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The soil moisture regime and groundwater recharge in aged forests in the Sand Ridge region of Hungary after a decline in the groundwater level: an experimental case study

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Abstract: The decline in groundwater levels is a cause of concern in many regions of the world, including the Sand Ridge of Hungary. The causes of the regional depletion range from rising air temperatures, changes in precipitation, domestic and agricultural groundwater use and past amelioration and recent afforestation, including the effects of drilling for crude oil exploration. The relations between the decline, the soil water regime and groundwater recharge under existing aged forests remained unclear thus far. Based on our monitoring of groundwater and soil moisture we aim to clarify this interplay in a new experimental site on the hilltop of the Sand Ridge. We compared three land-uses: a 41-year-old black locust (*Robinia Pseudoacacia*) offshoot forest, an 83-year-old first generation black pine (*Pinus nigra*) forest, and a grassland control site. The observed differences in the soil moisture profiles and dynamics were connected to the use of water by the given type of vegetation. We indicated a connection between the disruption of the groundwater recharge and the loss of contact of the rooting system of the forests with the deepening of the unconfined aquifer. Even if the aged forests could locally contribute to the decline, we conclude that the decline at the hilltop site that may be more strongly driven by other regional factors.

Keywords: Recharge; Groundwater decline; Soil moisture monitoring; Forest hydrology; Black locust; Black pine.

INTRODUCTION

The decline in available water resources is a global concern. Decreasing water table levels pose an increasing challenge to local populations and governments in many lowland regions around the world, since groundwater resources provide a significant part of regional water supplies. Anthropogenic influences and climatic impacts affect these to varying degrees. Places where significant decline in groundwater levels have already been observed, which indicate an imbalance between the natural groundwater recharge and groundwater abstraction, include parts of northeastern China, Mexico, Iran, Saudi Arabia, parts of northern Africa (Aeschbach-Hertig and Gleeson, 2012), northeast India (Rodell, et al., 2009), the Pampas in Argentina (Engel et al., 2005), and the Central Valley of California (Famiglietti et al., 2011). The primary causes behind this worldwide phenomenon are usually groundwater extraction for irrigation purposes and a reduced recharge as a consequence of climate change (Famiglietti, 2014; Wu et al., 2020).

Since groundwater depletion is a regional phenomenon, it requires regional strategies for the management of groundwater resources. With respect to groundwater recharge, Xanke and Liesch (2022) reported an observable groundwater decline in many Euro-Mediterranean countries, which indicates an imbalance between the natural groundwater recharge and groundwater abstraction as well as significantly negative trends in countries in Central and Eastern Europe. Effective management requires conclusive evidence and understanding of the effects of climate and land use changes on groundwater recharge (Owuor et al., 2016). However, beside climate, groundwater recharge may also be affected by a variety of factors with substantial spatial variability, particularly the topography, soil characteristics, and geology (Dean et al., 2015; Mattos et al, 2019). With respect to changes in land use especially in forest management, there is not sufficient and conclusive knowledge as to how afforestation or forest conversion may impact water resources on a regional scale (Dean et al., 2016).

It is accepted that in general, that forests can evaporate more water than herbaceous vegetation due to their larger leaf area index (LAI) and deeper root systems (Calder, 1998; Jackson, 1999; Kelliher et al., 1993; Nosetto et al., 2005; Schenk and Jackson, 2002). Afforestation is therefore expected to have the potential of reducing groundwater recharge, particularly in low-rainfall, high-evapotranspiration regions. On the other hand Sonnenborg et al. (2017) showed with catchment simulations that replacing current conifer forests in Denmark with broadleaf forests could, result in a significant increase in ground-water recharge and groundwater level. Ouyang et al. (2019) also demonstrated that forest land in a humid subtropical region slightly increased rather than reduced water recharge from the land surface into the groundwater as compared to that of agricultural land. Ilstedt et al. (2016) found that moderate tree cover could increase groundwater recharge in a cultivated woodland in West Africa and concluded that tree planting and various tree management options could improve groundwater resources. To the contrary, Owuor et al. (2016), who reviewed 27 studies (2 modelling and 25 experimental), studies reached different conclusions on changes in pre- and post land use concerning groundwater recharge. Their analysis indicated that forests have lower groundwater recharge rates than the other land uses investigated in semi-arid tropical/subtropical regions. Due to the variability in the reported magnitude of responses to environmental changes, it is clearly indicated that there is a need for site-specific studies to understand their effects. Owuor et al, (2016) also stressed that it is important that such studies also quantify the combined effect of multiple stressors.

In Hungary's Sand Ridge lowland region, a large-scale depletion in regional groundwater has been observable since the mid-1970s. For over four decades, it has also been a topic of interest for researchers from diverse fields such as forestry, hydrology, and nature conservation. The factors allegedly behind the process include climate change; river regulation; pumping of groundwater for industrial, agricultural, and domestic water demand; changes in land use and settlement structures; oil and gas exploration drilling; and afforestation. Impact studies also hypothesise the water uptake of the local aged forests as a potential factor. Sometimes it has even been named as the primary cause (Major and Neppel, 1988; Major, 1993; Major, 2002; Szilágyi et al., 2012; Tölgyesi et al., 2020); thereby also raising serious concerns related to existing and future land use policies.

Forests can also use the groundwater as an additional water source, as noted in regions of the Great Hungarian Plain (Ijjász, 1939) and in the forest steppe zone of Hungary in general (Mátyás and Sun, 2014). It has been documented that roots are able to reach greater depths if groundwater is accessible (e.g., Fan et al., 2017). Earlier studies concluded that in general forest stands in Hungary are likely to use groundwater supplies to survive during dry periods (Ijjász, 1939; Magyar, 1961; Major, 1993, 2002). In the course of rising air temperatures, these factors could amplify the decrease of groundwater levels on local (Major, 2002) or even on regional scales, particularly in the case of new, large-scale afforestation projects (e.g., Lu et al., 2016; Szilágyi et al., 2012). Based on the findings of earlier studies, forests might potentially decrease groundwater levels via two mechanisms: direct or indirect (through capillary rise) groundwater uptake (Major and Neppel, 1988) or decreasing the amount of recharge as an input by interception and water uptake from the unsaturated zone of the soil (Tölgyesi et al., 2020).

Although researchers worldwide (and in Hungary in particular) have extensively studied the topic, the effect of lowland forests on the groundwater balance and the hydrological regime remains a subject of intensive investigation (e.g., Bosch and Hewlett, 1982; Farley et al., 2005; Gácsi, 2000; Ijjász, 1939; Járó, 1992; Jobbágy and Jackson, 2004; Major, 1993; Major, 2002; Nosetto et al., 2007; Pálfai, 2010; Szodfridt, 1990; Tölgyesi et al., 2020; Wilske et al., 2009; Wu et al., 2020). These studies generally reflect the complexities of the given local hydrological and socio-hydrological systems, including the effects of the changing climate. The regional decline in groundwater level is also a cause of concern in the Sand Ridge region of the Great Hungarian Plain, which is at the centre of interest of this paper. The causes of regional depletion may be complex, and can range from rising air temperatures, changing seasonality and the amount of precipitation; increased domestic, industrial and agricultural groundwater use; large scale amelioration in the past and recent areal afforestation campaigns up to exploration drilling for crude oil in the region (Kovács, 1984, ex. verb: Mining and Geological Survey of Hungary). As a consequence, such developments could impact the local hydrological regime and processes locally. The lack of monitoring systems that examine the effect of different driving factors in a complex way and could thereby offer data with an adequately detailed spatiotemporal resolution hinders the research considerably in drawing conclusions on land management to propose mitigation measures. Consequently, only general estimates exist concerning these factors in groundwater depletion thus far (see Table 3; Pálfai, 1994; Szilágyi and Vörösmarty, 1993; Völgyesi, 2006).

The recently established monitoring system of the Forest Research Institute of the University of Sopron in Hungary collects detailed and comprehensive local data starting in 2018 about the hydrological cycle in the existing local aged forests in the region (Bolla and Szabó, 2020). Since the consequences of the decline under existing aged forests on the soil water regime and the potential changes in groundwater recharge remain unclear so far, our main goal is, to shed light on the soil moisture regime and groundwater recharge at two forested and one control grassland sites and make comparisons about the spatial differences of the processes as well.

We have employed exploratory data analysis and comparative reasoning with emphasis on an explanation of the patterns observed in the processes monitored. We aim at clarifying the above-mentioned effects of the changing groundwater levels on the local soil moisture profiles on three hilltop locations of the Sand Ridge. In particular, we have compared the temporal and spatial differences of the soil moisture dynamics of the 41-year-old black locust (*Robinia Pseudoacacia)* offshoot forest, the artificially planted first generation 83-year-old black pine (*Pinus nigra)* forest, and a grassland control site at 10, 90 and 200 cm depths. These data were complemented by integral soil moisture monitoring in a range of 0 to 80 cm depths and groundwater level monitoring at the control site and a remote site. We intend to explain the effects of the changed water uptake of the local vegetation on the soil moisture dynamics above the deepened unconfined aquifer and relate the observed differences in the soil moisture profiles and dynamics at the study points to the type of the given vegetation. We have also attempted to underpin our hypothesis of the potential disruption of the local groundwater recharge as a consequence of the regional groundwater level decline.

Data monitoring

The Sand Ridge is an approximately 10,000 sq. km area at the Danube-Tisza Rivers Interfluvial. It belongs to the subhumid climate zone of the Great Hungarian Plain with an aridity index between 0.5 and 0.65 (UNEP, 1992) (Fig. 1).

In the Pleistocene era the flow of the Danube was directed towards the depression at Szeged. By the Holocene it had changed its course to a southerly direction and the main riverbed reached its current position (Somogyi, 1961). In the process the river built up the ridge through its alluvial deposits.

The altitude of the Ridges ranges between 85–134 (a.s.l.) m. The original land surface was characterised by relatively low, wind-induced sand dunes. These were partially flattened in the course of ameliorative works in the 1950s. There is no significant natural watercourse in the region. The network of amelioration canals may act as an intermittent river system.

The typical land use pattern over the Sand Ridge is mosaic-like and consists of agricultural fields, grasslands, residential plots, and forest stands of various compositions, ages and sizes (see Figs. 1, 2, and 3).

The mean annual precipitation in the area is 500–550 mm/year; the annual runoff is estimated to be 16 mm (Szinetár et al., 2018); and the annual average air temperature is 10–11 °C with the monthly minimum of –1.5 °C occurring in January and the maximum of 21 °C in July. Extreme meteorological events, especially long droughts and heavy rainfalls, occur increasingly often.

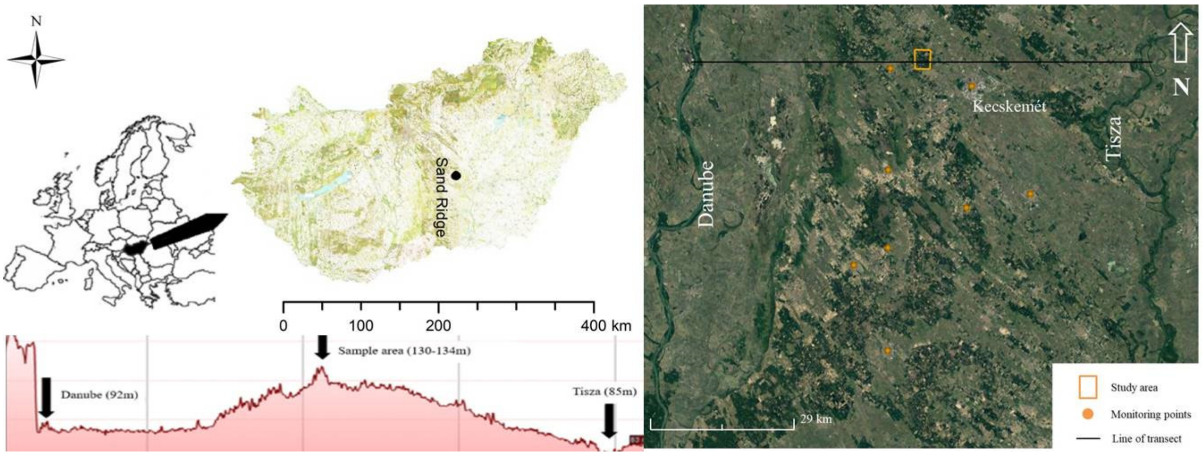

Fig. 1. Location of the study site and auxiliary measurement points.

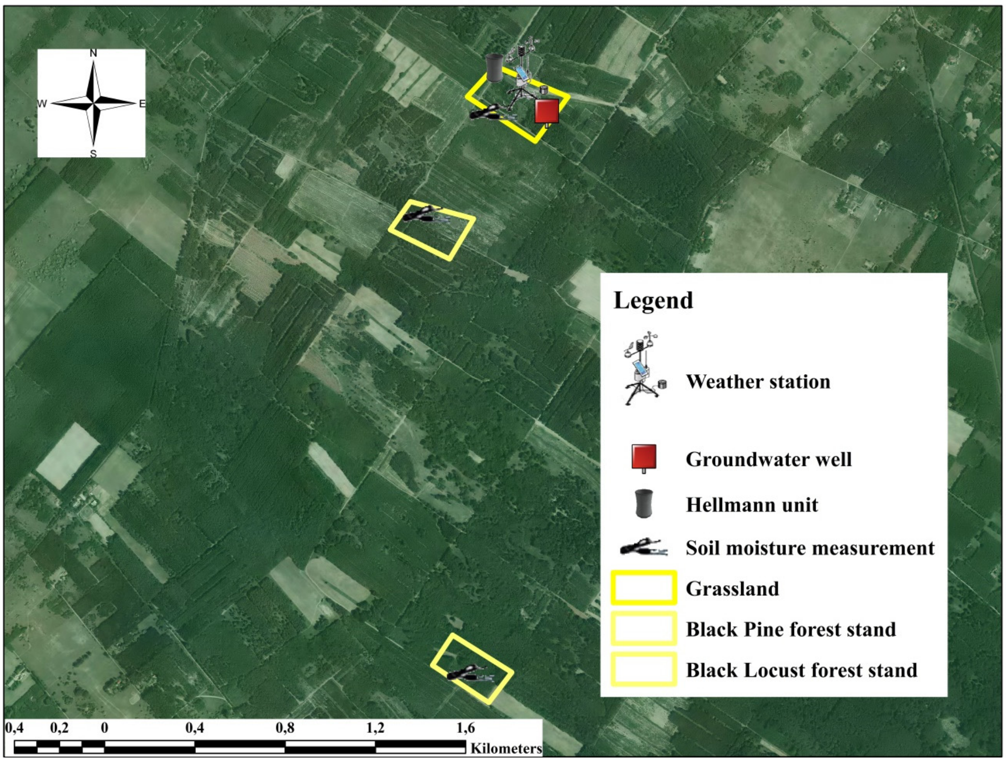

Fig. 2. Location of the monitoring points.

The source of the regional-scale temperature data was the Forsee database (http://nimbus.elte.hu/FORESEE/index.html). Data of the utilized pixel: latitude - 46.95813; longitude - 19.43986; horizontal resolution - 0.1 × 0.1 degrees.

The results in this paper are based on two data sets for the soil moisture content in the Sand Ridge region. The first offers manually measured data with a degree of low latency, while the latter contains high frequency data collected by automated methods. The topographical cross section of the Sand Ridge between the Danube and Tisza Rivers is depicted in Fig.1. We collected most of the data from sites lying around the highest point at Kecskemét-Méntelek (the “Nyíri” forest).

The two forest sites differ with regard to the age, composition, and planting technology of the trees. The black locust (*Robinia Pseudoacacia)* stand is a 41-year-old offshoot, and the black pine (*Pinus nigra)* stand is a first generation, artificially planted, 83-year-old forest. The third site, which is considered as the control point is an open grassland. The topsoil on the three stands investigated is similar and characteristic of the region, sand with a low or moderate amount of humus.

The integral soil moisture values have been manually measured down to the depth of 80 cm with a TDR-type (PT-1, Kapacitív Ltd., https://kapacitiv.hu/ [in Hungarian]) instrument at all three monitoring points since 2018. We have also conducted automated soil moisture measurements at the same sites since May 12, 2021, with a TDR probe (TSM-06 type, Boreas Ltd, http://www.boreas.hu/index.php?src=&lang=eng) at depths of 10, 25, 50, 70, 90, 110, 130, 150, 175, and 200 cm. This paper mainly presents the results from the data collected at 10, 90, and 200 cm depths.

The automated groundwater data collection used a 15-minute time step with a DA-LUB 222-type instrument (Dataqua Ltd, https://www.dataqua.hu/index.php?lang=en) near the open field control point of the soil moisture measurements (Fig. 2).

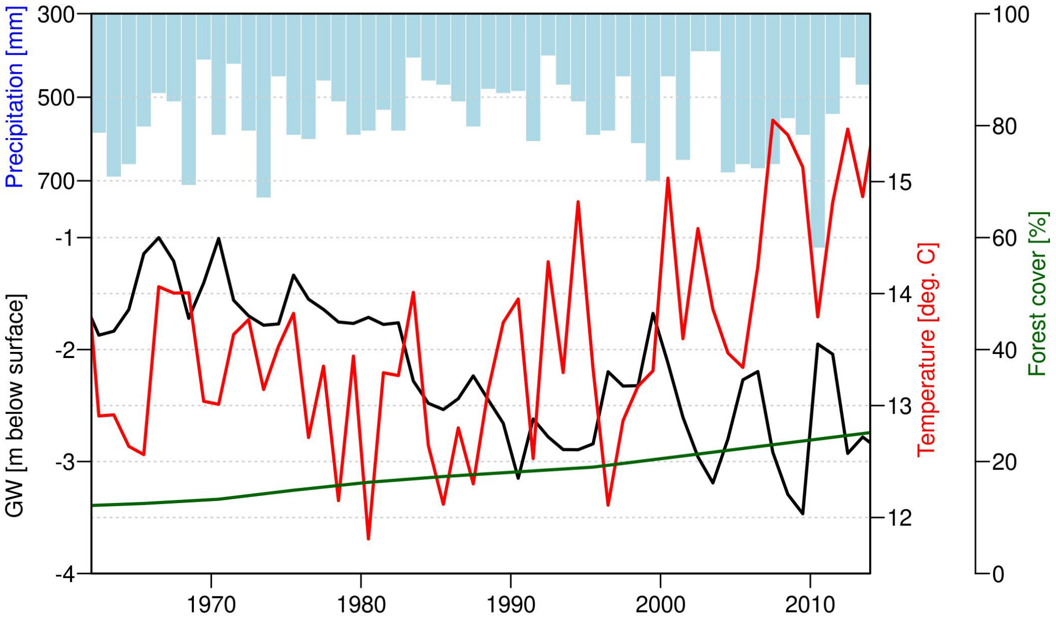

Fig. 3. Yearly precipitation, average groundwater level, and percentage of forest vegetation at the Sand Ridge region (1961–2014; Based on Gőbölös, 2002; Major and Neppel, 1988; Data from National Land Centre and Hungarian Meteorological Service, Hungary).

Table 1. Main properties of the monitoring points.

Type of collected data	Type of study site	Coordinates		Start of data collection	Frequency of measurements	Depth
		Latitude	Longitude			
Soil moisture (manual)*	Control	N46°58'3.47"	E19°33'10.65"	03.07.2018.	weekly	0–80 cm
	Black locust	N46°56'40.75"	E19°32'52.13"			
	Black pine	N46°57'46.72"	E19°32'50.10"			
Soil moisture (automatized)	Control	N46°58'3.47"	E19°33'10.65"	12.05.2021.	10 minutes	10, 90, 200 cm
	Black locust	N46°56'40.75"	E19°32'52.13"			
	Black pine	N46°57'46.72"	E19°32'50.10"			
Groundwater (manual)	Control (agricultural and residential)	N46°56'30.53"	E19°37'52.56"	04.07.2018	3 days	
Groundwater (automatized)	Control	N46°58'2.69"	E19°33'12.86"	09.07.2018.	15 minutes	

* data collection occurred within 10 meters of the given coordinates

The data on the annual precipitation for the regional analysis was supplied by the Hungarian Meteorological Service at eight meteorological stations evenly distributed over the whole Sand Ridge area. The groundwater data was collected by the Lower-Tisza Water Directorate and the Lower-Duna Water Directorate (ADUVIZIG) at the same locations.

A meteorological station operated by the Forest Research Institute at the University of Sopron within the framework of the Measurement and Monitoring System of Forest Protection (EMMRE) project provided additional meteorological data. This station is located close to the open field control point of the soil moisture measurements. In addition, we manually performed supplementary measurements of the precipitation at a weekly interval with a Hellmann-type rain gauge manually at both forest points.

Table 1 presents the coordinates and main properties of the different study sites. The measured data is partly available online at the http://met.boreas2.hu/erti_test/ and http://met.boreas2.hu/ertitalaj/ websites.

RESULTS

Groundwater

The groundwater level is a parameter that we can measure with a high degree of accuracy and resolution. The local biotic, meteorological and soil factors can have complex effects on the water table, which enables us to evaluate the water balance of a specific area by observing and analysing the groundwater level.The areal average of the precipitation data for eight stations and the averaged measured groundwater data are presented in Figure 3. The long-term data set shows no trends in the yearly amount of precipitation (R^2 = 0.002) but there is a clear increase in the temperature after 1985. According to our measurements, an average yearly increase of 1.8 °C occurred between 1999 and 2020 (Bolla, 2021). This increase induces more potential evaporation (PET), which has a negative effect of the overall hydrological balance on the area as there is no increase in the precipitation.

The groundwater level decreased between 1970 and 1994 on a regional level. After this period, its depth has stabilized on

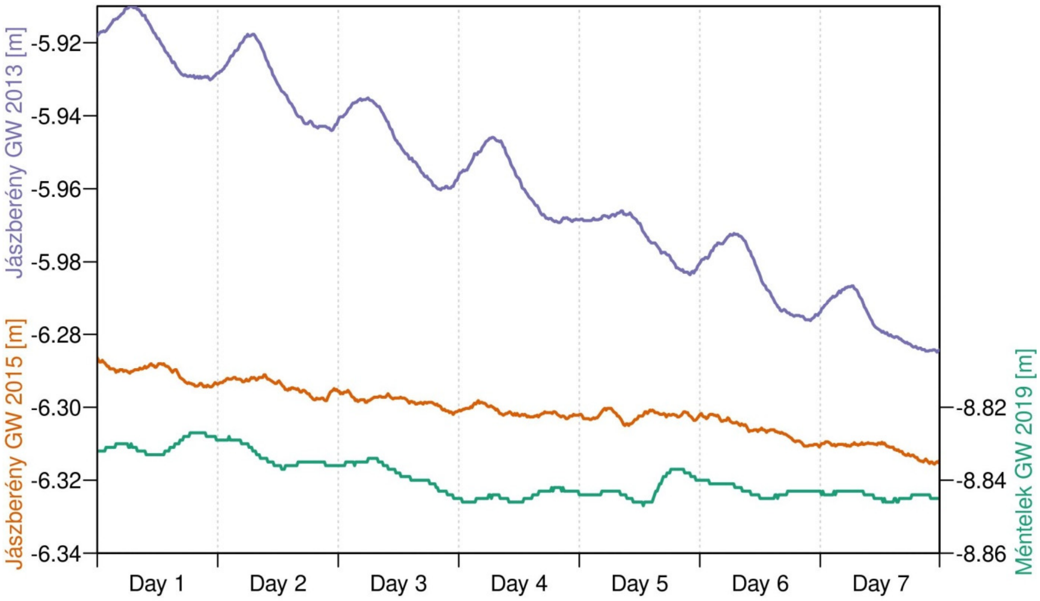

Fig. 4. Groundwater levels of 8 consecutive, dry days with high evapotranspiration at Méntelek study site (2019.08.12.–2019.08.19.) and at an auxiliary measurement point (Jászberény; 2013.07.26.–2013.08.01.; 2015.07.26.–2015.08.01.).

average. The correlation between the annual change in the GW level and the annual precipitation is relatively high (r = 0.66), thereby indicating the existence of a regional recharge.

Simultaneously, there was a continuous growth in the forested area. This indicates that the forest cover is not the primary factor behind the decrease in groundwater on a regional level.

The White method (White, 1932) evaluates the direct and indirect groundwater uptake of the vegetation based on the connection between the diurnal (24-hour period) groundwater fluctuation with the help of a soil-dependent factor. As a result of the photosynthetic cycle, the minimum of the diurnal pattern is at sunset, which is after the active period of the vegetation, and the maximum is before sunrise, after the recharge period at night. Thus the method requires a high-resolution (minimum frequency of 1 hour) data set. The method and its developed variants have been employed many times worldwide and in Hungary (Gribovszki et al., 2014; Loheide, et al., 2005; Móricz et al., 2016).

The data in Fig. 4 presents the groundwater data from the same period of 2013 and 2015 at the monitoring point near Jászberény (60 km northeast of Méntelek), which is situated in a black locust stand on sandy soil. It shows that a decrease in the watertable (from 6 m in 2013 to 6.3 m in 2015) could disrupt the above-mentioned diurnal pattern, which is driven by the photosynthesis. This pattern is totally absent at the Méntelek study site, where the observable fluctuation is small and the period length is rather 12 hours instead of 24 hours. According to Senitz (2001), short-term periodical changes in the groundwater level for 12-hour periods are caused by the tidal cycles of the earth. This phenomenon is mainly observable at deeper groundwater levels or in cases of confined aquifers.

Even if the data shows two superimposed cycles (a 24-hour cycle caused by the groundwater uptake and a 12-hour cycle caused by the earth's tide), the amplitude of these fluctuations is very small. The possible groundwater evapotranspiration calculated using the signal is no more than 10–20 mm/year.

Thus, we concluded that the local forests do not use the groundwater. This conclusion contradicts earlier studies in the area conducted in the 1970s and 1980s (Major and Neppel, 1988). The reason for the conflicting results is that the water table dropped from 3–5 meters to almost 10 meters during the last couple of decades and the vegetation root systems could not adapt to this drastic decrease.

This is corroborated by the results of other authors indicating that the maximum root depths are around 3.3 m based on the available direct and indirect data of the studied tree species (Bolla and Németh 2017; Kárász, 1986; Móricz et al. 2016; Musters and Bouten,1999; Tóth et al., 2014).

Soil Moisture
Manual measurements

Our long-term results indicate that the soil moisture values are 0.7–1.64% lower below the forest stands than on the control site (grassland) during the growing season (Table 2). Based on our previous research, we could assume that the soil moisture values could not be much higher on treeless sites, (also in poor production sandy soils) (Fig. 5). (http://met.boreas2.hu/erti_test/).

Table 2. Mean difference in soil moisture between control point and the different forest stands (results of paired T-test).

	Black locust	Black pine
Mean Difference (to control)	0.70%	1.64%
Confidence interval	95% 0.52–0.89	95% 1.43–1.86
p-value	3.04e–12	< 2.2e–16

As expected, the order of the soil moisture values is: black pine < black locust < control due to the difference in the interception values between the different surface cover: control: 5%; black locust: 19%; and black pine: 33% (evaluated by own measurements).

Notably, the overall soil moisture is not reflecting to the high amount of precipitation occasionally (e.g., May, 2019; May, 2021). This anomaly could be explained by the fact that manual measurements were made on a weekly basis; thus evaporation and/or surface runoff could have significantly decreased the initial soil moisture in the time period between the precipitation event and the measurement.

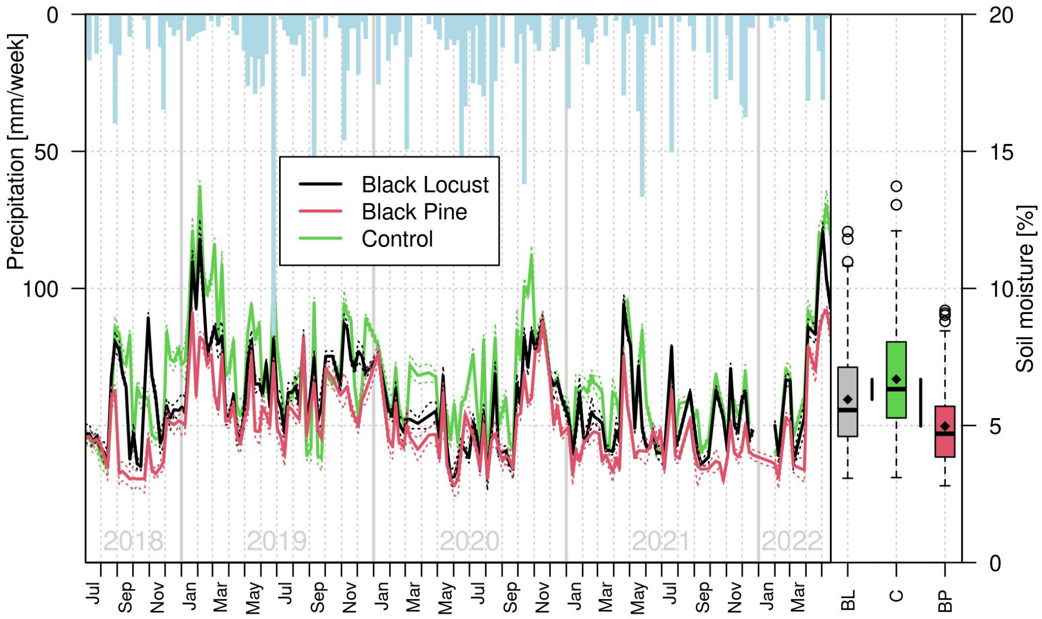

Fig. 5. Total soil moisture based on a grassland and two forest stands in Méntelek study site (2018.07.03.–2022.05.17.; 0–80 cm; BL – Black locust, C – control, BP – Black pine).

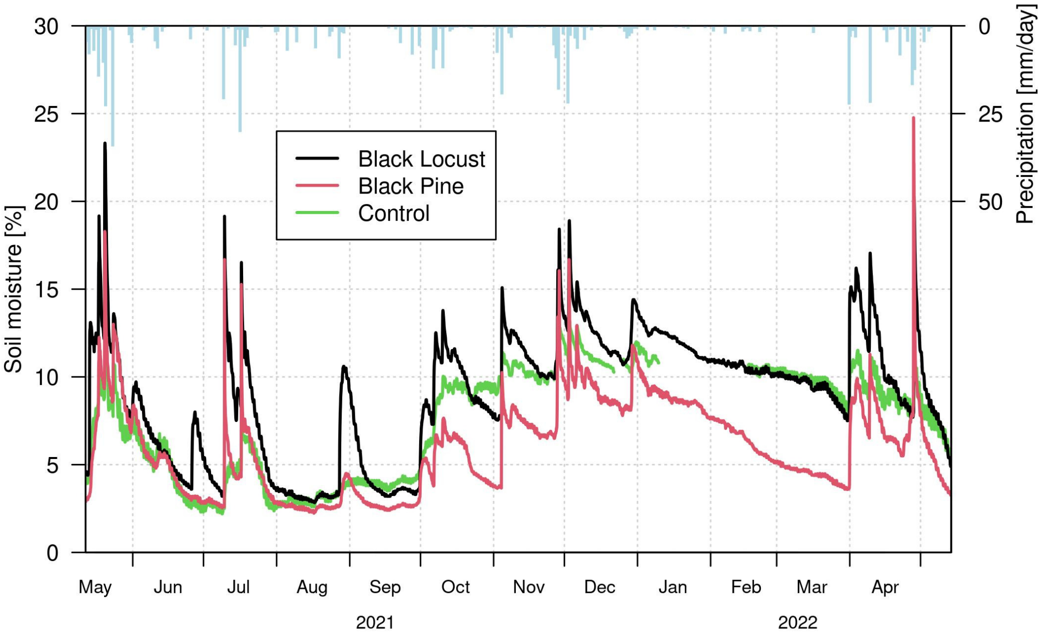

Fig. 6. Short-term, automated soil moisture data in Méntelek study site at a depth of 10 cm (2021.05.12.–2022.05.17.).

Automated measurements

The total precipitation throughout the observed period was 495.6 mm. This is slightly less than the local average annual precipitation. As an example of the extreme distribution of the precipitation, 81.7 mm fell between 17.05 and 23.05 in 2021. According to the Hungarian Meteorological Service, this figure represents 161% of the long-term average precipitation in the area in May.

As we expected, the surface (0–10 cm) soil moisture data exhibits clear effects of the precipitation events (Fig. 6). The highest soil moisture content occurs under the black locust and the lowest under the black pine stand.

These differences between the forested points are possibly caused by the combined effects of the litter layer and undergrowth vegetation, which prevents evaporation under the black locust; thus the soil moisture values remain higher than on the grassland, which is directly exposed to the sunshine. In the dormant period when the trees and the undergrowth vegetation lose their canopy, the soil moisture values are similar to the control point.

Under the black pine thick litter layer increases the extent of the litter evaporation and thus weakens the connection between the precipitation and the soil moisture. The drying effect of wind is also more significant at the more open black pine stand.

It has to be noted that the amount of precipitation at the two forest points was different at the end of June and August, 2021, due to local rainfalls.

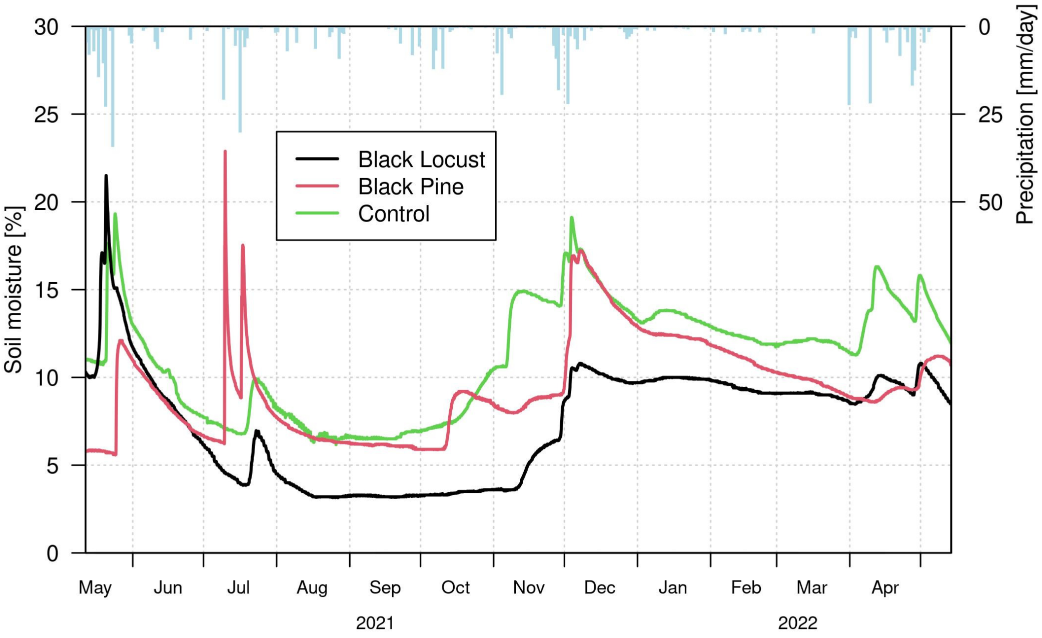

Fig. 7. Short-term soil moisture data in Méntelek study site at a depth of 90 cm (2021.05.12.–2022.05.17.).

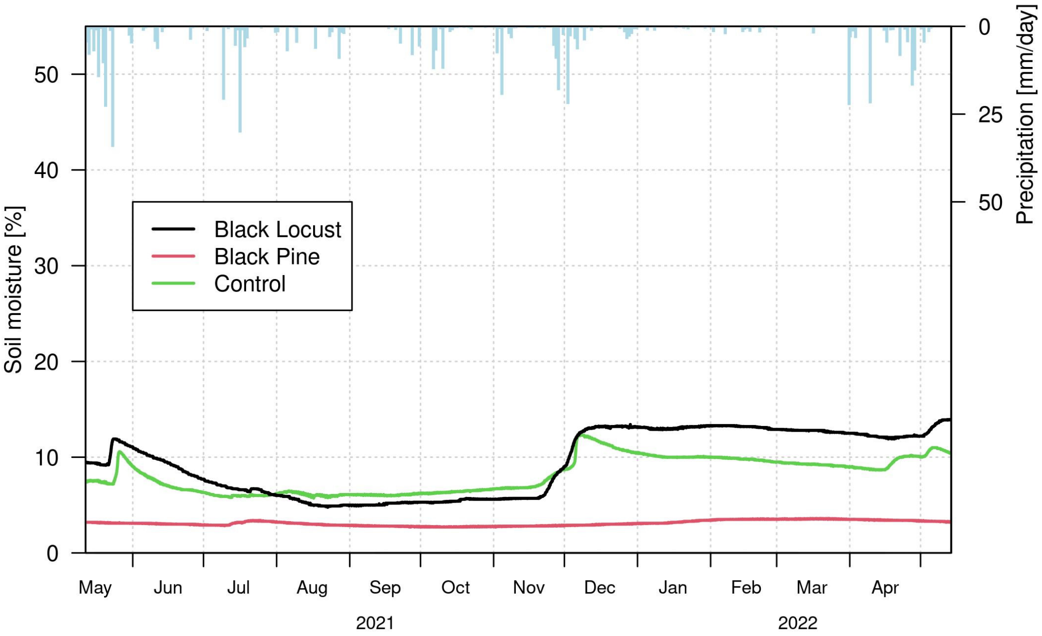

Fig. 8. Short-term soil moisture data in Méntelek study site at depth of 200 cm (2021.05.12.–2022.05.17.).

The measurements at 90 cm indicate a clearly different picture at every measurement point (Fig. 7). After the above-mentioned heavy rainfall at the end of May, 2021, there was an overall decline until mid-July, 2021, and a relatively stable period with low soil moisture values (Control: 6–8%; Black pine: 6–8%; Black locust: 3–5%) This ended in mid-October (and in early November in the case of the Black locust) after which the soil moisture content increased significantly to reach a peak in connection with the precipitation at the end of November (Control: 19.2%; Black pine: 17.3%; Black locust: 10.8%). These values decreased again in the case of the control and black pine points and were stable in case of Black locust until the precipitation at the beginning of April. This yearly dynamics is caused by the soil moisture uptake of the vegetation at the given depth. The overall order of the soil moisture content under the different measurement points (Black locust < Black pine < Control) reflects to the transpirational water demands of the black pine and black locust (185 mm/year and 271 mm/year, according to Járó (1981), and 369–419 mm/year and 483–489 mm/year according to Csáki (2020). There is no soil moisture uptake under the grassland at this depth due to its shallower root zone. These data support the results of Tölgyesi et al. (2020).

The black pine keeps its canopy during the dormant period; consequently, the effect of the water uptake and canopy interception is not limited to the growing season. This difference is observable in the dynamics of the soil moisture values between December and April, 2022.

There was an anomaly in October, 2021, when the soil moisture only increased under the black pine stand, which was probably caused by local rainfall, which did not affect the other study sites.

Significantly different soil moisture dynamics was observed at a depth of 200 cm (Fig. 8). The highest values were measured from August to November under the control point, with the maximum difference of 1.6% to black locust. Meanwhile, in most of the year (May – July, 2021, and December, 2021 – May, 2022), the highest soil moisture content was observed under the black locust. The average difference was 3.5% and the maximum difference was 5.6% compared to the control.

The lowest values were measured under black pine with negligible fluctuation (values were between 2.8% and 3.6%). which were due to the combined effect of the above-mentioned high interception and the water uptake of the black pine stand. Although the effect of the various factors is very difficult to determine at deeper soil levels, we assume that the macropores developed by the root system of the black locust could have a draining effect at a shallower depth, thereby resulting in better drainage, which could result in higher soil moisture values, especially in the dormant season. Moreover, the typical type of soil texture in the area is coarse sand, which is noteworthy because even a small increase in the clay or in the humus content (for example, in the case of a buried soil layer) could significantly influence the hydrological properties of the soil.

Based on the data presented, we conclude that the yearly vegetative cycle has a much higher impact on the soil moisture content at this depth than the precipitation. After the especially high amount of precipitation at the end of May, 2021, the increase was 2.7% (from 9.2% to 11.9%) in the case of the black locust and 3.4% (from 7.2% to 10.6%) in the case of the control vegetation.

The possibility of a considerable downward soil moisture movement was restricted to the period between December, 2021 – May, 2022, under the black locust, and to the period between December, 2021 – January, 2022 under the control as the field capacity of the sand is around 10% according to Stefanovits et al. (1999).

Based on this data, we can assume that even heavy rainfall events could not affect the local groundwater, which was typically at a depth of 9 meters.

DISCUSSION

The interplay between decline in the groundwater under the existing aged forests at the highest point of Sand Ridge on the soil water regime and potential the changes in the natural groundwater recharge under these locations was targeted at three sites at the hilltop location of the Sand Ridge in this study. We employed exploratory data analysis and comparative reasoning with an emphasis on explaning of the observed patterns in the monitored soil moisture processes and GW levels at the sites.

The results of this study need to be embedded into a broader framework of the long term and regional of groundwater level decline. The decreasing trend of the groundwater decrease on a regional scale has been observed since the beginning of the 1970s at Sand Ridge. We did not intend to explore the phenomenon itself but just to succeed to showing, that the decline is also locally present in the pilot region of the study. We indicated that, based on the data from eight groundwater wells that the decline is occurring in each of these simultaneously. We also showed that at this sub-regional level the annual fluctuations of the average GW level change is correlated with the temporal fluctuations of the areal precipitation (Fig. 9).

This result is important with respect to the natural recharge. Our results indicate that a connection between the precipitation and groundwater exists and indirectly demonstrates that the natural recharge was not disrupted. However, given the persistent decline of the GW levels, these results also warn that under the present climatic conditions, the natural recharge may not be sufficient to cover the losses due to the changing climate and the increased anthropogenic influence on the GW resources.

The following three major factors are usually identified as possible causes of the decline in GW levels: a decrease in precipitation and the increasing temperature as consequences of climate change (Rakonczai, 2011; Rakonczai and Bódis, 2002; Völgyesi, 2006); groundwater extraction (from both unconfined and confined aquifers) for municipal and agricultural use (Berényi and Erdélyi, 1990; Csatári, 1994; Szilágyi and Vörösmarty, 1993), and increase in the forested area. Other affecting factors (such as river regulation and crude oil survey drilling) and quake tests for geophysical exploitation were also mentioned in other sources (Kovács, 1984, ex. verb: Mining and Geological Survey of Hungary).

Extensive deep and shallow abstractions (both legal and illegal) for drinking water and land use-related water consumption (such as intensive vegetable production in greenhouses, orchards, and fish ponds) put additional pressures on the groundwater.

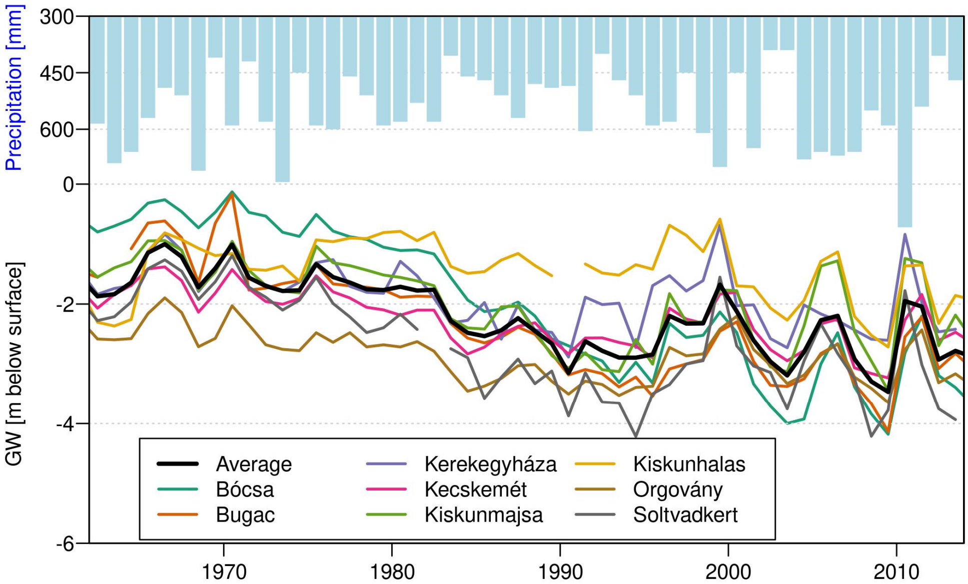

Fig. 9. Yearly precipitation and groundwater level from eight different monitoring wells in the Sand Ridge region (1961–2014).

Table 3. The estimated effect of different factors on groundwater level on the Sand Ridge (Based on Kohán, 2014).

Publications	Climatic factors	Water extraction (unconfined and confined aquafiers)	Forests	Water regulation works	Other factors
Pálfai (1990,1994)	50%	31%	10%	7%	2%
Szilágyi and Vörösmarty (1993)	15%	70%	15%	n.a.	n.a.
Völgyesi (2006)	80%	2%	13%	5%	n.a.

For example, the water works of the city of Kecskemet maintain a system of 23 deep boreholes constructed between depths of 106.6 m and 267.0 m with a capacity of 16,500 m^3/day and a group of 26 deep boreholes installed between depths of 132.0 m and 410.0 m depth with a capacity of 24,000 m^3/day. The interplay between the confined and unconfined aquifers was not studied here, but it is recognised as a locally and regionally potential important factor.

The estimates of the respective impacts of the suspected main causes of the decline (Table 3) in the GW levels vary greatly in different evaluations. Only the effect of the forests was consistently estimated, to be between 10 and 15%. The role of forests in a natural recharge is of particular interest and was examined through the in situ experimental research herein.

Looking at the above-mentioned impacts in detail and connecting them with the recharge problem, the hydromorphology and the hydrogeology of the region may be an appropriate starting point in the discussion. The Sand Ridge area of about 10,000 square kilometres lies between Budapest and Szeged in the Great Plain between the Danube and the Tisza rivers. It is elongated with a 120–150 km length and a width of about 90 km. It forms a ridge, the northern and southern boundaries of which are higher than the saddle in the middle part; toward the west and south, it slopes down gently toward the two large rivers. Due to its north-south elongation, it can be safely considered as an independent infiltration/recharge unit with its natural groundwater resources fed by the precipitation. There are no natural watercourses in the upper parts of the Ridge, where the drainage system is essentially made up of artificial inland water drainage channels. The lower parts are drained through a thin-bodied system of watercourses that flow towards larger amelioration canals and the main rivers. These, and other human interventions, have led to a massive loss of wetlands. It is estimated, that in the Danube-Tisza area, there were some 600 natural lakes at the beginning of the 20th century, but it is documented that the number of saline lakes fell from 230 to 37 between 1951 and 2001 (only the geographical names of the lakes have remained till today as a reminder of the natural waters of the past). In the higher areas, the water table in the region has subsided by 3-6 metres or more.

This subsidence and its persistence may be due to the combined, mutually reinforcing, effects of the meteorological conditions and human interventions. The mean annual climatic water deficit in large parts of the area was estimated to be above 350 mm according to the National Atlas Climatic in 1998 and has likely risen since then. To underpin that in this study, we have looked at the trends in rising air temperatures and changes in the precipitation and stated that the deficit has been deepening since then. These trends clearly increase the risk of the insufficient intensity of the natural recharge to compensate for the decline in general; however, they do not exclude the possibility of the existence of local sites with a sufficient recharge. The role of forests and the recharge below aged and newly planted forests needs to be studied in particular.

The high-frequency groundwater data acquired from monitoring well at the study site presented no observable diurnal dynamics that could have signalled water uptake of the vegetation. The auxiliary data showed that the groundwater decline could have resulted the in the forest – groundwater disconnection. Thus it was concluded that the water uptake of the forests is currently restricted to the unsaturated zone. This is due to the water table depth and the relatively shallow root system of the examined two tree species as Kárász (1986) found, that in the case of black locust, the bulk of the root system is in the upper 30 cm of the soil with some roots reaching the depth of 3 m. The diurnal cycles under the black locust were found at the maximum depth of 3.1 m by Móricz et al. (2016), 3.2 m by Tóth et al. (2014), and 2.5 m by Bolla and Németh (2017). Similar root zone depths (from 0.8 to 3.3 m) were measured by Musters and Bouten (1999) and Stokes et al. (2002) under black pine. This hinders recharge to happen and mitigate the declines locally.

There are clear signs of soil moisture uptake induced by the seasonal photosynthetic cycle in the soil moisture data from 90 and 200 cm, although the observed dynamics at the monitoring points are essentially different. Meanwhile there is a clear connection between the soil moisture values and the transpirational water demand of the given vegetation at 90 cm, there is no such connection at 200 cm. The high amount of macropores formed by the root system of the black locust, which induces bypass flow (Radcliffe and Simunek, 2010), could help explain this result, although the effect of the soil layers also could not be ruled out. The difference also indicates that the effect of the surface vegetation on soil moisture is decreasing in deeper soil layers. Our conclusion is that the surface cover has a limited effect on the local recharge of the groundwater hydrological regime at our study site with deep GW level, mainly due to the distance between the root zone and water table level. Other factors such as differences in the soil layers, the root structure of the tree species, and macropores could have an important role, but were not studied due to the lack of data.

Based on our data, it was also not possible to indicate a threshold for the start of the disruption of the water uptake by the roots from the groundwater. It most probably is decided by the interplay between the speed of the decline and the capability of the root zone to cope with it. The importance of the local factors implies that the impact of the forest vegetation on the local groundwater level may be highly variable throughout the Sand Ridge region. Studies would be needed in this respect to support sustainable forest management, including afforestation.

While plans were proposed to establish managed aquifer recharge systems in order to prevent desertification and stop the GW decline (https://www.ovf.hu/hu/korabbi-hirek-2/homokhatsag-vizhaztartasi-es-vizgazdalkodasi-problemainak-enyhit/, in Hungarian), these need to be supported by the restoration of the natural recharge everywhere it is appropriate. As with any decision concerning land use, one should consider the ecological, social, and economic costs and the benefits of forest management and afforestation projects. Forests have a higher water demand than herbaceous vegetation, which clearly counts as a cost in arid regions. The water use efficiency (WUE) of crops is generally lower (0.4–2.8 gC/kgH2O, Wang. et al., 2018) than that of forests (0.9–5.4 gC/kgH2O, Zhou et al., 2014). Nevertheless, forests have several positive effects that also need to be considered when assessing their roles, besides the fact of being a CO_2 sinks. These include:

- The interception of temperate forests significantly cools the environment in the summer, reducing evaporation, evapotranspiration, and erosion (Bolla, 2021; Li et al., 2015). Interception also induces the formation of precipitation further away (on the mesoscale and even at the macro-scale) (Meier et al., 2021; Zemp et al., 2017)
- Through their root system, forests reach and use groundwater reserves so that forests can preserve moisture in the upper soil layers due to crown shading and forest litter.
- Through the phenomenon of "hydraulic-lifting" (Horton and Hart, 1998), forests can also use groundwater to increase soil moisture in upper soil layers.

Ensuring substantiated decisions in connection with highly complex systems such as local hydrological regimes under forests requires automated and long-term monitoring of the groundwater-soil-vegetation-atmosphere system. Examples of this type of research are the work of Bolla and Németh (2017), Gácsi (2000), and Móricz (2011). Unfortunately, the number of similar studies on Sand Ridge is small. Collaboration between different disciplines on such complex topics is also advisable in the future.

CONCLUSIONS

The observed regional groundwater level decline in the Sand Ridge region of the Great Hungarian Plain, which lies between the two largest rivers of Hungary, the Danube and the Tisza, is a cause of concern and the topic of occasionally controversial discussions. In the past amelioration works changed a dune character and drained the landscape. Recently, rising air temperatures not followed by increases in areal precipitation have raised evapotranspiration and reduced the potential of the natural groundwater recharge. Rising demands in domestic and agricultural groundwater use which puts pressure on the water resources have also been reported. Areal afforestation has accompanied changes in the land use. Crude oil exploration works have included deep drilling in the region and may have impacted the connection between the confined and unconfined aquifers.

In this paper these complexities have not been targeted. As only a tile in the mosaic of complexities and a boundary condition for the main topic, we have indicated, based on the groundwater level data from eight wells that the decline is occurring in each of these locations simultaneously. On the regional level we showed that the annual change in the groundwater level is correlated with the temporal fluctuation of the areal precipitation, thereby indicating a connection between these and indicating the existence of natural recharge.

The interplay of the groundwater decline under the existing aged forests at the highest point of the Sand Ridge on the soil water regime and the potential changes in groundwater recharge under these forests has remained unclear so far. We aimed here at clarifying these issues at three sites at the hilltop location of the Sand Ridge. We employed exploratory data analysis and comparative reasoning with an emphasis on the explanation of the observed patterns in the monitored soil moisture processes at the sites.

Based on the measurements of the soil moisture in the three newly-established experimental sites, the interaction of the vegetation type and the groundwater level decline on the local soil moisture profiles on these hilltop locations of the Sand Ridge was described. The vertical differences in the soil moisture regime 10, 90 and 200 centimetres below ground in a 41-year-old black locust (*Robinia Pseudoacacia)* offshoot forest, an artificially planted, first generation 83-year-old black pine (*Pinus nigra)* forest and a grassland control site were compared. We found that the infiltrated precipitation in the course of the water uptake of the local vegetation from the soil profile potentially does not exhibit any significant influence on the dynamics of the relatively deep water table (9 meters) anymore. The typical diurnal fluctuation of the groundwater level below forests was not observed in the well at the control point near the forest stands. At a remote sandy soil observation point we measured such fluctuations, which however exhibited a tendency to gradually flatten out with the growing decline. Based on that we hypothesised that in the course of the decline at the locations we surveyed at the highest point of the Ridge the rooting system of the trees had already lost the connection with the groundwater. According to this hypothesis, the observed behaviour of the vertical differences and temporal changes in the soil moisture dynamics up to a depth of 200 cm were explainable by the differences in the interception capacity of the particular type of forests and the grassland, the differences in the evapotranspiration capacity of the trees, and the water holding capacity of their litter respectively. The observed soil moisture values at 200 cm were low and indicated that the local vertical groundwater recharge may be disrupted most of the time at the hilltop of the Sand Ridge. Based on that it could be concluded that the observed differences in the soil moisture profile at all depths at the study sites mainly reflected the water use of the given vegetation type and the precipitation regime without allowing for any recharge to deeper horizons. As a consequence of our observations it can be stated that the aged forests could locally enhance the groundwater decline, which, however, may be more probably driven by other regionally acting factors among which we were not able to discriminate based on our data thus far.

To conserve water resources under the present climate with rising temperatures, stagnation in the rainfall and higher evapotranspiration, pine tree planting could be preferable to avoid the recharge zones. Areas where the water tables are deeper and the trees are less likely to access the groundwater and transpire it directly could be targeted instead. The results of this study indicate that spatial variations in the recharge are to be sought after and the driving factors explained. Topographically lower parts of the Sand Ridge and areas along the drainage lines, which are reached not only by local precipitation but also by runoff from the higher elevations, could be a starting point. Climatic, hydrogeological and economic frameworks for forestry need to be considered, which in turn require the implementation of extensive monitoring networks and detailed water use inventories.

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