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Does afforestation increase soil water buffering? A demonstrator study on soil moisture variability in the Alpine Geroldsbach catchment, Austria

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ABSTRACT

This study employed an operational monitoring network to measure soil moisture and runoff behaviour continuously in the Alpine catchment Geroldsbach-Götzens, Austria. We hypothesize that afforestation can have a positive impact on soil water buffering. To analyse the impact of soil properties and vegetation cover changes on soil water dynamics, four experimental plots were established on grassland and monitoring stations were installed in the forest. The rainfall test site is equipped with an automatic weather station to obtain meteorological observations, and weirs to measure surface runoff of natural occurring precipitation events and artificial rainfall simulations. In the plots, 200 soil moisture sensors were installed at five different depths, aimed to track and visualize infiltration and subsurface flow processes. Another twenty sensors monitored soil moisture at different afforestation stages in the forested part of the catchment. The measurements show that soils covered with young and old-growth forest have a higher and more stable soil moisture content than grassland and soils with a lack of vegetation throughout the seasons. We observed large spatial differences at plot scale, where the spatial variability of soil moisture increases with depth and is highest during convective precipitation. The initial conditions and rainfall characteristics play an important role in infiltration processes and soil water storage. Our rainfall test site demonstrated the challenges of innovative monitoring techniques and that it offers opportunities for more experiments to gather evidence-based data as input for flood models. Overall findings confirm the sponge effect of forest soils and indicate that afforestation as Nature-Based Solution reduces the temporal soil moisture variability, buffering soil water during precipitation events, which can be beneficial for runoff reduction in Alpine catchments.

1. Introduction

Natural hazards such as severe floods and landslides occur frequently in mountainous areas. These hydro-meteorological risks are foreseen to increase given the projected changes in climate, more convective precipitation, degradation of ecosystems, population growth and urbanization (IPCC, 2019). Soil moisture is a hydrological state variable that plays an important role in the generation of hydro-meteorological risks such as floods (Mayerhofer et al., 2017; Penna et al., 2011; Singh et al., 2021).

Nature-Based Solutions (NBS) can be effective measures to respond to land degradation processes and flood events. To promote large-scale NBS such as afforestation and reforestation, further research and demonstration is needed (Ruangpan et al., 2020). In mountainous regions forests act as NBS and provide protection against natural hazards. Protective forests play an important role in the Alpine Region in protecting human lives, infrastructure, and resources from catastrophic events such as floods, debris flows, snow avalanches or rockfall (Freudenschuß et al., 2021; Markart et al., 2021; Sebald et al., 2019).

Anthropogenic activities such as urbanization and agriculture tend to

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decrease the retention capacity of catchments, and afforestation is a potentially beneficial measure to improve flood mitigation (Buechel et al., 2022; Stratford et al., 2017). Not only does forest vegetation influence flood runoff, but the soil characteristics are also altered by trees. Potential (peak) runoff reduction shows a strong dependency on event characteristics as well as on pre-event soil moisture (Blöschl et al., 2015; Merz & Blöschl, 2009; Wahren et al., 2012). Afforestation in the upstream part may improve water retention by increasing infiltration and lowering pre-event soil moisture (Naef et al., 2002; Vichta et al., 2024; Wahren et al., 2009). Land management such as grazing intensities and planting trees also affects runoff processes. Experimental plots in upland UK showed significant improvements in soil infiltration rates in tree-planted plots compared to those that were grazed as well as those where livestock was excluded (Marshall et al., 2014).

In this observational study, we focus on increased infiltration rates and soil water storage as a desirable hydrological ecosystem service of forests, the so-called “sponge effect”. The “sponge-effect hypothesis” has often been debated to suit a broad range of beneficial characteristics of soil hydrology attributed to the presence of forests compared to other land covers (Bruijnzeel, 2004; Ogden et al., 2013; Peña-Arancibia et al., 2019). It is the local interplay between infiltration, groundwater recharge, and increased evapotranspiration due to afforestation that ultimately determines the impacts of afforestation. Positive hydrological effects can include increased dry-season flow associated with greater wet-season infiltration and the reduction of peak runoff rates and volumes. Increased forest cover upstream may help to ameliorate the smaller and moderate floods, although the effect on larger floods is often more limited (Bathurst et al., 2020; Buendia et al., 2016; Nadal-Romero et al., 2016; Salazar et al., 2012; Soulsby et al., 2017). In contrast, the potential for decreasing summer low flows through enhanced interception and evapotranspiration processes may be viewed as a negative effect (Strasser et al., 2019). Although higher evapotranspiration caused by afforestation could lead to a lower soil moisture content, there is also research that shows that an increase in forest cover enhances the amount of precipitation (Hoek van Dijke et al., 2022; Meier et al., 2021; Teuling et al., 2017).

To determine the role that forests play with respect to runoff, it is important to understand the hydrological behaviour of the environment that depends on the soil, climatic conditions, and vegetation characteristics (Cosandey et al., 2005). Long-term watershed experiments in a catchment where old-growth forest was converted to planted forest show that processes of transpiration, interception, snowmelt, and flow routing continue to change with forest growth and disturbance in the catchment (Segura et al., 2020). Where young forest strongly improves infiltration rates, in older forest podzolization processes can start that make the soil more acidic, deteriorates soil organisms and therefore reduces hydrological permeability. Trees can have a limited beneficial effect in situations with high rainfall intensities, when the capacity limits of interception and soil water storage are exceeded, and flood events are triggered (Freudenschuß et al., 2021; Hegg, 2006; Markart et al., 2004). Pasture-dominated areas produce high surface flow rates during short precipitation events with high rainfall intensities, while forested areas often develop shallow subsurface flows. Dry pre-conditions can lead to a slight reduction of surface flow, long rainfall events to a dominance of deep subsurface flow and percolation (Marshall et al., 2014; Meißl et al., 2021).

Field-based, data-intensive studies have shown a strong influence of soil moisture on runoff generation in forested headwaters (Famiglietti et al., 2008; Haga et al., 2005; James & Roulet, 2007; Juez et al., 2021; Nadal-Romero et al., 2016; Penna et al., 2011, 2013; Zehe et al., 2010). Monitoring of (antecedent) soil moisture conditions can provide more insight into the behaviour and thresholds when runoff occurs (Mayerhofer et al., 2017; Meißl et al., 2020, 2023; Nadal-Romero et al., 2016; Penna et al., 2011; 2015). Moreover, it is important to describe soil moisture conditions for different soil depths, distinguishing shallow and deeper layers, which can serve as an indicator of runoff generation and hydrological processes at the hillslope and catchment scale (Segura et al., 2023).

Continuous local measurements of soil moisture in the surface layer, as well as of its vertical profile, have a crucial role in the upscaling and disaggregation methods required to obtain moisture estimates at the catchment scale (Penna et al., 2013). However, it is challenging to measure a single representative soil moisture content at the catchment scale due to the spatial variability of soil properties, precipitation and topography (James & Roulet, 2009). Furthermore, (in situ) measurements can be costly, not so common in remote locations and time-consuming at the required scale (Chifflard et al., 2018; Corradini, 2014; Vereecken et al., 2008).

The coefficient of variation (CV) can be useful for characterizing soil moisture content variations and estimating the accuracy of a set of sensors (Brocca et al., 2007; Famiglietti et al., 2008; Yao et al., 2013; Zucco et al., 2014). Where soil moisture can be estimated at the point scale through in-situ sensors, coarser-scale measurements can be obtained using satellite observations or other ground-based monitoring methods such as cosmic ray neutron sensors (Bogena et al., 2022). However, such soil moisture measurements provide coarser spatial and temporal resolutions (Brocca et al., 2017). Furthermore, soil moisture conditions in the upper layer do not necessarily represent the water storage state of the deeper layers and strongly depend on soil characteristics, underlining the importance of proper spatial information and in-situ measurements (Hagen et al., 2020).

A large variety of automated probes and sensor systems are frequently used to monitor soil moisture states (Jackisch et al., 2020; Nieberding et al., 2023). These findings indicate that substantial uncertainties exist for all types of sensor systems. In this context, various attempts have been made to determine both the number of samples required to predict the mean soil moisture content and the optimal placement of soil moisture sensors (Molina et al., 2014; Vereecken et al., 2014). The number of samples required is highly dependent on topography and increases with complex topographic structures. Soil moisture sampling in key landscape units can be a valuable opportunity to resolve spatiotemporal variability and predict runoff (Chifflard et al., 2018; Zehe et al., 2010). Another important question to take into account when monitoring soil moisture is the sampling frequency (Molina et al., 2014; Robinson et al., 2008).

Monitoring of soil moisture over grassland sites, which is usually employed for the sake of simplicity in the set-up of continuous sensors, was found to be appropriate for obtaining measurements representative for different land uses in a catchment in Italy (Zucco et al., 2014). However, to confirm and extend these findings, it is recommended to implement similar procedures for other regions and climates, and different distributions of land cover types. Adams et al. stated that more insight is needed into the effects of afforestation on soil moisture behaviour (Adams et al., 2010). Jost et al. investigated the influence of tree species on soil moisture patterns and lateral flow processes (Jost et al., 2012). The results of this study suggest that different tree species can lead to different rainfall–runoff responses for the same soil type.

Runoff plots can provide a better understanding of rainfall–runoff relationships in mountainous areas (Badoux et al., 2006; Bettoni et al., 2023; Jourgholami et al., 2021; Marshall et al., 2014; Mayerhofer et al., 2017; Meißl et al., 2023; Retter et al., 2006; Schindler Wildhaber et al., 2012). These experiments demonstrate the role of land use management and soil moisture conditions in estimating runoff coefficients. Although studies on seasonal soil moisture patterns exist (Rosenbaum et al., 2012), we still lack strong evidence of how seasonal changes in soil moisture conditions are related to land cover change and surface runoff generation. A detailed understanding is needed of the dominant controls on runoff generation for specific precipitation events and to quantify the interplay between dry and wet pre-conditions, and vegetation in Alpine catchments. For example, a prolonged period of drought can change the nature of the soil, hampering its ability to absorb water and increasing the risks of floods (Gimbel et al., 2016). On the other hand, a period of excessive rainfall can lead to saturated soils, which can play a significant role in the runoff response during extreme storm events (Manoj et al., 2023).

The aim of this study has been to evaluate the effects of long-term afforestation as NBS on soil moisture behaviour and the importance of the initial conditions in relation to soil water storage during rainfall events. The Alpine catchment Geroldsbach-Götzens is used as a demonstrator study. This headwater catchment is characterized by afforestation and reforestation as NBS that started in the early 1950s (Schiechtl, 1962; Stangl, 2003; 2007). We hypothesize that afforestation can have a positive impact on soil water buffering. To test this hypothesis, we employed an operational monitoring network to obtain measurements at plot and catchment scale. More specifically, we addressed the following research questions:

- What is the difference in soil moisture behaviour between different stages of afforestation and grassland?
- What is the importance of initial conditions in relation to soil water storage during convective precipitation events?
- What monitoring strategies should be used to understand the hydrological processes at plot and catchment scale in response to afforestation.

Furthermore, we describe the challenges of sensor installations, automized monitoring techniques, data losses, data validation, post-processing, data visualization, practical challenges and maintenance issues.

2. Materials and methods

2.1. Study area

The study area is the Geroldsbach-Götzens catchment (5.6 km^2) that is located in the Inn River Basin and is nearby Innsbruck in the Austrian state of Tyrol (Fig. 1a). The settlement area along the Geroldsbach has a history of flood events and was threatened in the 1950 s by debris from a steep meadow area called Blaike that was prone to erosion. Since then, these open areas have been renatured and constantly monitored to investigate the hydrological effects of the measures taken at that time. Over the years, mixed forest has been able to re-establish itself and an increase in forest cover can be observed in the catchment (Schiechtl, 1962; Stangl, 2003; 2007). However, some open areas remained and are still not fully afforested and reforested.

The catchment stretches from a height of approximately 2400 m a.s.l. to the community of Götzens at approximately 870 m a.s.l. and is north-orientated. Coniferous and mixed forests are the dominant land cover types, and a proportion of the area is grassland pasture that is grazed by livestock. The area is also characterized by recreational opportunities such as a ski area that is present in the catchment. The mean annual precipitation is around 998 mm, given by the Spatial Reanalysis Dataset for Climate in Austria for the period 1991–2020 (Geosphere Austria, 2023). A large part of the catchment is covered by snow during winter

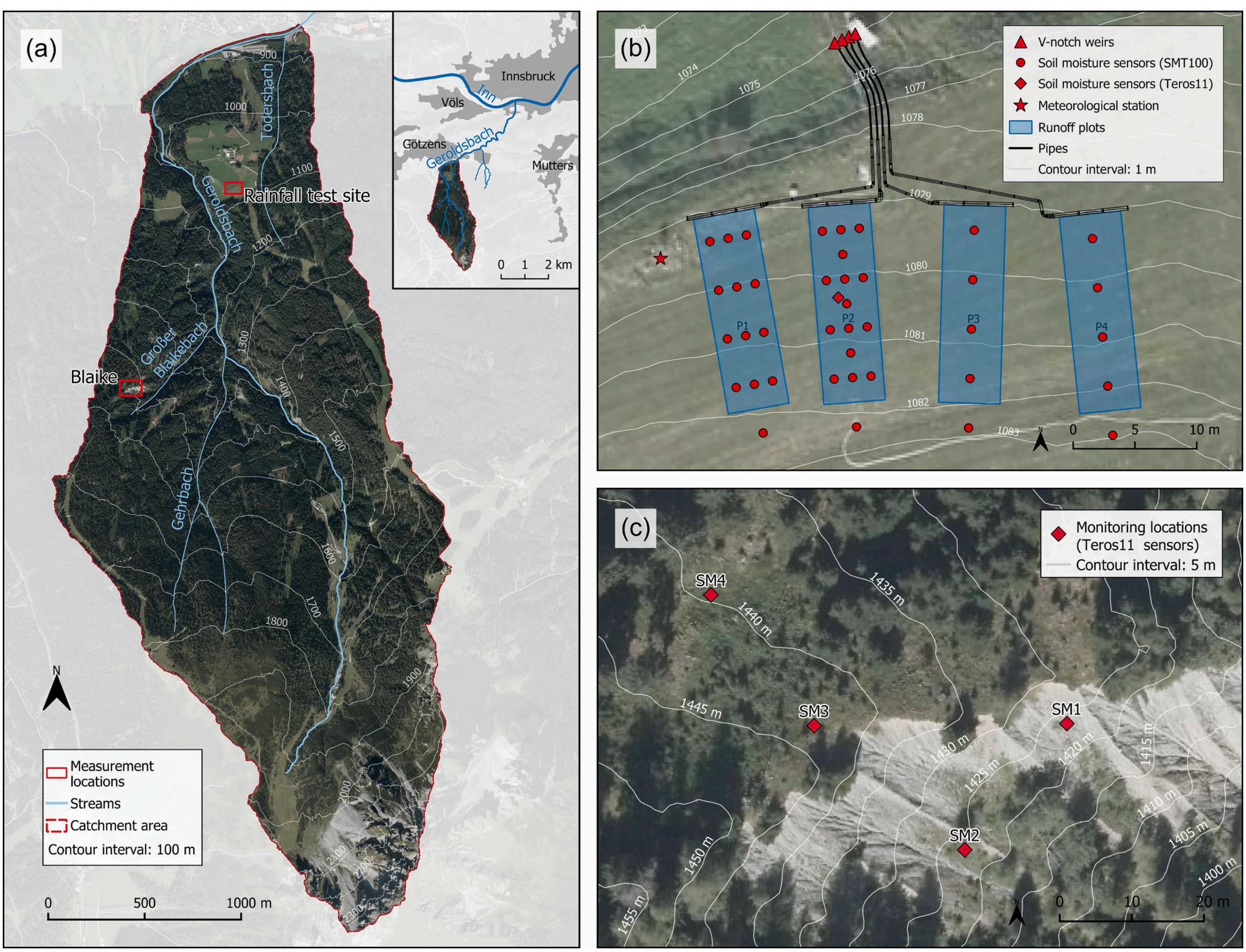

Fig. 1. (a) The study area: the Geroldsbach-Götzens catchment; (b) Rainfall test site; (c) Soil moisture monitoring locations at Blaike.

and the summer is characterized by convective precipitation events.

To determine soil conditions and vegetation types, a field study was conducted in August 2020. Over 30 soil profiles were taken, transects were made to determine the soil depth and tree genera were described. We found that the main soil types are rendzic leptosols, chromic cambisols and carbonaceous cambisols. From a geological point of view, the study area can be divided into two parts, by the Geroldsbach (Moser, 2011). In the western part of the study area, cambisols and lithic leptosols were found, which are affected to different degrees by podsolization processes. In some of the undisturbed areas, soil development has progressed so far that there are small-scale associations of semi-podzols and podzols. In the eastern part, also rendzic leptosols and chromic cambisols were found at higher altitudes. The soil types differ fundamentally along the geology and can be related to forest types as well (Forest Site Classification Tyrol, 2023. Waldtypenhandbuch, 2019). The dominant tree genera are spruce, larch and pine in the catchment.

2.2. Rainfall test site

To analyse the impact of soil properties and vegetation cover changes on soil water dynamics, four experimental plots were established at the rainfall test site at Götznerberg (Fig. 1b and 2a). These runoff plots are situated on grassland at an elevation of ∼1080 m a.s.l., with slopes ranging from 10.2° to 12.7°. The plots each have an area of 80 m^2 and measure 16 m (down-slope) by 5 m (cross-slope). The soil type is classified as chromic cambisol (carbonate-free) consisting of loamy sand and sandy silt with a low to moderate amount of coarse material, characterized by moderate storage capacity and permeability.

Generally, soil moisture content is specified as the volumetric water content (VWC), which refers to the volume of water in a given volume of soil. To measure the VWC two different types of soil moisture sensors were used for in-situ measurements. After testing several soil moisture sensors indoors, Teros11 (METER Group) and SMT100 (Truebner GmbH) sensors were selected to monitor VWC and soil temperature in the field. These are capacitance sensors that use the surrounding soil as the dielectric of a capacitor in their circuitry and measure the charge times of this capacitor (Bogena et al., 2017; Lo et al., 2020; Nieberding et al., 2023).

In the runoff plots, a total of 195 sensors of the type SMT100 were installed at depths of 5, 10, 20, 40 and 80 cm in the period May-July in 2021. Another five sensors of the type Teros11 were installed at depths of 5, 10, 20, 40 and 60 cm in August 2020, aiming to have technically compatible measurements as installed in the forested parts. The spatial distribution of the installed soil moisture sensors at the rainfall test site can be seen in Fig. 1b and Fig. 2a. The profiles were dug by hand to disturb the soil as little as possible and sensors were inserted slightly offset underneath each other into the undisturbed wall of the pit. Because the runoff plots can be affected by experiments, a single pit of five soil moisture sensors was installed outside each plot as reference measurement. The density of moisture sensors differs per runoff plot, where plot 1 (P1) and plot 2 (P2) have a relatively higher number of sensors installed than plot 3 (P3) and plot 4 (P4). The horizontal distances of the sensors in P1 and P2 are 1.5 m, and the downslope distances are 4 m in all plots where P2 has distances of 2 m in the middle section. The aim was to understand the added value of a higher number of sensors and how this helps to provide better insight into small-scale runoff processes and soil moisture behaviour at the plot scale.

Measurements of meteorological observations, V-notch weirs, and SMT100 sensors at the rainfall test site were all stored on a single datalogger of type DT85M Series 4 (Cosinus Messtechnik GmbH). The weirs and rain gauge use a 5-minute measurement interval and the SMT100 sensors use a 15-minute measurement interval. The measurement data is automatically uploaded and stored to an FTP server, allowing further processing at other service and visualisation platforms.

2.3. Soil moisture monitoring Blaike

Twenty sensors of the type Teros11 were installed in the forested part of the catchment to monitor VWC at different afforestation stages (Fig. 1c and Fig. 2b). These four locations at Blaike represent key landscape units for soil moisture monitoring where: SM1 is the zero-state that represents the initial state without vegetation (bare soil); SM2 early state pioneer vegetation; SM3 young forest; SM4 old-grown forest. The dominant tree species are spruce at these locations.

The sensors were installed at altitudes between 1420–1445 m a.s.l. in the study area and installation occurred in August 2020. Sensors were installed at location SM1 at depths of 5, 10, 15, 20 and 25 cm; at location SM2 at 5, 10, 15, 25 and 40 cm; at SM3 at 5, 10, 15, 25 and 40 cm of depth; at SM4 at 5, 10, 15, 25 and 40 cm. The installation depths of the Teros11 sensors slightly differ between the forest locations and grassland for the deeper layers due to the strong skeleton of the soil and the limited soil profile at some locations. The five Teros11 units in each pit are connected to a ZL6 datalogger (METER Group) for recording sensor readings every 15 min and uploading data every hour to a web portal. The ZL6 datalogger has a small solar panel and runs continuously, which is of importance since the monitoring locations at Blaike are hard to access.

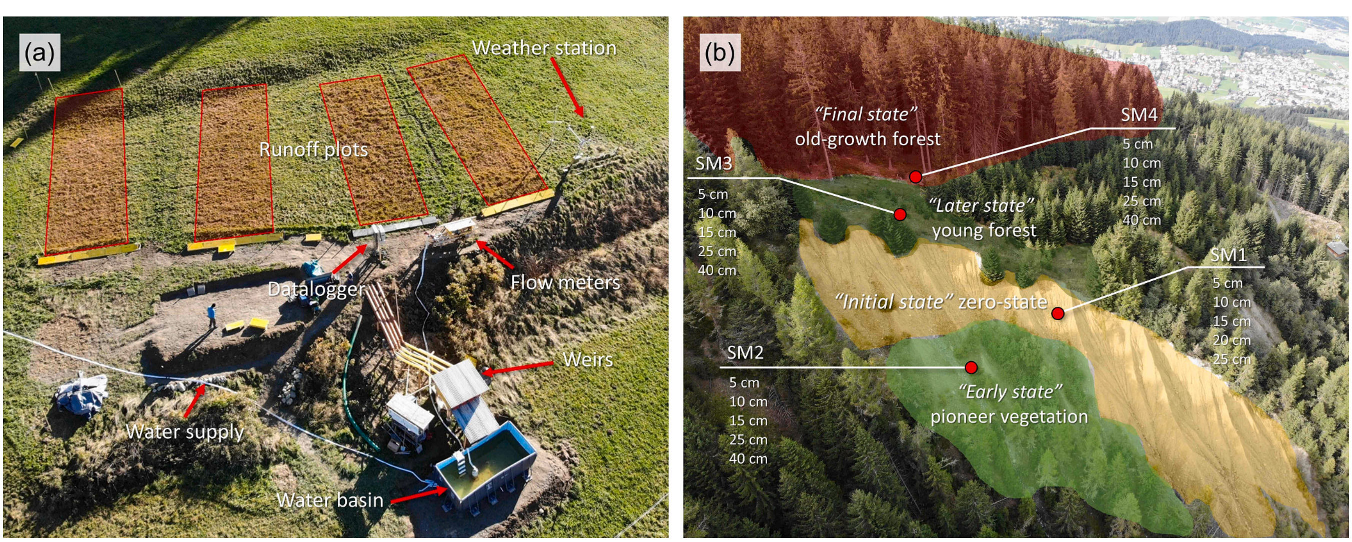

Fig. 2. (a) Rainfall test site; (b) Key monitoring locations of soil moisture for different stages of forest development at Blaike.

2.4. Meteorological observations

The rainfall test site is equipped with an automatic weather station (AWS) that measures precipitation, radiation, humidity, temperature, air pressure, wind speed and direction. The AWS was installed at the rainfall test site in the summer of 2021 and operational from the beginning of June 2022. The rain gauge that was used for the analysis is a rain[e]400 with a heater (Lambrecht Meteo GmbH). The AWS observations were compared with precipitation measurements of the weather station in Axams (Tyrol Hydrographic Service, 2022), which is approximately 2 km away from the rainfall test site, for validation.

In addition to the local measurements, INCA hourly precipitation data on a 1 km x 1 km spatial grid from the Austrian National Meteorological Service was used for the analysis, which uses a combination of rain gauge data, weather radar estimates, and high-resolution topography (Geosphere Austria, 2023). Time series for point locations were retrieved for the coordinates 47° 12′ 58.68′′ N, 11° 18′ 25.506′′ E for Blaike and 47° 13′ 32.1708′′ N, 11° 18′ 53.388′′ E for the rainfall test site.

2.5. Method of soil moisture analysis

Data quality assurance relied on regular site visit reports, where influences on data quality were noted, and on visual inspection of the measurement data. The time for consolidation of the soil moisture sensors was more than two months prior to the selected evaluation period. In a few cases, data was downloaded manually at the site and added to the records later when data was not automatically uploaded completely. Small data gaps (up to a few hours) in the time series of the soil moisture measurements were linearly interpolated.

To generate an initial impression of the different soil moisture responses at various locations (Teros11 sensors), statistical metrics (median, minima, maxima, standard deviations, and percentiles) were computed. These values were then presented as time series and box-and-whisker plots with an average taken over multiple years to calculate the values for the different seasons. In addition, we looked at how water propagates into the soil and calculated the soil water storage change (ΔS), which equals the change in VWC (Δθ) multiplied by the soil depth (Δz), of precipitation events for the different land covers:

$$\Delta S = \sum_{i=1}^{n} \Delta\theta_i \Delta z \quad (1)$$

Manfredwhere $\Delta\theta_i$ is the difference in VWC before and after the event of layer i; Δz is the thickness of layer i and n is the number of calculation layers.

For the SMT100 sensors in the runoff plots, we summarized the soil moisture metrics for the monitoring period and analysed a number of interesting precipitation events. To understand the spatial patterns of soil moisture, a geostatistical method of ordinary kriging was applied to produce spatial interpolated maps of the point measurements in the plots. We used the module SciKit-Gstat in Python for the variogram analysis. Different variogram functions were tested such as the spherical model with and without nugget effect as well as exponential, gaussian and cubic models. The spherical model (without nugget effect, n lags of 2 and max lag of 15) was selected to fit the variogram, which provided statistically and visually the best results. This model was found appropriate for the soil properties as similar methods were used in other studies on the spatial organization of soil moisture (Molina et al., 2014; Rosenbaum et al., 2012; Schume et al., 2003).

All the SMT100 soil moisture data points were spatially interpolated simultaneously for each individual layer, because we assumed identical undisturbed states between the plots since no artificial rainfall simulations were carried out during the selected analysis period. Furthermore, a convective precipitation event was analysed and the related spatial patterns of soil moisture were described.

3. Results

3.1. Soil moisture dynamics afforestation stages

Results in this section focus on the soil moisture measurements obtained by the Teros11 sensors for the key landscape locations with different stages of afforestation at Blaike and for grassland at the runoff plots. Fig. 3 presents the INCA precipitation (mm/h) and the recorded VWC (m^3/m^3) from mid-August 2020 to November 2023. The resulting time series for this 3-year monitoring period contains numerous rainfall events and several dry spells. Strong VWC fluctuations were recorded in the upper layer at 5 cm depth. The zero-state and pioneer vegetation locations showed stronger fluctuations and a relatively lower VWC compared to the more vegetated locations. The highest VWC was found in the old-growth forest with values above 0.50 after rainfall events in July and August 2021. Several decreases in VWC were observed for grassland and pioneer vegetation during spring and summer. In the winter period, when these areas are covered with snow, VWC remains relatively more constant. However, a couple of strong decreases can be observed during cold spells, specifically for the zero-state location. Overall, the soil moisture dynamics tend to decrease with increasing depth, especially for the zero-state and pioneer vegetation locations. On the other hand, for the more vegetated locations, the soil moisture dynamics seem to remain more persistent in the deeper layers in response to rainfall.

The box-and-whisker plots (Fig. 4) present a visualization of the VWC with depth for different land cover types over the seasons from September 2020 to August 2023. If we compare the distribution of VWC between land cover types, we see that they clearly differ for each depth and over the seasons. However, grassland also has many similarities with young and old-growth forest compared to the zero-state. For all seasons the median VWCs are higher for the young and old-growth forest sites with the greatest difference in the topsoil (5 cm) compared to the other locations. The median VWC for the forest sites is more than twice as high in the topsoil than for the zero-state location in every season. The zero-state location exhibits drier conditions in the topsoil than in the deeper soil layers, while the VWC median remains more constant with increasing depth for the other locations. For grassland, the quartiles and whiskers are larger than for the young and old-growth forest in the upper layers.

Fig. 5 shows the VWC and soil water storage change between 0 and 40 cm depth for different land cover types before, during and after larger precipitation events, illustrating the varying behaviour of the infiltration processes. On 22 July 2022, the cumulative amount of precipitation was 24.5 mm at Blaike and 30.3 mm at the rainfall test site according to the INCA data (Fig. 5a). The event started with an intense rainfall peak and relatively dry initial conditions. Especially the zero-state location retained significantly less water compared to the other locations. The highest soil water storage was measured in the young forest and for grassland, where more than half of the precipitation was retained. Remarkable is that the increase in VWC at deeper soil depths was smaller in old-growth forest than in young forest and grassland where rainwater infiltrated deeper. Although more precipitation was received for grassland, the percentage of soil water storage was also the highest. Remarkably, most of the water initially propagated towards deeper layers at the start of the event and it took more time before water was absorbed in the first 10 cm for grassland.

During a longer and less intense precipitation event on 25 July 2022, we measured that the share of soil water storage is higher for all locations and almost all the precipitation is retained (Fig. 5b). Another large precipitation event took place on 5 August 2022 when 26.7 mm at Blaike and 30.7 mm at the rainfall test site was recorded (Fig. 5c). The event started with 2 hours of heavy precipitation and was followed by light precipitation for more than 6 hours. For the zero-state location, the changes in VWC were again mainly in the topsoil, while for the young forest location and grassland, the propagation of water was also visible

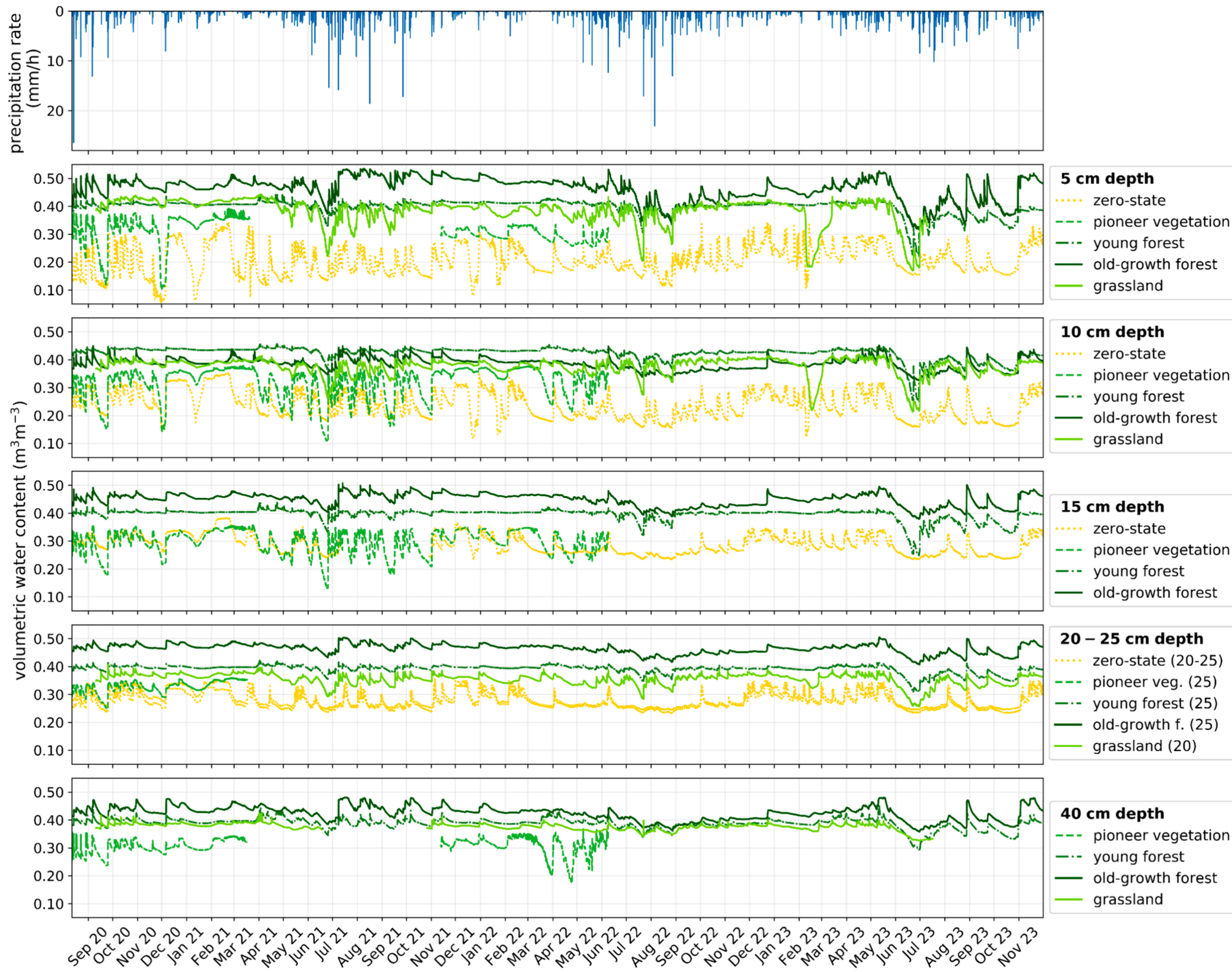

Fig. 3. INCA precipitation (mm/h) and volumetric water content (m^3/m^3) for locations with different stages of afforestation at Blaike (1420–1445 m a.s.l.) and for grassland at the runoff plots (~1080 m a.s.l.), measured by the Teros11 sensors at different depths from mid-August 2020 to November 2023 with a 15-minute measurement interval.

at a soil depth of 40 cm during and after the rainfall event. Especially during wet initial conditions, the forest soils still seem to be able to absorb water, while the percentage of soil water storage of the total precipitation for grassland decreases. The measurements show that soils eventually absorb more water with dry initial conditions, but that the infiltration rate is lower at the start of a convective precipitation event.

3.2. *Soil moisture behaviour runoff plots*

This section focuses on the high-density soil moisture monitoring results obtained by the Teros11 sensors at the rainfall test site. Fig. 6 shows the time series of the precipitation measured by the rain gauge, mean VWC and percentiles for different depths at the runoff plots for the period June-August 2022 when several interesting events occurred. Of the 195 sensors of the type SMT100 that were installed, 187 were usable for analysis. During these summer months, a number of precipitation events took place and several dry spells occurred. These changing wet and dry weather conditions give insight into the soil moisture dynamics for the different soil depths. In the topsoil layers, we can see more fluctuations in the mean and percentiles of VWC than in the deeper layers. With increasing depth, the soil moisture changes in response to rainfall are dampened and peak later. This can be seen most clearly for the events around 7 June and 5 August 2022. The percentiles stay closer to the mean in the topsoil layers at 5 and 10 cm depth. At greater soil depths, the bandwidth of the percentiles increases, with the largest deviation observed at 80 cm of more than 0.10 VWC for the 5–95 percentiles compared to the mean.

Table 1 gives a summary of the measured precipitation by the rain gauge and the mean, SD and CV values of soil moisture at the runoff plots for the period June-August 2022. The highest mean soil moisture values were found for the soil layers at 5 and 10 cm depth. On average, the soil moisture percentages were around 24% in these depths that was more than double than at 80 cm depth. The largest differences between dry and wet conditions were measured in the topsoil. At 5 cm depth, the minimum of the mean was 8.5% and the maximum was almost 38%, resulting in a difference of almost 30%. For the deeper layers, the differences between the minimum and maximum were smaller and less than 3% at 80 cm depth. SD averages were below 4% at 5 and 10 cm depth and increased with depth up to 6% at 40 cm depth. The minimum and maximum SD values were between 2% and 10% at 5 and 10 cm depth. The mean CV increased with depth ranging from 0.15 in the topsoil (5 cm depth) to 0.46 (80 cm depth). This is an increase by a factor of three with the highest variation visible at 80 cm depth.

In order to visually understand the spatial organization of soil

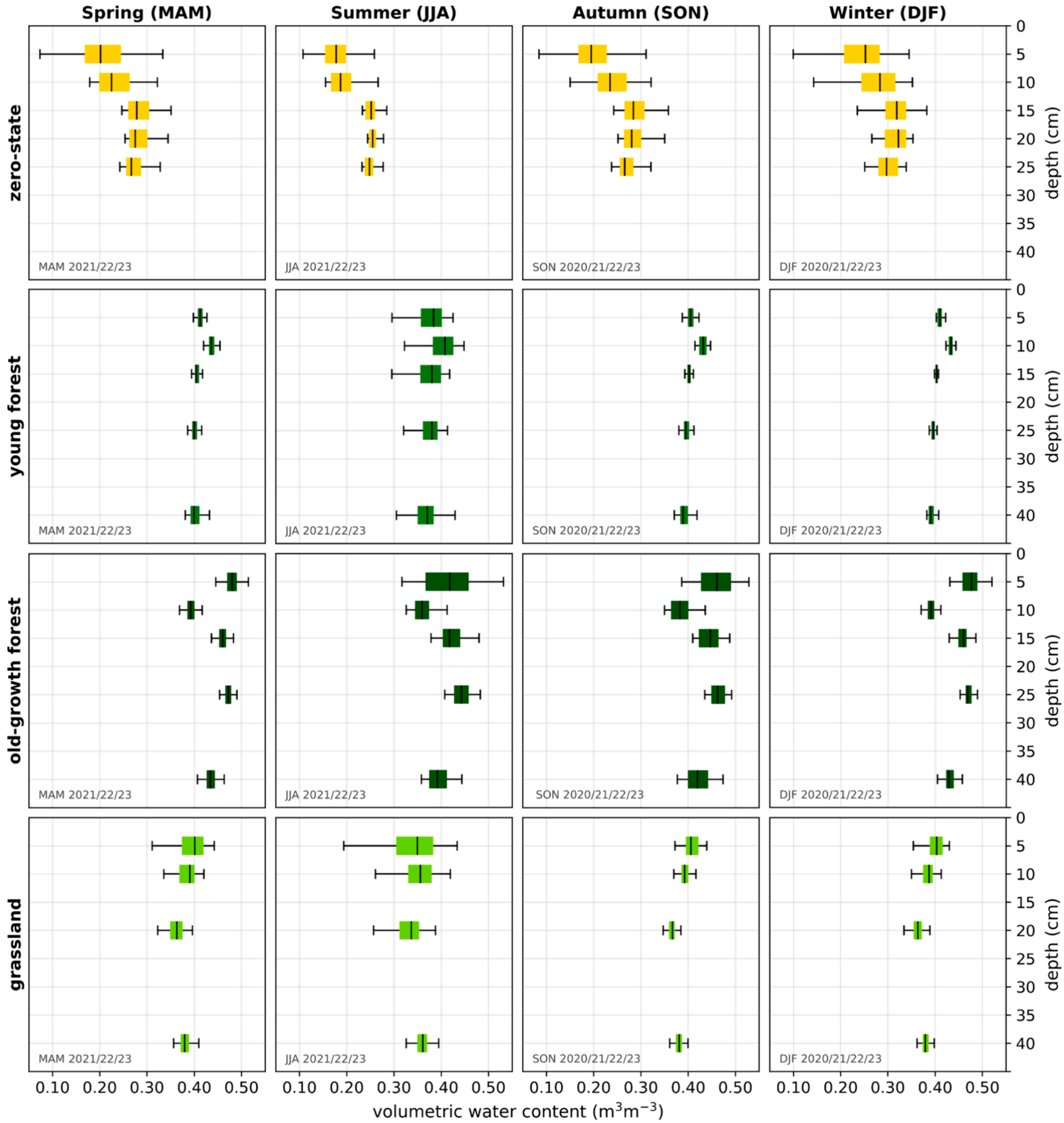

Fig. 4. Horizontal box-and-whisker plots of the distribution of volumetric water content (m^3/m^3) with depth for different land cover types over the seasons from September 2020 to August 2023. The boxes indicate the 25th and 75th percentile, the whiskers indicate the 10th and 90th percentile, the horizontal line within the box marks the median.

moisture at the five depths, interpolated maps were created for the runoff plots (Fig. 7a-e). An ordinary kriging interpolation method was used to produce the maps based on the mean soil moisture content at 5, 10, 20, 40 and 80 cm depth for the period June-August 2022. The sensor locations include the average soil moisture values and red dots indicate sensor locations where measurements were not available. Large spatial differences were observed for all the depth layers, where soil moisture can vary by more than 11% within 1.5-meter distance in the topsoil layer, and up to 26% in the deeper layers at the same depth. For example, at 5 cm depth, in the most left plot, the highest content is 30% and 1.5-meter to the right we see a value of 19% (Fig. 7a). Note that we have fewer sensors in two plots on the right that show different spatial patterns. On average the topsoil layers at 5 and 10 cm depth contain relatively more soil moisture than the deeper layers (Table 1).

3.3. *Spatial patterns during convective precipitation*

Table 2 presents the metrics of the measured soil moisture at

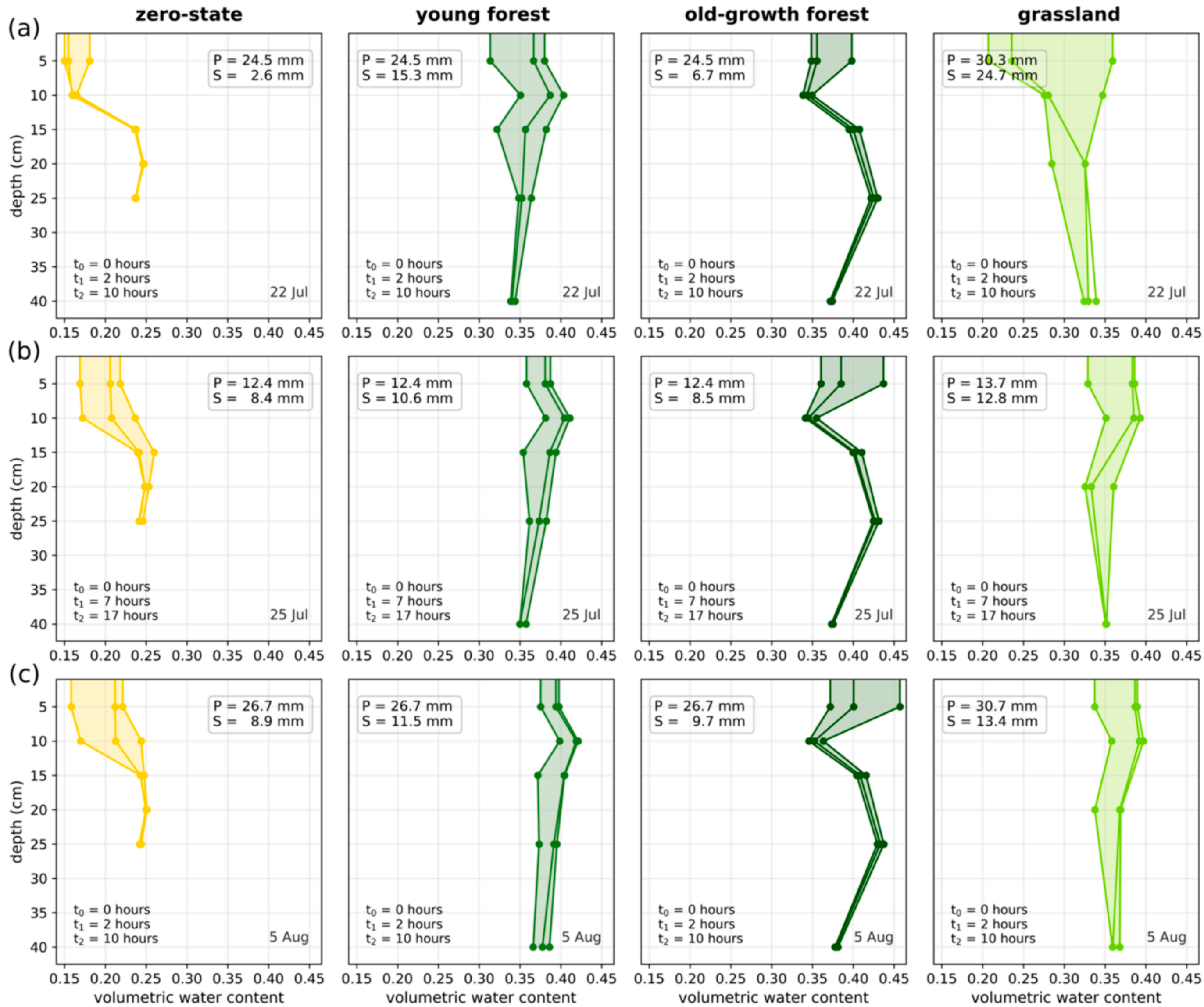

Fig. 5. Volumetric water content (VWC) with depth measured by the SMT100 sensors for different land cover types before (t_0), during (t_1) and after (t_2) precipitation events on 22 July (a) 25 July, (b) and 5 August 2022 (c). The total precipitation (P) according to the INCA data is given for the forest sites at Blaike (1420–1445 m a.s.l.) and for grassland at the rainfall test site (~1080 m a.s.l.). Soil water storage change (S) is based on the differences in VWC between t_0 and t_2.

different depths for the most notable precipitation events measured on-site by the rain gauge. The soil moisture metrics of the mean, SD and CV are given at the start of each event and directly afterwards.

On 22 July 2022, a strong convective precipitation event swept over parts of Tyrol in Austria and caused damaging floods and mudslides in several valleys. In our catchment also a lot of precipitation was received and one of the highest rainfall intensities was recorded for that year. The cumulative amount of precipitation was 34 mm in less than 4 hours and a peak rainfall intensity was recorded of 17.9 mm in 15 minutes between 17:30–18:00 UTC. This precipitation event led to rapid changes in soil moisture content that were visible even at greater depths. During this event, the mean soil moisture increased by 10% at 5 cm depth and by 1% at 80 cm depth. The SD increased especially for the layers between 5–20 cm depth. In addition, the CV shows that the variation after convective precipitation noticeably increased in the upper layer of 5, 10 and 20 cm. For the deeper layers at 40 and 80 cm, the opposite occurred and the variation decreased.

On 5 August 2022, another substantial precipitation amount was recorded of 34 mm at the rainfall test site. This event started with a rainfall peak (10.3 mm in 15 minutes) with heavy rainfall for 2 hours and was followed by light precipitation for more than 6 hours. The accumulated precipitation was similar to the amount on 22 July 2022; however, the total event duration was longer and the rainfall peak was lower. The direct visible changes in soil moisture were limited to a depth of 40 cm. Also, notice that we had wetter conditions before the event on August 5 (20.7%) than on July 22 (9.3%) at 5 cm depth. However, we still measured a similar increase of 10% at this depth.

If we compare these two previously mentioned events to an event with a lower intensity and longer duration on 25–26 July 2022 then we observed that with half the amount of precipitation, we see again a similar increase of 10% in soil moisture at 5 and 10 cm depth. However, for the deeper layers (40 and 80 cm) we see no large changes in the mean, SD and CV values.

Fig. 8 presents the measured precipitation (mm/15 min) and interpolated maps (ordinary kriging) of soil moisture values for 5, 10, 20, 40 and 80 cm depth at the runoff plots for three stages: before (16:00 UTC), during (18:00 UTC) and after (22:00 UTC) a convective precipitation event on 22 June 2022. In a relatively dry situation before the rainfall started, the mean soil moisture values were relatively close to each other for each depth layer and varied from 9.3% at 5 cm depth up to 12.5% at

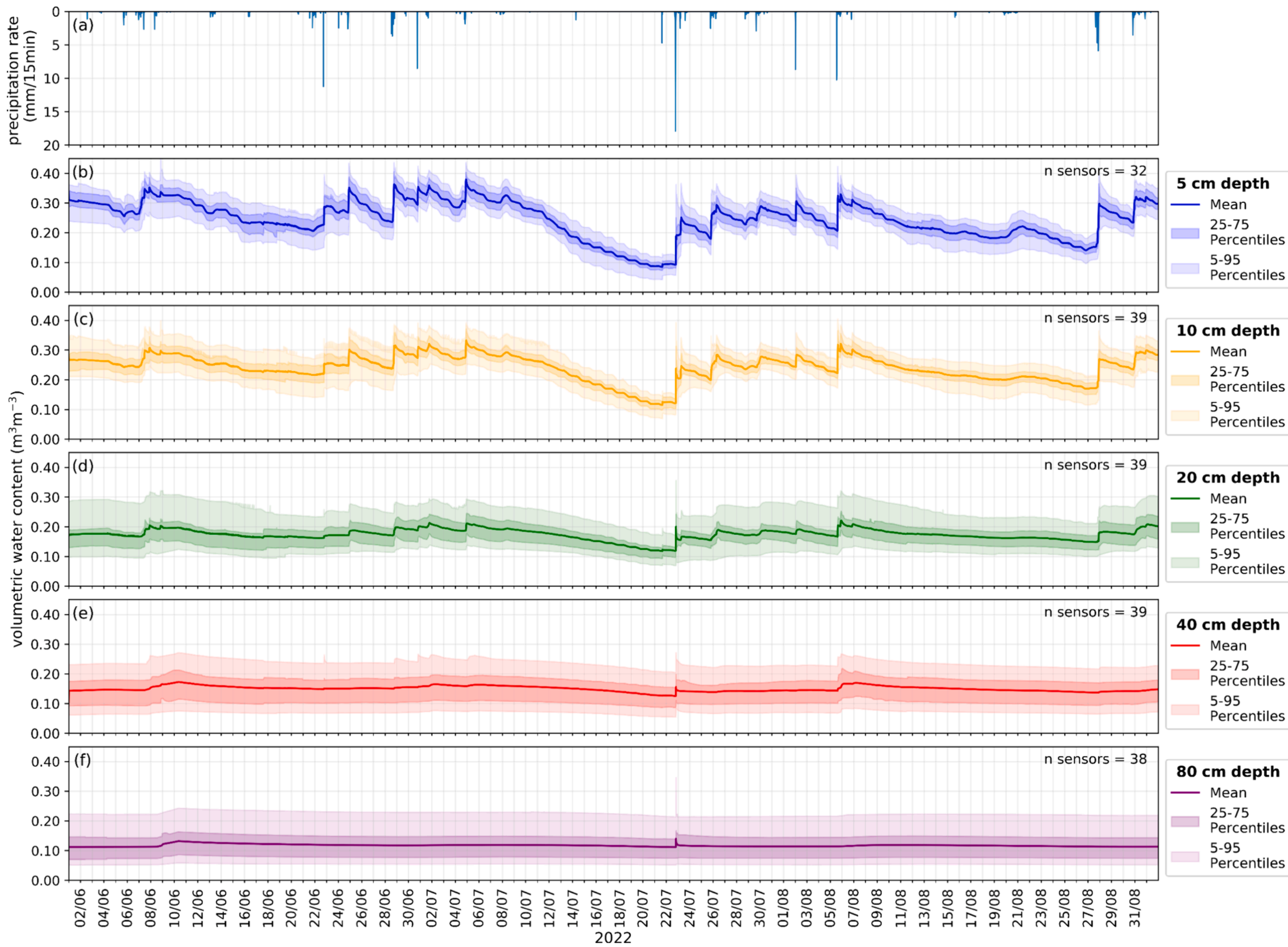

Fig. 6. Measured precipitation (mm/15 min) and volumetric water content (m^3/m^3) for 5, 10, 20, 40 and 80 cm depth at the runoff plots. The volumetric water content is presented as mean values, 25–75 and 5–95 percentiles for a three-month period (June-August 2022) with a 15-minute measurement interval.

Table 1
Measured total precipitation, mean, maximum, minimum, standard deviation (SD), and coefficient of variation (CV) of the mean soil moisture content (%) for five different layers at the runoff plots for the period June-August 2022.

Period	Total precipitation (mm)	Soil moisture									
		Depth	Min	Mean	Max	SD_{min}	SD	SD_{max}	CV_{min}	CV	CV_{max}
June-August 2022	317.3	5 cm	8.5	24.5	37.9	2.3	3.7	10.2	0.09	0.15	0.54
		10 cm	11.5	24.1	33.2	2.3	3.8	10.0	0.12	0.16	0.42
		20 cm	11.8	17.4	22.1	3.3	4.9	8.3	0.24	0.28	0.41
		40 cm	12.6	15.0	17.3	5.3	6.0	6.9	0.38	0.40	0.43
		80 cm	11.2	11.7	14.0	5.2	5.4	9.8	0.45	0.46	0.70

40 cm on average. The other depth layers showed similar values of around 11–12%. The SD was relatively lower at the surface layers than in the deeper soil layers. The SD resulted in 2.3 at 5 and 10 cm depth, 3.3 at 20 cm depth, 5.3 at 40 cm and 5.2 at 80 cm depth.

When the rainfall peaked between 17:30 and 18:00 UTC soil moisture content responded rapidly. Especially at 5, 10 and 20 cm depth, spatial patterns and strong differences were visible. This can also be seen in the SD, which was the largest for these topsoil layers. Remarkable is that at some locations the changes at 10 cm of depth were greater than at 5 cm of depth, especially for the plot at the most left and right. Also, the plot at most right was noticeably wetter in the topsoil than the plot near it during rainfall. Notice that at 80 cm the soil moisture content also increased by preferential flow for some individual sensors and sometimes even more than the sensors above it, although at most other points the soil moisture content remained more stable and constant.

A few hours after the rainfall peak, the spatial patterns became less strong and the SD decreased. The mean soil moisture content also decreased for all the layers, except at 10 cm of depth. At 5 cm of depth, the mean content more than doubled from 9.3% to 19.1%. The highest mean soil moisture content (20.5%) was found at 10 cm of depth. The SD values were also higher for all the layers than before the rainfall event. Especially for the surface layers the SD was higher, but lower than during the rainfall event.

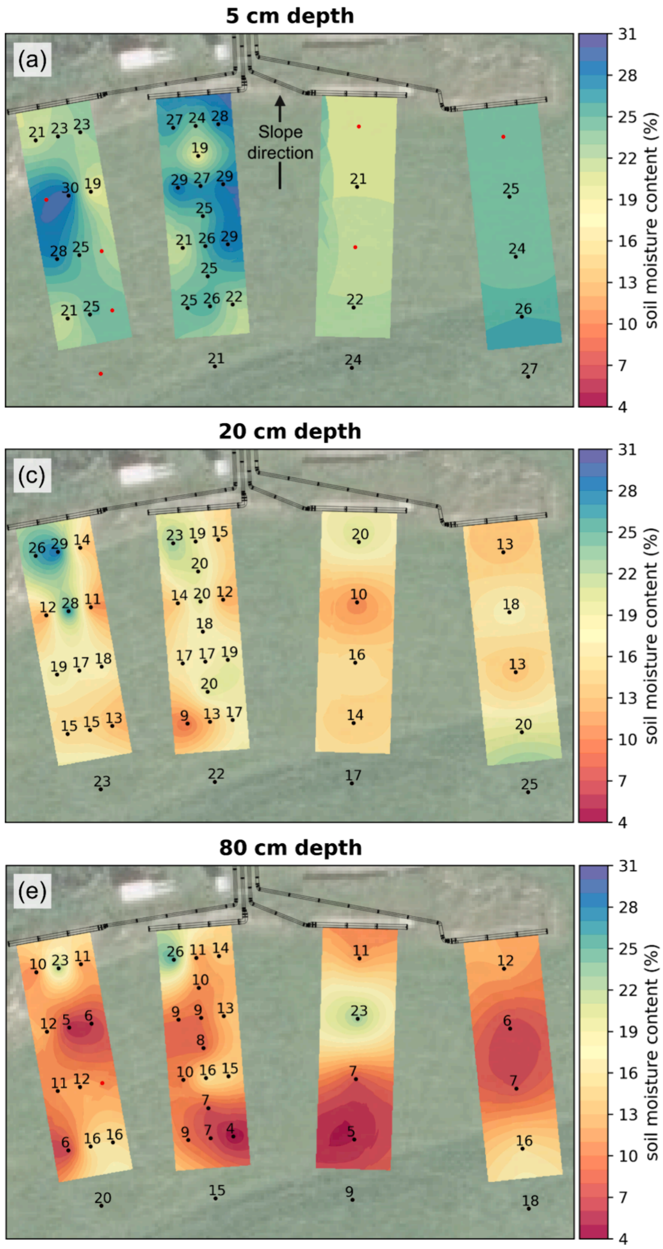

Fig. 7. Interpolated maps (ordinary kriging) of the mean soil moisture content (%) for 5, 10, 20, 40 and 80 cm depth at the runoff plots for the period June-August 2022. Outside each plot is a single pit of five sensors as reference measurement. Sensor locations include the average soil moisture values, red dots indicate sensor locations where measurements are not available. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Measurement set-up and challenges in continuous monitoring

Our operational measurement network with a large number of sensors provides insight into the soil moisture dynamics on different scales and land cover types in an afforested Alpine catchment. However, these innovative monitoring technologies of in-situ measurements come with challenges and issues. The challenges that we faced are mainly related to installations and maintenance in such remote locations. These alpine soils can be heterogeneous, where the soil profile can be limited, and rocks are close to the surface.

In the forested part of the catchment at Blaike, we obtained a measurement record for soil moisture of more than three years. While we aimed to monitor continuously with the Teros11 sensors, sometimes data gaps occurred and data was not always uploaded completely. This occurred possibly due to a weak signal in such remote locations sometimes, so data was manually uploaded in a few cases and added to the records later. Apart from that, we observed that in the forest a few cables were permanently damaged, likely by animals or rockfall. Especially at the pioneer vegetation location fewer measurements were available.

The rainfall test site has been built to be robust, but the lifetime of the equipment should be considered, and proper maintenance is required. Nevertheless, the result of 187 out of 195 well-working operational SMT100 sensors and five Teros11 sensors in the runoff plots is an achievement in monitoring soil moisture behaviour. In the surface layer, relatively more sensors got broken and fewer observations were available. Also, with our high-density soil moisture network at the runoff plots, good cable management was required. During the installation of the soil moisture sensors, we encountered many rocks that we had to

Table 2
Measured accumulated precipitation, durations and peak intensities by the rain gauge. Soil moisture mean, standard deviation (SD), coefficient of variation (CV) and differences of soil moisture (%) based on the measured data at the runoff plots before and directly after precipitation events.

Date	Precipitation			Soil moisture									
	Total (mm)	Duration (h)	Peak intensity (mm/15 min)	Depth	Mean			SD			CV		
					Before	After	Δ	Before	After	Δ	Before	After	Δ
22 July 2022	33.9	3.5	17.9	5 cm	9.3	19.2	+9.9	2.3	7.0	+4.7	0.25	0.36	+0.11
				10 cm	12.1	21.3	+9.2	2.3	6.2	+3.9	0.19	0.35	+0.16
				20 cm	11.9	16.2	+4.3	3.3	4.7	+1.4	0.28	0.34	+0.06
				40 cm	12.6	14.5	+1.9	5.3	5.9	+0.6	0.42	0.33	−0.09
				80 cm	11.2	12.3	+1.1	5.2	6.1	+0.9	0.46	0.32	−0.14
23 July 2022	8.0	2.8	2.5	5 cm	19.4	24.9	+5.5	5.0	6.3	+1.3	0.26	0.24	−0.02
				10 cm	20.5	24.6	+4.1	4.1	5.6	+1.5	0.20	0.23	+0.03
				20 cm	15.6	16.6	+1.0	4.4	4.8	+0.4	0.28	0.23	−0.05
				40 cm	14.2	14.2	0.0	5.7	5.6	−0.1	0.40	0.23	−0.18
				80 cm	11.8	11.7	−0.1	5.3	5.3	0.0	0.45	0.22	−0.22
25–26 July 2022	14.6	13.8	2.6	5 cm	18.0	28.9	+10.9	3.4	4.4	+1.0	0.19	0.15	−0.04
				10 cm	19.9	28.4	+8.5	2.9	4.3	+1.4	0.15	0.15	+0.01
				20 cm	15.5	18.9	+3.4	4.3	5.5	+1.2	0.28	0.29	+0.01
				40 cm	13.8	14.0	+0.2	5.5	5.6	+0.1	0.40	0.40	0.00
				80 cm	11.5	11.5	0.0	5.3	5.3	0.0	0.46	0.46	0.00
5 August 2022	33.8	8.8	10.3	5 cm	20.7	32.4	+11.7	3.4	4.0	+0.6	0.16	0.12	−0.04
				10 cm	22.2	31.7	+9.5	3.2	4.2	+1.0	0.14	0.13	−0.01
				20 cm	16.7	22.1	+5.4	4.8	5.7	+0.9	0.29	0.26	−0.03
				40 cm	14.3	15.9	+1.6	5.7	6.4	+0.7	0.40	0.40	0.00
				80 cm	11.4	11.4	0.0	5.3	5.3	0.0	0.46	0.46	0.00

remove at some places to install the sensors and cables. However, by removing a small part of the soil skeleton and only placing sensors in the soil material, measurements can slightly overestimate the VWC and therefore be less representative of this alpine soil in general. With regard to the measurement set-up, the soil properties and slope between the runoff plots differ slightly that could have affected the results.

No artificial rainfall experiments were carried out during the selected monitoring period because runoff measurements were not operational at the analysed period, so we assume an undisturbed state at the plots. However, the plots could have been influenced by runoff from uphill, microtopography, vegetation differences and differences in soil disturbances because of the installations as well.

Although the outcomes of soil moisture measurements can be sensitive to temperature changes (Bogena et al., 2017; Nieberding et al., 2023), the temperature effect has been neglected in our study.

4.2. Representative monitoring locations and measurement strategies

We installed soil moisture sensors at four experimental plots (grassland), as well as in the forested part of the catchment covering different stages of forest growth and assumed these to be the key landscape locations within our catchment. A point of discussion is the representativeness of the monitoring locations at the forest sites, because we only had one monitoring location available for each land cover type. We learn from our high-density soil moisture monitoring network at the runoff plots that there are many processes that lead to spatial differences in these heterogeneous alpine soils. Soil moisture values can deviate significantly from the mean at the plot scale, especially during rainfall events. We believe it is likely that similar patterns can be present in the forested part of the catchment. This local variation could mean that a point measurement does not necessarily provide a good representation of the average soil moisture conditions of a land cover type. Although soil moisture values can vary considerably at local scale, the results suggest that the differences in land cover types contribute more to soil moisture variation than local processes at plot scale, especially for the upper soil layers. Nevertheless, more sensors would be recommended to reduce the uncertainty and to better understand preferential flow paths in the forested part of the catchment.

Moreover, differences in altitude, slope, soil and vegetation characteristics, which are often discussed in other studies (Cosandey et al., 2005; Jourgholami et al., 2021; Marshall et al., 2014; Naef et al., 2002; Penna et al., 2013; Teuling & Troch, 2005; Zhang et al., 2022), are likely to have contributed to the different outcomes between the forest locations and the rainfall test site. The zero-state monitoring location is on a steep hillslope, which is relatively steeper and more exposed than the forest sites and the grassland location. This exposed soil is also less developed and contains more coarse material at the surface. The old-growth forest has a thicker root system and more layered soil that could locally reduce the permeability. The grassland site is located more downslope and may receive additional runoff, which may have resulted in more water retention at this location.

Different tree species were planted during the afforestation and reforestation that might affect hydrological processes as well. Forest structure and age should be considered as the main influencing factors, but also specific tree species can be discussed in relation to soil moisture and runoff behaviour (Freudenschuß et al., 2021). Other researchers have suggested that different tree species can lead to different hydrological responses for the same soil type (Jost et al., 2012). Moreover, differences in soil characteristics between locations can influence storage capacity and runoff coefficients (Badoux et al., 2006).

In addition, the amount, intensity and type of precipitation can vary locally and at different altitudes within the catchment (Giorgi et al., 2016). Our rain gauge has been installed at the rainfall test site, which is approximately one kilometer away from the forest site and at a different altitude, with the forest sites located approximately 350 m higher. For this reason, we used INCA precipitation data that uses a 1 km x 1 km spatial grid as well to analyse the soil moisture behaviour in the forest in response to rainfall. However, this might be less accurate than having local measurements at the forest sites using a rain gauge. Nevertheless, we assume that the difference in land cover has more influence on soil moisture behaviour than the elevation difference between our sites affecting the precipitation.

In the runoff plots, spatial variability of the mean of the soil moisture content (June-August 2022) was relatively large. This could be

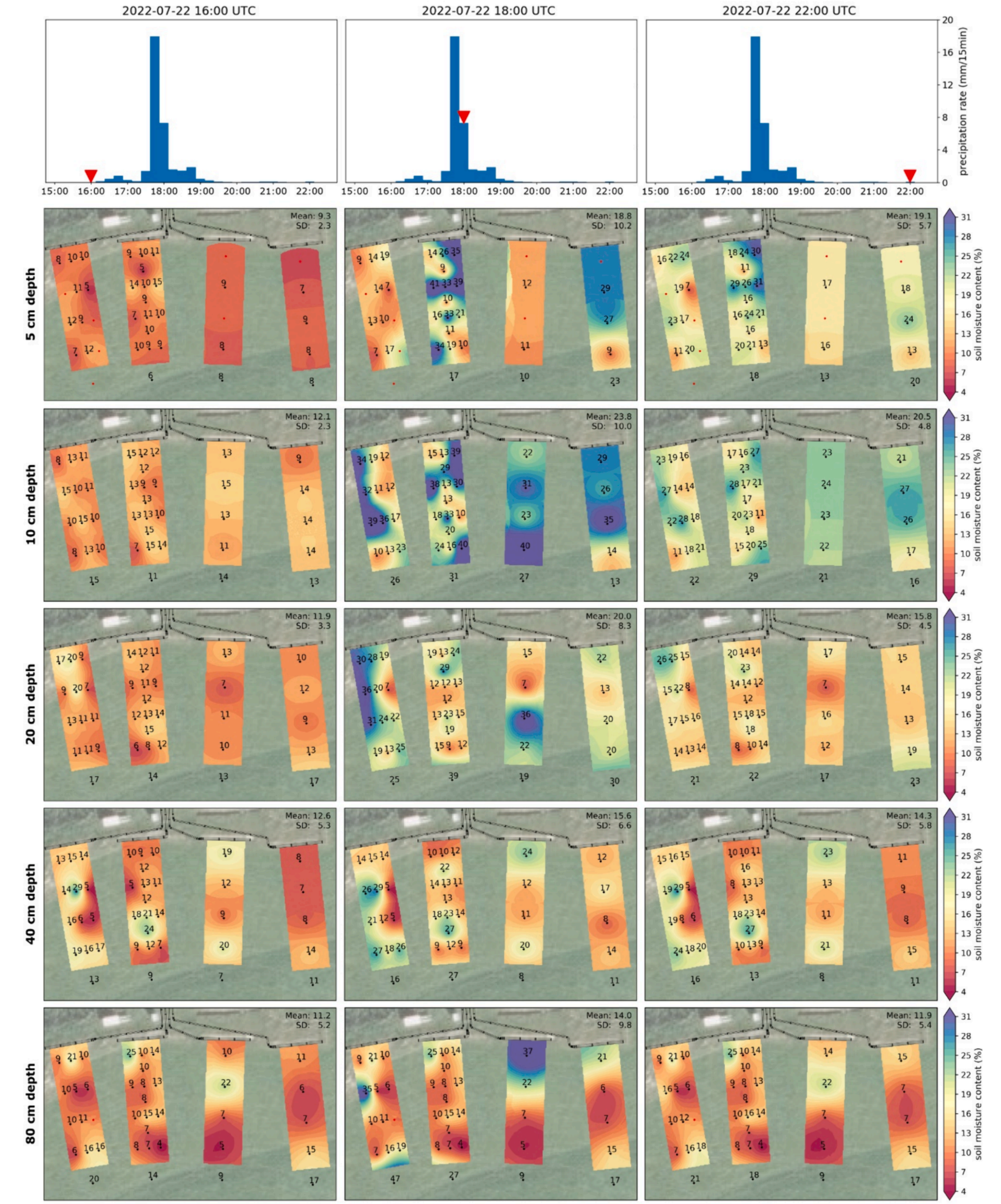

Fig. 8. Measured precipitation (mm/15 min) and interpolated maps (ordinary kriging) of soil moisture values (%) for 5, 10, 20, 40 and 80 cm depth at the runoff plots before (16:00 UTC), during (18:00 UTC) and after (22:00 UTC) a convective precipitation event on June 22 in 2022.

explained by the high heterogeneity and strong skeleton of alpine soils that leads to a large variation in VWC. A number of prior studies have addressed changes in surface soil moisture variation with increasing or decreasing mean moisture content (Choi et al., 2007; Famiglietti et al., 1998; 2008; Hupet & Vanclooster, 2002; Wilson et al., 2003).

While most of the existing research focuses on soil moisture measurements in the topsoil layers (Korres et al., 2015; Meißl et al., 2023; Molina et al., 2014; Penna et al., 2013; Wilson et al., 2003; Zucco et al., 2014), in this study we also looked at the deeper layers and installed a large number of sensors at different depths even till 80 cm. Results show that spatial variability at the plots increases with depth by a factor of three during the analysed summer period. This would suggest that more sensors are required to obtain representative soil moisture values in the deeper layers and to better understand interflow processes in these alpine soils.

The high-density soil moisture network at the plot scale provided a good indication of the spatial patterns of soil moisture in the horizontal and vertical. The two plots on the west side (P1 and P2) showed more detail than the two plots on the east side (P3 and P4). When artificial rainfall experiments are carried out, it is recommended to interpolate each plot separately for only the points inside the plot. Due to the limited number of measurement points in P3 and P4, interpolation would be less suited for these plots. Although more sensors seem to provide better results, the drawbacks of a denser sensor field are soil disturbances due to cable handling, installation efforts, and increased costs. Furthermore, our analysis of the measurements at the plots was focused on a three-month summer period. To better understand the seasonal effects such as rain on snow, it would also be interesting to look at winter and melt seasons as well.

4.3. Soil moisture behaviour in response to afforestation

Soil moisture content varied significantly between locations with different stages of afforestation and grassland in response to precipitation. Our observations indicate that soils covered by forest have a higher soil moisture content on average than grassland and soils that lack vegetation. Remarkable were the findings that in the deeper soil layers covered with forest, soil moisture dynamics remained strongly visible. This could indicate that water transport still occurs in these layers and processes such as percolation and subsurface flow may take place. It was previously also found that macro- and micro-topographic properties affect soil moisture and runoff behaviour, where forests can enhance the infiltration capacity. That forests play an important role in enhancing infiltration to deeper soil layers was also shown in other forested headwater catchments and seems to be consistent with our observations (Vichta et al., 2024).

Fig. 9 gives a conceptualization of soil moisture behaviour in response to afforestation based on the measurements, where an average of the different forest covers (young and old-growth) has been taken. In Fig. 9a the dashed line represents the end of the left whisker (dry conditions) and the solid line is the right whisker (wet conditions) based on the results (Fig. 4) for the summer season. This difference between dry and wet conditions is larger for the forest, indicating more soil water storage than unvegetated soils (bare soils) during the summer season. Fig. 9b provides a conceptual representation of the varying behaviour of the infiltration processes between land covers, based on the rainfall events presented in Fig. 5. The results indicate that bare soils represent a shallow soil water storage and that grassland and forest land cover types can infiltrate more water and also deeper during a rainfall event. Fig. 9c illustrates that forest cover and grassland minimize soil evaporation, which contributes to a delayed decrease in soil moisture compared to bare soils during a dry spell. From our measurements we learn that forest soils act like a sponge, buffering soil water during rainfall events and slowly releasing it during dry spells.

The higher soil moisture content and more gradual changes observed in the forest could be reflected by higher infiltration rates and more retention, leading to a smaller loss of rainwater as downslope surface runoff (Mongil-Manso et al., 2022). This can be explained by the macroporosity, macropore connectivity and presence of roots in the forest that are important for determining infiltration rates (Archer et al., 2016; Beven, 2004; Weiler & Naef, 2003). Vegetation composition and plant species richness have a clear relationship with rooting parameters and infiltration capacity (Tasser et al., 2021). Another effect that can explain the higher soil moisture content in the forest, is the higher water storage capacity of the soil and ground cover by vegetation that reduces evaporation from the ground. Other influencing factors that may have contributed to wetter soils in the forest are local root systems, shade by the canopy, mosses and litter cover that retains soil moisture longer (Tiebel et al., 2023; Williams et al., 1993).

Important mechanisms that continue to change with forest growth are water demand, rooting depth and canopy cover. Our results differ in some respect with a study on juvenile forest and mature forest that indicated soil moisture is higher in younger forest due to a lower physiological water demand (Rabbai et al., 2023). However, during high rainfall events, mature forest showed a greater adaptability to uptake soil moisture that is consistent with our results. However, during high rainfall events, mature forest showed a greater adaptability to uptake soil moisture that is consistent with our results. More similar results of high soil moisture values were found in another region, where a field study indicated that soil moisture tends to decrease first and then increase again as the afforestation years increase (Yao et al., 2023).

It is generally known that a forest has a higher evapotranspiration than grassland or other land cover types without vegetation (Zhang et al., 2001). The hydrological effects of greenings with NBS, which leads to more percolation and evapotranspiration, can result in a reduced fraction of surface runoff and potentially also a lower soil

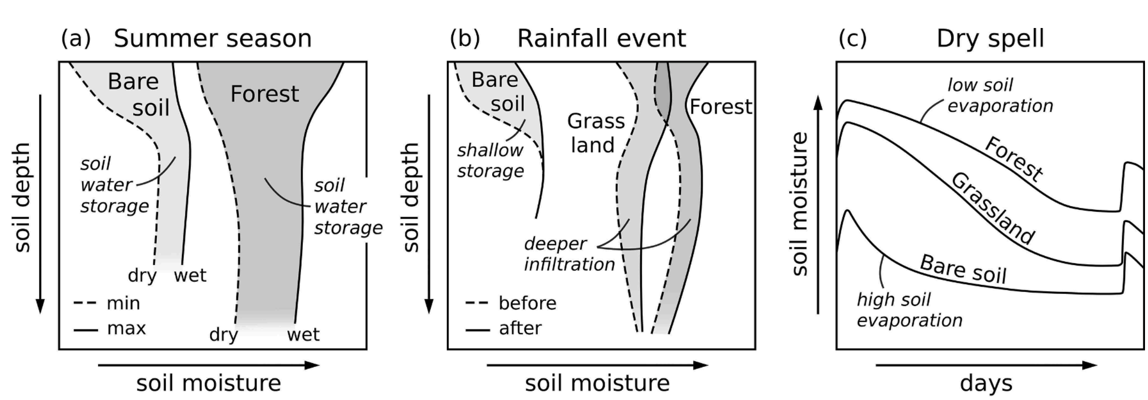

Fig. 9. Conceptual comparison of soil moisture between dry and wet conditions and the related soil water storage for (a) different land cover types during the summer season; (b) before and after a rainfall event; (c) soil moisture behaviour in the topsoil layers during a dry spell.

moisture content (Ilstedt et al., 2016). This reducing effect on soil moisture seems to be less decisive in our catchment, because we measured a relatively higher soil moisture content in the forest than for grassland. This finding differs in that respect from other research in a Mediterranean area that indicated soil moisture content was lower on hillslopes under forest cover than in downslope areas covered by grasses (Llorens et al., 2018). In addition, there are also other important influencing factors that can increase soil moisture and should be considered such as a higher organic matter content and the effect of morning dew (Penna et al., 2009; 2013).

Also notable were the results that during the cold spells, soil moisture content decreased significantly at the zero-state and grassland locations while this was less the case at the forest sites. This behaviour could be due to lower temperatures and soil freezing at the open exposed sites that can lead to freeze–thaw processes as well. Such freeze–thaw processes are known to be stronger in bare soils and grasslands than in forests (Xu et al., 2021).

In Fig. 10 we visualised our soil moisture monitoring locations and possible influencing factors on soil moisture variability in an Alpine catchment that we based on our field observations and the literature mentioned in this paper. In this study we focussed on monitoring the soil water dynamics in response to afforestation. However, forests can also increase water storage through the litter layer and interception by the canopy in addition to soil water buffering. This means that the total water retention may be greater than our estimated soil water storage for the selected precipitation events. In addition to soil water storage also surface roughness may change with forest growth that can contribute to runoff reduction.

4.4. *Capturing soil moisture behaviour during convective precipitation events*

The results show the importance of continuous measurements and the added value of a high sample frequency. The spatial variability of soil moisture for the five depths at the plots varied throughout the selected monitoring period of June-August 2022, especially during convective precipitation events. During convective precipitation events, rapid changes in soil moisture were measured that strongly depended on the rainfall amount and intensity, but also on the initial conditions (wet or dry state). Significant changes in soil moisture can occur within a few minutes where even rapid changes in soil moisture can be observed for individual sensors at a depth of 80 cm, while others remain constant. The short soil moisture peaks for individual sensors in the deeper layers may indicate that water can infiltrate more rapidly to deeper soil layers.

In Fig. 11 we highlighted the soil moisture responses of two events with different initial conditions and rainfall characteristics. These two events had a similar cumulative rainfall amount, but different intensity and duration as mentioned in Table 2. We assume that the observed rapid local soil moisture responses at greater depths were caused by preferential flow paths during convective precipitation favoured by dry initial conditions (Fig. 11a). Rainfall intensity and antecedent soil moisture conditions are often discussed as variables associated with faster soil wetting processes, originated by preferential flow (Kang et al., 2023; Lozano-Parra et al., 2015). Our observations are consistent with studies that concluded that relatively dry initial soil moisture conditions provide more suitable conditions for preferential flow (Demand et al., 2019; Hardie et al., 2011; 2013; Wiekenkamp et al., 2016) On the other hand, a rainfall event with a longer duration can also lead to a soil moisture response in the deeper soil layers, but at a slower rate and only visible after several days instead of minutes or hours (Fig. 11b). These slower soil wetting processes are often more related to flow velocity, soils or vegetation (Lozano-Parra et al., 2015).

Although the infiltration rate was lower at the start of the event with dry initial conditions, dry soils seemed to be able to store more water eventually. This observation is consistent with other studies that stated that dry pre-conditions can lead to more infiltration in total and a slight reduction of surface runoff (Meißl et al., 2021).

We used a higher measurement frequency than other high temporal resolution monitoring studies (Lozano-Parra et al., 2015). However, the infiltration processes appear to be even faster in some cases and show that significant local increases in soil moisture can take place within minutes. Subsequently, this high temporal resolution provides insight into percolation and interflow processes as well. Our observational data indicates that smaller time steps are mainly of interest during convective precipitation events and for artificial rainfall simulations. A high sample frequency is less of interest during dry conditions when changes in soil

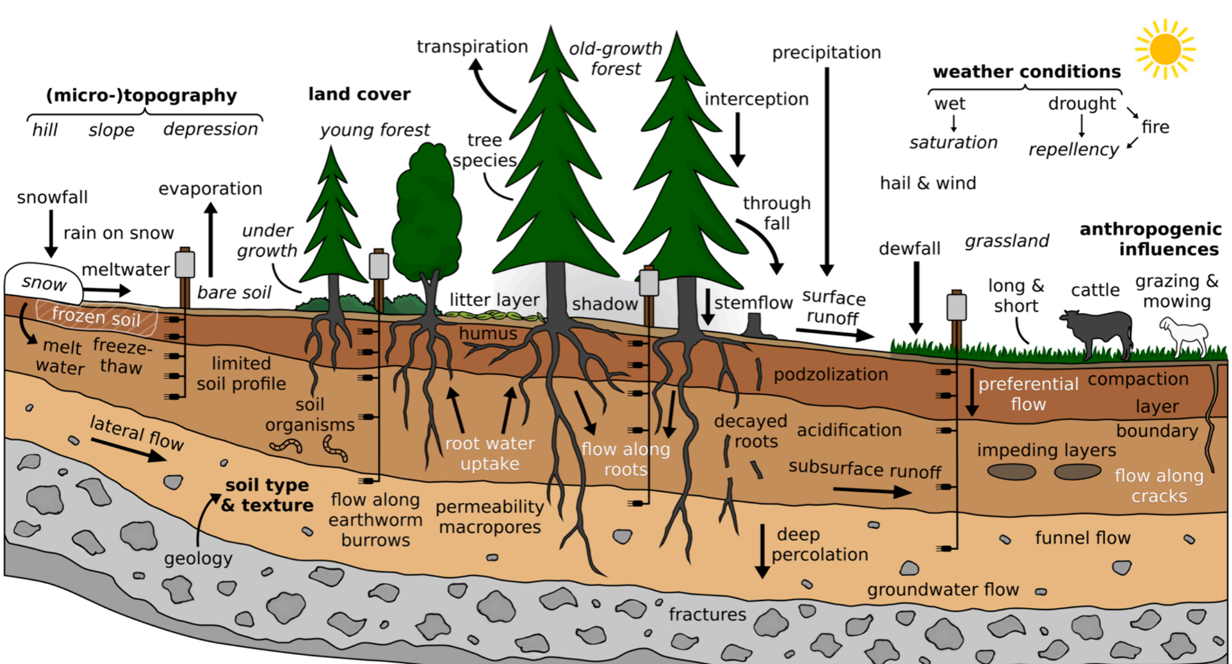

Fig. 10. Conceptual overview of soil moisture monitoring and possible influencing factors on soil moisture variability in an Alpine catchment.

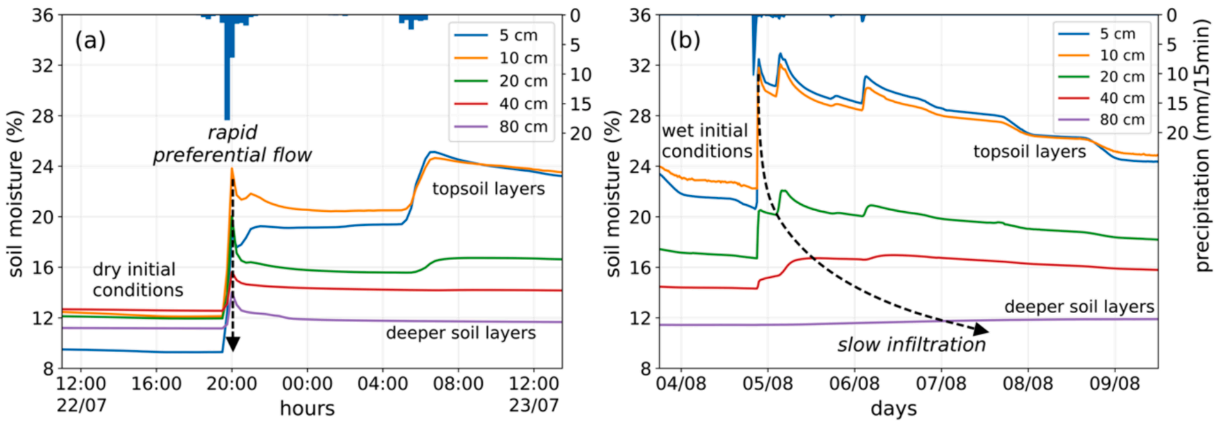

Fig. 11. Responses of the soil moisture mean at the rainfall test site (grassland) for different soil depths for (a) an event with heavy rainfall on 22 July 2022 and dry initial conditions and (b) an event on 5 August 2022 with a similar total rainfall amount but a longer duration. Horizontal time scales differ (hours vs. days) and vertical axes are similar.

moisture take place at a slower rate compared to the wetting-up phase.

Although our monitoring equipment allows to increase the sample frequency, in remote locations, such as the forest, it is important to find the right balance between the data quantities and measurement intervals. Smaller time steps provide more insight, but can go at the cost of battery resources and transmission speeds. Especially during dark, cold and snowy winter months, the battery capacity of the datalogger in the forest sometimes decreased. Moreover, it is important to have precipitation measurements available with a comparable measurement interval. At the rainfall test site, the datalogger requires some computational time to get through all measurement points, saving and uploading them. This procedure is a limiting factor for smaller measurement intervals.

5. Conclusions

In summary, the findings from the continuous monitoring data provide a significant addition to quantitative evidence of soil moisture behaviour on different spatial–temporal scales in an afforested Alpine catchment. We obtained a soil moisture record of more than three years in the forested part of the catchment covering different stages of forest growth and established a high-density soil moisture network in four experimental plots that provided insight into the small-scale soil moisture variability including the deeper soil layers. Our observations contribute to an improved process understanding of the effects of afforestation on soil moisture dynamics and are relevant to many practical questions related to land-use management, ecosystem restoration and water management throughout the Alpine Region.

The measurements show that the soil moisture dynamics differ between different stages of afforestation and grassland throughout the year. Higher and more stable soil moisture values are found in soils that are covered with young and old-growth forest than in soils with a lack of vegetation. The greatest temporal differences in soil moisture occur in the topsoil (5 cm), where soil moisture for every season is on average more than twice as high in the forest soils than in the bare soil. Grassland has on average a lower soil moisture content at all depths than the forest locations. During larger precipitation events, the vegetated locations have a higher soil water storage change than unvegetated locations and show that rainwater can infiltrate deeper. The young forest showed a stronger improvement in infiltration rates than old-growth forest. Furthermore, forest soils can retain soil moisture longer than grassland and bare soils during dry spells.

Initial conditions of soil moisture, precipitation amount, peak intensity and duration are important factors in determining how much water can infiltrate and be retained in the soil. When the initial conditions are dry, soils are able to retain more water in total during a convective precipitation event, however the infiltration rate is lower at the start. During wet initial conditions, forest soils still seem to be able to absorb water, while the percentage of soil water storage change of the precipitation decreases for grassland. In the deeper soil layers, soil moisture content stays in general more constant, but during heavy precipitation events rapid changes can be observed even at 80 cm of depth within minutes. These short local soil moisture peaks at greater depths, caused by preferential flow, occur especially with convective precipitation after dry spells, while changes take place at a slower rate (order of days) at these depths with longer duration rainfall events and wetter pre-conditions.

We demonstrated that our high-resolution soil moisture monitoring strategy provides more insight into the soil moisture variability, especially during convective precipitation when processes take place within minutes. A strong heterogeneity of this alpine soil was observed for each soil depth layer, where the mean soil moisture content can horizontally differ up to 11%–26% within 1.5-meter distance depending on the depth. In the upper soil layers at 5 and 10 cm depth, the spatial differences are smaller than in the deeper soil layers at 40 and 80 cm. Interpolated maps of soil moisture indicated that spatial variability of soil moisture increases with depth by a factor of three (CV 0.15 at 5 cm; CV 0.46 at 80 cm) on average at plot scale for the analysed summer period.

Our findings confirm "the sponge effect" of alpine forest soils and indicate that afforestation has a positive impact on soil water buffering, which can be beneficial for runoff reduction. Furthermore, we have demonstrated that many processes play a role on different scales and that our rainfall test site offers opportunities for more experiments to gather evidence-based data on soil moisture conditions related to surface runoff generation. Future work could involve hydrological modelling where our field data can be used as input to determine hydrological states and for validation. As a next step, more field experiments are needed to determine runoff coefficients and to define thresholds of runoff generation that can be used as validation and to determine the upscaling potential of NBS.

CRediT authorship contribution statement

Roy E. Molenaar: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manfred Kleidorfer:** Review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Bernhard Kohl:** Review & editing, Supervision, Conceptualization. **Adriaan J. Teuling:** Writing – review & editing, Conceptualization. **Stefan Achleitner:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2024.131984.

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