characteristics for different land use sites (15 cm). Different letters indicate significant differences between the soil physical parameters. θ_{sat} – saturated water content; θ_{FC} – field capacity water content; θ_{res} – residual water content; EC – the electrical conductivity of the soils. The results are presented in the form: arithmetic mean ± standard deviation, with 3 replicates per land use type.

Land use types		Vineyard	Grassland	Forest
Coordinates	Lat.	46.9165474 N	46.9122988 N	46.9128225 N
	Long.	17.6897680 E	17.6975406 E	17.6972401 E
Soil texture		Clay	Clay loam	Silty clay loam
Bulk density	g/cm^3	1.23±0.0b	1.33±0.1ab	1.40±0.1a
Sand	%	12.1±1.3c	22.7±0.8a	15.9±0.3b
Silt	%	36.2±2.7b	39.9±2.8b	54.9±0.5a
Clay	%	51.8±2.7a	37.5±2.3b	29.2±0.3c
θ_{sat}	%	57.1±0.6a	51.8±2.8b	47.8±3.7c
θ_{FC}	%	44.0±2.2a	40.0±2.0a	33.1±1.7b
θ_{res}	%	4.6±0.7a	4.4±0.3a	2.8±0.4b
$EC_{2.5}$	mS/cm	0.32±0.04a	0.32±0.12ab	0.21±0.08b

Table 2. Chemical characteristics of the soils for the land use sites investigated in the experiment. SOC – soil organic carbon content. Different small letters indicate significant differences between the soils from different land use types per chemical parameter. The results are presented in the form: arithmetic mean ± standard deviation, with 36 replicates per land use type.

Land use types		Vineyard	Grassland	Forest
pH_{H2O}		7.89±0.1a	6.61±0.3b	5.98±0.4c
K_2O	mg/kg	942.1±226.3a	317±81.0b	214±53.9c
P_2O_5	mg/kg	127.4±66.0a	17±9.6c	30.5±9.33b
Total N	%	0.23±0.03c	0.35±0.08b	0.45±0.12a
NH_4^+-N	mg/kg	7.2±2.0b	9.0±3.0a	8.8±2.2a
NO_3^--N	mg/kg	12.3±9.2a	3.1±2.4b	13.6±9.4a
SOC	%	2.0±0.3c	3.3±0.9b	4.3±1.2a

Meteorological data between 2015 and 2021

The meteorological data of the catchment area are summarized in Table 3. For the purpose of better understanding the different intervals of meteorological data on plant growth, there are three time intervals analyzed: full year, growing period (May 1 – October 31), and non-growing or winter period (November 1 – April 30). The yearly precipitation totals varied over the monitoring period, with the largest annual precipitation registered in 2016 (740 mm) and the lowest – in 2020 (547 mm). The year 2020 was particularly dry with a substantially lower precipitation sum compared to the other years (35.2% less than in 2016). However, the driest growing season was in 2019. While the annual and the growing season precipitation totals varied among years, the differences were not statistically significant ($p > 0.05$). The total precipitation of the summer months (June 1 – August 31) was also investigated and it was found that 2019 had significantly lower precipitation during this period compared to 2016 ($p < 0.05$; data not shown).

Neither the average annual air temperature nor the average temperature of the growing season differed significantly between the studied years. However, when only the summer months (June 1– August 31) were considered, the air temperature in 2019 was significantly higher than in 2016 (data not shown).

The monthly distribution of precipitation and the average monthly air temperature over the investigated period are presented in Figure 2. The highest average monthly precipitation within the studied period was measured in July and August (83.3 and 81.2 mm, respectively) and the lowest was in January (24.4 mm). The hottest average monthly air temperature within the studied period was measured in July (21.0 °C) and the lowest in January (–0.4 °C). Lower monthly precipitation totals were registered during the first months of 2019 and 2020, if compared to the same months of the other studied years.

Changes in soil water content and temperature over the time

Figure 3 shows the changes in SWCs over the years for all the investigated land use sites. As the sites had diverse vegetation and were covered with the soils significantly differing in physical properties, the SWC at different depths of these soils was also significantly different. The lowest average SWC was observed for the grassland soil, which was almost 40% lower than the SWC at the other two sites (Figure 3). The average SWC of grassland was lower at 40 cm depth than at 15 cm (9.9 and 13.7%, respectively), while the other two soils had the highest average SWC at the 40 cm depth compared to the other two depths (Figure 3).

Table 3. Total annual precipitation and average annual air temperature for different studied years. *n* – number of days. Minimum and maximum temperatures were based on daily average values. * – data were not gathered throughout the entire years. † Growing season – period between May 1 and October 31.

	n	Temp ave (°C)	Temp min (°C)	Temp max (°C)	Total precipitation (mm)	Growing season † precipitation (mm)
2016–2020	1801	10.7			645.3	403.7
2015.11–12*	57	5.9*	–3.7*	16.8*	13.8*	–
2016	366	11.2	–7.9	26.8	740.0	530.8
2017	365	10.1	–12.8	27.4	720.0	436.2
2018	365	11.0	–11.4	25.5	652.7	354.5
2019	361	11.0	–4.8	25.9	566.2	304.2
2020	365	10.5	–4.8	25.4	547.3	392.6
2021.01–04*	113	4.0*	–7.6*	13.4*	250.6*	–

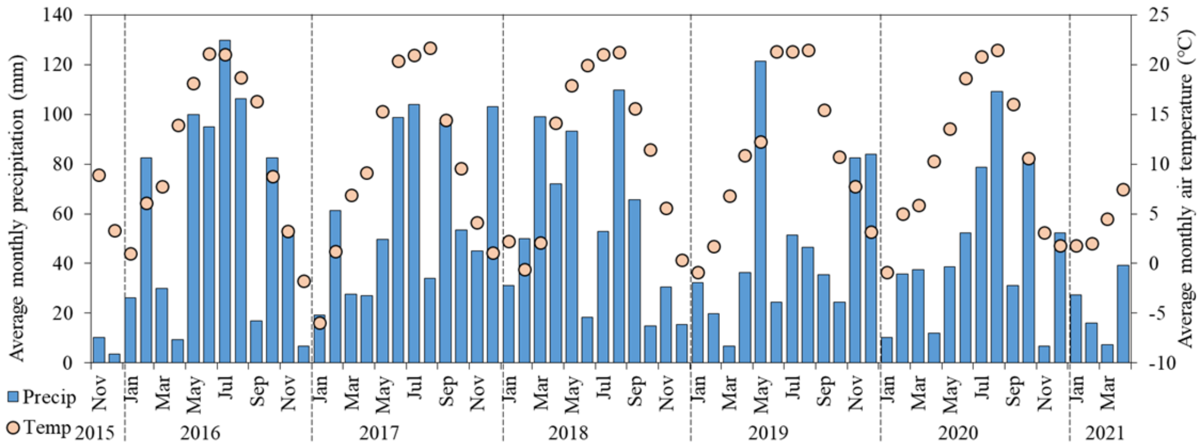


Fig. 2. Monthly precipitation and monthly average air temperature during the investigated period.

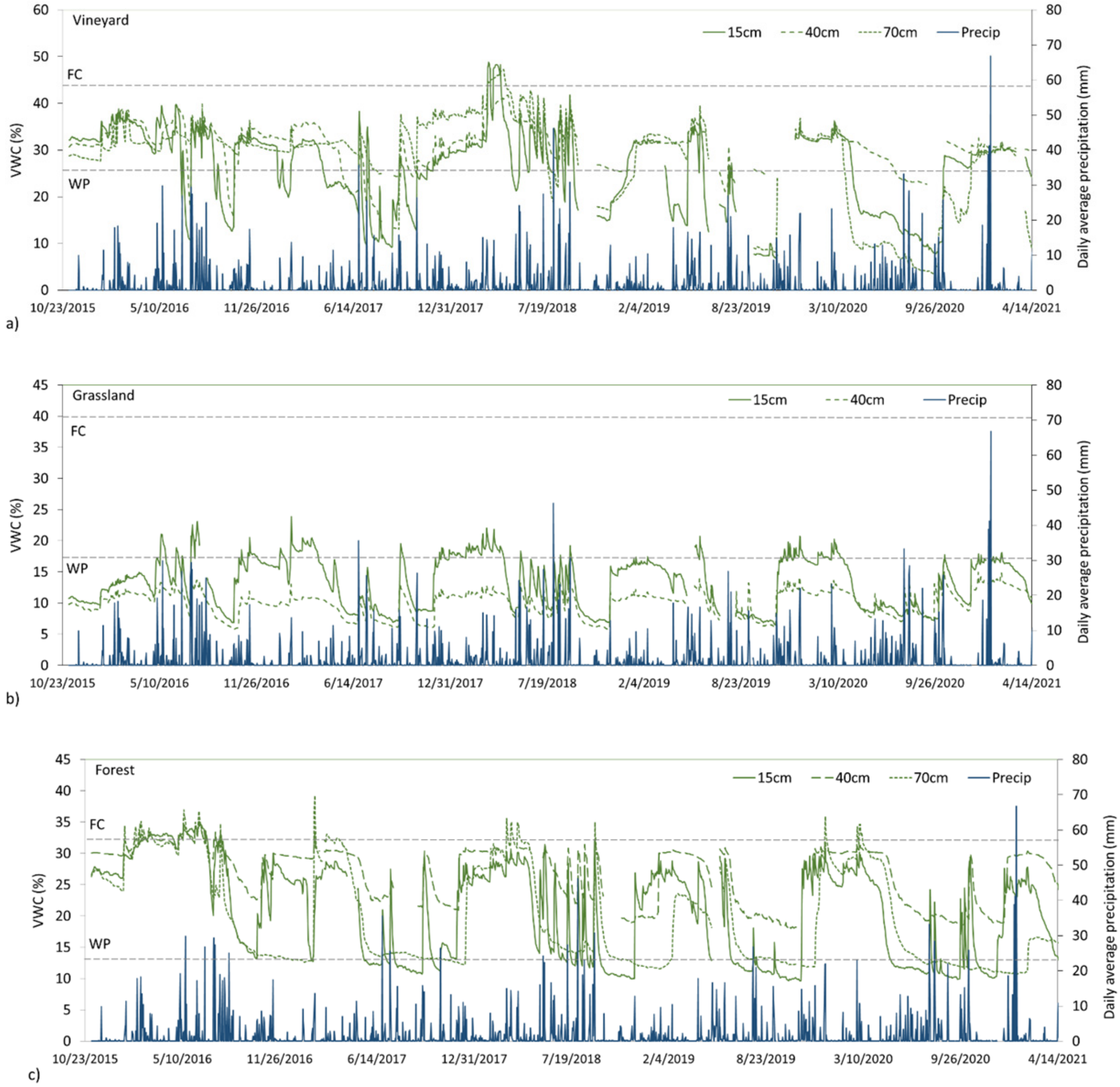


Fig. 3. Volumetric soil water contents (VWC) and daily total precipitation over the studied period of time at different depths for a) vineyard, b) grassland, and c) forest soils. *FC* – field capacity and *WP* – wilting point of the soil, for the 15 cm soil depth. 144 measurements per day were taken.

The average soil temperature was the highest for the grassland (12.3 and 12.4 °C for 15 and 40 cm depths, respectively), it was similar for the vineyard (12.2 and 12.3 °C for 15 and 40 cm depths, respectively) and the lowest for the forest (10.8 and 10.6 °C for 15 and 40 cm depths, respectively). Therefore, average annual soil temperature changes (data not presented) showed the largest difference for the forest soil ($p < 0.05$) compared to the other sites, where the canopy shade caused lower daily deviations related to the changes in air temperature compared to the other two sites. Based on the filtered data (after removing all days when data was not available for all the three sites) between 2015 and 2021, the average soil temperature in the forest was 9.7 °C, while in the vineyard and grassland it was 11.2 and 11.3 °C, respectively. Forest soil was characterized by significantly lower soil temperature compared to the soils of the other two sites at all investigated depths.

Changes in the average annual SWC and temperature

Variations in annual SWC were investigated within each land use site to better understand how the changes were dependent on the environmental parameters. The continuously decreasing yearly precipitation resulted in a similar SWC for 2019 and 2020, while most data from earlier years were significantly different ($p < 0.05$).

For the vineyard site, the lowest differences in SWC were observed in 2017 compared to the other years (Figure 4). At the 15 cm depth, both in 2016 and 2018 average SWC was significantly higher from all the other years, as well as at 70 cm depth in 2018 (Figure 4). The smallest variations to the annual precipitation and air temperature changes were observed for the grassland site, where the differences in the average SWC for 15 cm depth were not significant between 2017, 2018, and 2019 ($p >$

0.05), but in 2016 the SWC was significantly higher than in 2020. At the lower depth of 40 cm, SWC was significantly lower for 2017 compared to all the other years (Figure 4). For the forest site, SWC in the top layer differed significantly between the years, except for 2017 and 2019 (p = 0.657), with the highest SWC observed in 2016, and the lowest in 2020. At the 40 cm depth, all the years but 2018 compared to 2019 (p = 0.061) and 2019 compared to 2020 (p = 0.111) were significantly different, with the highest SWC noted in 2016. Similar differences in SWC were observed for the 70 cm depth as well: only in 2019 and in 2020 the differences were not statistically significant (p = 0.173) and the highest SWC was observed in 2016 while the lowest – in 2019 and 2020 (Figure 4).

The continuously decreasing SWC was observed at each land use site over the investigated time. The average annual SWC at the vineyard site was 29.3, 13.3, and 47.4% lower at 15 cm, 40 cm, and 70 cm depths, respectively, in 2020 (which was the driest year) compared to 2016 (which was the wettest year of our study). The grassland showed 13.4% lower SWC in 2020 at 15 cm depth, however, at 40 cm depth no change was observed over the investigated times, which might be due to the already very low SWC of this depth. The forest site also showed decreasing SWC at all the three depths in 2020 resulting in 37.7, 19.8, and 24.8% lower SWC at 15 cm, 40 cm, and 70 cm depths, respectively, compared to 2016 (Figure 4).

At the vineyard site, according to the statistical analysis, soil temperature did not differ significantly at 15 cm soil depth between the years, while at the lower depths soil temperature differed significantly (Figure 5), showing the highest soil temperatures in 2020. Grassland soil temperature showed no significant differences between the years at either depth. Forest soil temperature was similar to the temperature of the vineyard site. It did not differ significantly between the years at 15 cm depth but varied at lower soil depths (Figure 5): the highest soil temperatures were observed at 40 cm depth in 2018 and at 70 cm depth in 2019. Increasing soil temperature was observed for each land use site. From 2016 to 2020 the 6.3% increase in the average soil temperature was observed for all the land use sites, with the highest change detected in the vineyard at 40 cm depth (14.2%) and the lowest increase – in the forest at 40 cm depth (2.0%).

Effects of the growing season on soil water and temperature

To better understand the effects of vegetation (e.g. root water uptake, canopy interception, or evapotranspiration) on SWC, we also separately analyzed the data for winter or dormant, and growing or active periods. The winter period was between November 1 and April 31, while the growing season was the period between May 1 and October 31; resulting in 6 winter (non-growing) and 5 growing periods for the studied time.

SWC in the winter periods at most of the studied soil depths differed significantly at all sites with a few exceptions (most differences were observed in 2018 and 2020). SWC in the summer periods was different between the years and the depths for the vineyard site, with a few exceptions (e.g. 2016; Figure 6). During the growing seasons SWC at the grassland and forest sites was significantly different (between the years at 15 and 40 cm depths) in all years except 2020. Soil water content for the vineyard soil in 2017 and 2019 was similar at 15-cm and 70 cm depths, but in the other years statistically significant differences were observed, with the highest SWC observed in 2018 and the lowest in 2020 (Figure 6). During the growing season for the forest site, when the black locust and oak trees were active, the annual average SWC did not differ in 2019 and 2020, but significant differences were observed in the other years at 15 and 40 cm depths ($p > 0.05$) with the highest annual average SWC noted in 2016 (Figure 6).

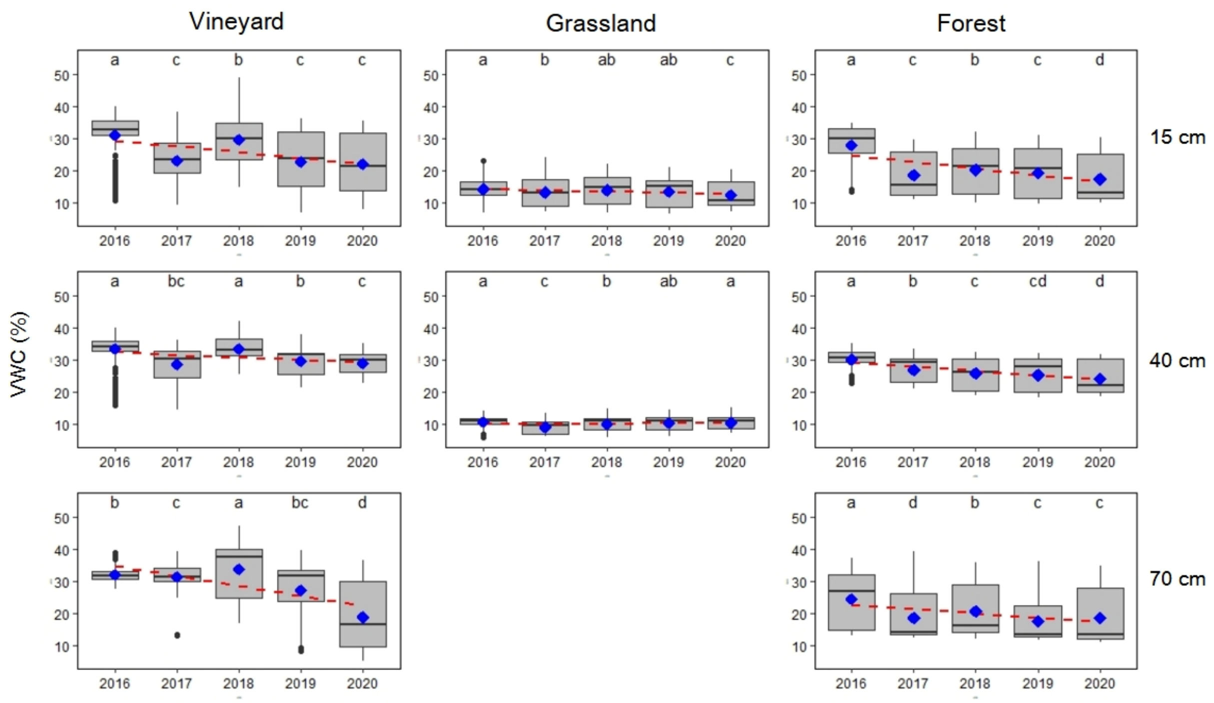


Fig. 4. Average volumetric soil water contents (VWC) at different sites at 15, 40, and 70 cm soil depths. Dotted lines show the SWC trendlines over time. Each data point shows yearly median (solid black line), mean (blue diamond), upper and lower quartiles, and minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range). Different letters indicate statistically significant differences between years of the given land use at specific depths. About 52,560 measurements of volumetric soil water content per year were taken.

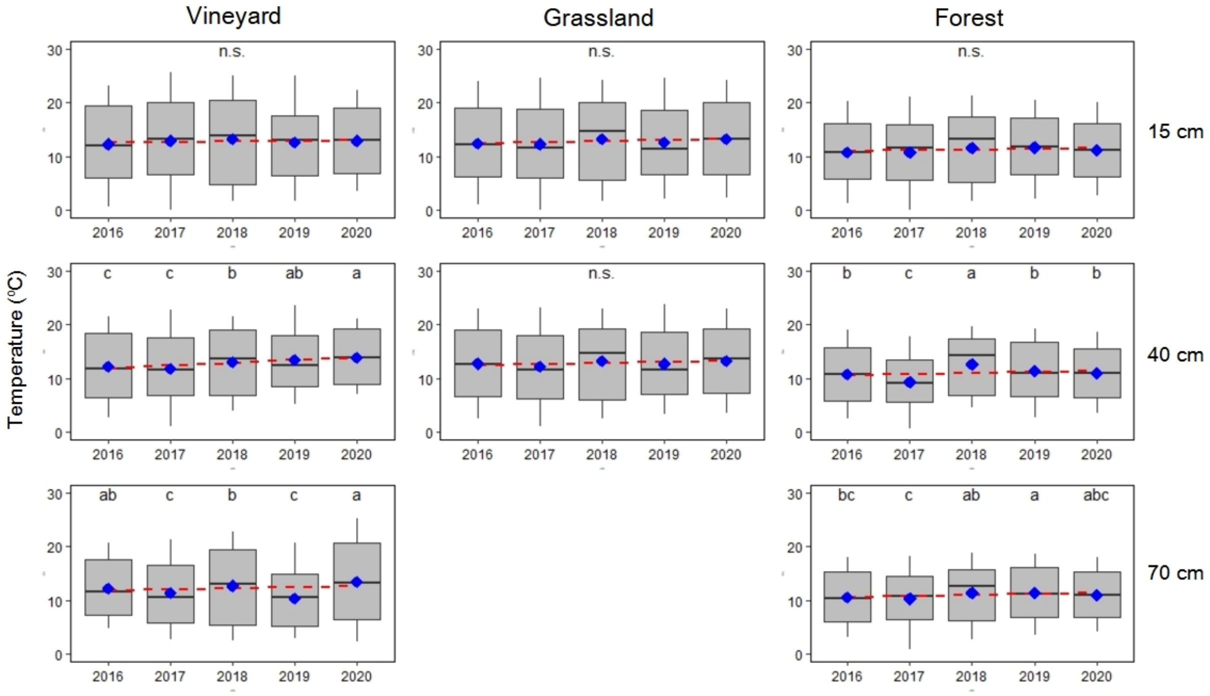


Fig. 5. Average annual soil temperatures for the different sites at 15, 40, and 70 cm soil depths. Each data point shows yearly median (solid black line), mean (blue diamond), upper and lower quartiles, and minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range). Dotted lines show the linear trend-lines for the soil water contents. Different letters indicate statistically significant differences between the years at specific depths. About 52,560 measurements of soil temperature per year were taken.

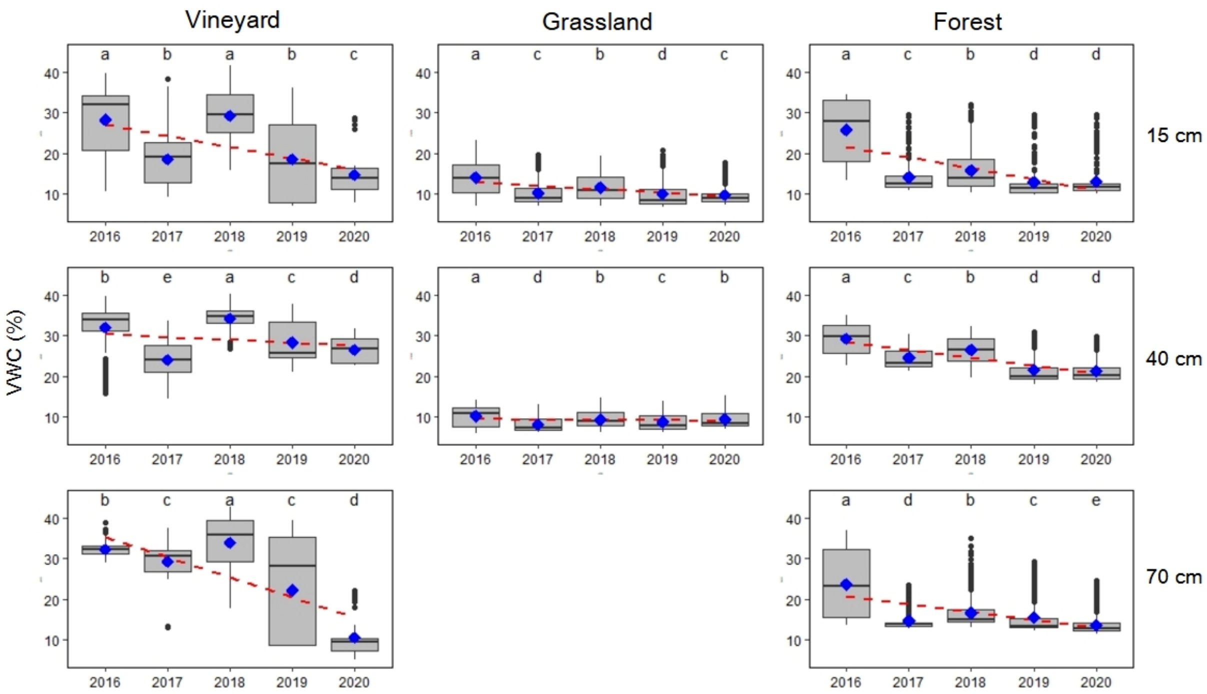


Fig. 6. Average annual volumetric soil water contents (VWC) during the growing season for the different sites at 15, 40, and 70 cm soil depths. Each data point shows median (solid black line), mean (blue diamond), upper and lower quartiles, and minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range). Dotted lines show the soil water content trend-lines over time. Different letters indicate statistically significant differences between years of the given land use at specific depths. About 52,560 measurements of volumetric soil water content per year were taken.

The winter of 2016 was characterized by significantly lower temperatures compared to the other five winter periods (data not shown). The year 2020 was characterized by the coldest summer period, with the average air temperature 16.8 °C compared to 17.9 °C in the hottest summer of 2018. The lower average air temperature in 2020 resulted in significantly lower soil temperatures ($p < 0.05$).

Table 4. Number of days when soil water (SWC) was below (< WP), within (Optimal), or above (> FC) optimal conditions for plants at different depths for the investigated period (2015 November – 2021 April). Data quantity refers to the percentage of data availability from the total study period, where 100% is the full 365 or 366 days of a given year.

	< WP	Optimal	> FC	Data quantity (%)
Depth		15 cm		
Vineyard	799	1016	22	92.0
Grassland	1675	255	0	96.6
Forest	561	1343	53	98.0
		40 cm		
Vineyard	363	1285	0	82.5
Grassland	1945	0	0	97.4
Forest	0	1727	29	87.9
		70 cm		
Vineyard	479	1245	38	88.2
Forest	531	1357	70	98.0

The obtained data enabled us to calculate the number of days when the soil water content was not optimal for plant growth, either below the wilting point (WP) or above field capacity (FC), which is summarized in Table 4. The majority of the grapevine roots develop in the top 100 cm of the soil and can go even much deeper (Bassoi et al., 2003), hence the grape sensitivity to drought conditions is lower if there is a sufficient SWC at deeper soil levels. The highest number of days (262) at the vineyard site with SWC below WP were observed in 2020 at 70 cm depth. In the vineyard, there were only a few days with SWC above FC in 2018 at the 15 and 70 cm depths (22 and 38 days, respectively). The highest number of days with SWC below WP was found for the grassland site, where most of the days during the years at 15 cm depth, and even through the entire years at 40 cm depth the SWC was below the WP. At the grassland site daily average SWC never reached the FC value for the entire period of the present study (2015–2021), not even after high precipitation events. However, as most of the vegetation at the grassland site has shallow and dense root systems, the upper portion of the soil layer is more crucial for the plant growth. Forest soils had an increase in the number of days when SWC was below WP over the time at 15 and 70 cm depths. 2016 was a distinguishable year for the forest with the SWC staying above FC most of the days.

DISCUSSION

In the present study five-year-long soil water and temperature data were used to investigate the effects of vegetation and changes in weather on the soil water regime at the land use sites. All analyzed land use sites of vineyard, grassland, and forest are distinctive in terms of vegetation, soil physical and chemical parameters but located in close proximity to each other and represent the majority of the catchment land use area. The conducted investigations allowed to have a closer look on the soil chemical and physical properties and plant traits in each land use area. These environmental factors help better understanding the differences between water movement through the studied soils.

Vineyards

In this region, the age of the grapevine often determines the soil management method. For younger grapevine, between rows tillage is a common method to help water infiltrate deeper for root development. However, after several years, grass strips are planted between the vine rows to reduce soil erosion as many vineyard sites are located on hillslopes. Grass strips help water retention (Van Dijk et al., 1996) and reduce pesticides and other pollutants leaching into the soil matrix, therefore preserving groundwater quality (Dousset et al., 2010). At the studied vineyard site, it was found that the SWC for most of the growing season of 2020 was below WP, especially at the 70 cm depth (184 days), which is a crucial depth for grapevine roots to extract water for plant development during drought periods. The soil of the vineyard site had the highest clay content, the lowest soil organic carbon content, and the lowest soil bulk density among the investigated soils. During drought conditions cracks can be observed frequently at the soil surface between the rows. These cracks might facilitate the drying of the soil deeper layers over a prolonged dry periods, but in the case of an intensive rainfall they also can help rainwater infiltration toward lower soil depths (e.g. 40 cm), promoting higher number of days with optimal SWC at this depth.

Grasslands

Water retention of soils can be closely estimated by the particle size distribution, organic matter content, and bulk density of the soil (Gupta and Larson, 1979; Mesoro et al., 2020). However, in grassland soils, organic matter content might better determine soil water contents than particle size distribution (Yang et al., 2014). The soil bulk density at the grassland site did not differ significantly from the soil bulk densities at the other sites, and the soil organic carbon content was similar to the soil organic carbon content of the other sites. Therefore, the lowest soil moisture content at the grassland site compared to the other two sites might be related to the differences in the particle size distribution of the soil and the vegetation of the area. Among the studied sites, the soil at the grassland site had the highest sand content (silty clay loam texture) with 3.3% of soil organic matter content, constraining water retention compared to the other sites. The grassland site has a shallow topsoil layer, varying from rocky surface to 30-50 cm soil depth depending on erosion levels. At the studied catchment, most of the grasslands are not managed and wild animal grazing occurs, but rarely. Also, the studied grassland site is located on a 10% slope, therefore, water ponding after heavier rains at this site is unlikely, while runoff is very common. Coupled with the dense vegetation at this grassland site, water infiltration is limited, hence low soil moisture is being observed at lower soil depths even after a substantial amount of precipitation. As the observed soil water deficit at this site is historically present, the vegetation is adapting to the conditions. Some of the vegetation at this site is known as drought tolerant, such species as *Helianthemum nummularium* L., *Salvia pratensis* L., or *Thymus* sp. Among them, *H. nummularium* L., or common rock-rose, and the prostrate shrubs (e.g. *Thymus* sp.) are two drought resistant plants known to adjust well to increasing drought conditions (Fridley et al., 2011; Grime et al., 2008). Zhao et al. (2017) investigated long-term changes in SWC at different land use types including croplands and grasslands, where the authors found that grassland soils had much lower average SWC compared to cropland soils and the main cause was most likely the deep grass roots absorbing a large amount of soil water. At the grassland site, studied in this paper, dense roots were present in the top 3-cm soil layer. The top 20 cm of the soil had visible mycelia present, consisting of a mass of thread-like hyphae growth binding soil particles, further influencing soil water entering the deeper soil layers.

Forests

The number of days with optimal SWC was highest at the forest site. However, from 2016 to 2020 a slight decrease in the average annual yearly SWC was also observed with the number of days with SWC below WP slightly increased. Based on future climatic scenarios, forests might be one of the most sensitive ecosystems to climatic changes in the region (Farkas et al., 2014). The forested area was 29% of the total catchment area, which was one of the highest total land areas beside vineyards (29%). As climate change is predicted to result in increased air temperatures and changes in precipitation patterns, trees may suffer from xylem embolism, restricted nutrient uptake capacity, or reduced growth when water availability is limited (Geßler et al., 2007). It has been shown that the phenotypic plasticity of oak trees, which is the ability to adapt to different environmental conditions, might be strongly adaptive towards warm margins (low altitude) but maladaptive towards cold margins (Duputié et al., 2015). Although black locust is a non-native tree species, it is wildly adapted to most European forest environments (Bolte et al., 2009), and is expected to further acclimate to climatic changes in this region as its presence is well known in drier regions around the world. Sessile oak, however, is native to this region and its adaptability requires further investigations. On a national level, climate change might lead to a severe reduction in sites climatically suitable for sessile oak forests (Czúcz et al., 2011); therefore in mixed forests, the different tree types might compete for the land, reducing ecological diversity of the sites.

CONCLUSIONS

Based on the obtained results it can be concluded that longer term soil water data are crucial when considering agricultural assessment and mitigating climate change related impacts. The meteorological data from 2016 to 2020 showed a decrease in precipitation amounts and a slight, non-significant, increase in air temperature highlighting the need for further investigations and application of water retention measurement techniques. In the conducted study, substantial differences in the soil water contents were observed between the investigated years and also between the different growing seasons. The results indicated that limited land use change potentials are present at the studied catchment as decreasing precipitation influences future land management. It was found that with an increased number of days when soil moisture is more scarce in the upper layers, mainly the longer-rooted plants can take the moisture up from the deeper soil layers, making these types of plants more preferable in this area. Moreover, a decrease in SWC of deeper soil layers at the vineyard site, which was found as a result of our study, coupled with hillslope location, can increase plant stress in the near future. The grassland site was characterized by the lowest average SWC, and by plants favoring arid conditions. Based on the results of the study, an increase in drought-related stress can be predicted for both vineyards and forests, while grassland is already displaying dominancy of drought-tolerant plant species. As climatic changes affect soil water regime in more distinct way year by year, long-term monitoring of soil water changes is becoming crucial for preparation for sustainable agricultural practices in the climate change conditions in the future.

Acknowledgements. This material is based upon work supported by the Hungarian National Research Fund (OTKA/NKFI) project OTKA FK-131792. This project has received funding from the Horizon 2020 research and innovation program of the European Union under grant agreement No. 862756 (OPTAIN). The authors would like to thank Szandra Baklanov and Imre Potyó for their help with field measurements and Ágnes Bányász for the laboratory work.

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Received 17 November 2021
Accepted 20 June 2022