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Field monitoring of Soil–Vegetation–Atmosphere interaction in a clayey hillslope for nature-based landslide mitigation

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ABSTRACT: The interaction between soil, vegetation, and the atmosphere (SVA), is governed by thermo-hydro-mechanical (THM), processes that control the soil cover state and strongly influence slope stability. To improve understanding of these processes, a comprehensive monitoring system was implemented at a clayey landslide-prone slope in Pisciolo (southern Apennines, Italy), where selected vegetation was seeded adjacent to a bare reference area, where only spare wild vegetation occurs. Vertically instrumented profiles were equipped with sensors measuring soil temperature, suction, and volumetric water content (VWC), at depths between 15 and 250 cm, complemented by a meteorological station. Data collected over more than two years revealed marked differences between vegetated and bare profiles. Vegetation reduced daily soil temperature fluctuations within the upper 100 cm and promoted an increase in suction and water depletion in the root zone (0–100 cm). Coupled suction–VWC data allowed reconstruction of in-situ soil water retention curves (SWRCs), which displayed a left-shifted air-entry values in the vegetated profile. Overall, the results demonstrate the role of vegetation in controlling energy-water fluxes and encourage its use as a nature-based strategy for landslide risk mitigation.

Keywords: Soil–Vegetation–Atmosphere interaction; Nature-based solutions; in-situ monitoring; soil water retention curves

1 INTRODUCTION

Part of the interaction between soil, vegetation, and the atmosphere (SVA), is governed by thermo-hydro-mechanical (THM) processes taking place in the topsoil, which critically influence the boundary conditions of slope equilibrium and, hence, the stability of slopes. A deep understanding of SVA interaction is therefore essential in geotechnical engineering for landslide risk assessment and for the design of effective nature-based mitigation strategies. Nonetheless, field monitoring of the vegetation effects on the THM processes below ground level is rare.

This research focuses on a full-scale field experiment conducted at the toe of the Pisciolo hillslope, location of weather-induced landslide activity, where selected vegetation was seeded alongside naturally occurring sparse vegetation (Tagarelli & Cotecchia, 2022). Through the analysis of a first-stage monitoring dataset (Stasi, 2024), vegetation was found to significantly influence the slope piezometric regime. The combined effects of transpiration, leaf interception, and root-induced changes in retention properties and saturated permeability in the clayey soil reduce the volumetric water content and lead to a rather constant high suction profile in the topsoil throughout the year, markedly different from the highly variable suction profile observed in the bare area (Stasi, 2024). An upgrading of the field monitoring system at Pisciolo (Figure 1), performed in May 2023, allowed continuous logging of all key variables governing the THM processes involved in the SVA interaction over time, enriching the database and enabling advancements in SVA interaction modeling. The installation and calibration procedure is described in detail in Stasi (2024). Moreover, the upgraded system also allows in-situ evapotranspiration measurements of the selected vegetation that can support the validation of THM modelling of the slope behavior accounting for the vegetation effect.

This study discusses the continuous monitoring data recorded in either the bare, or the vegetated parts of the Pisciolo test site, over more than two years, in order to characterize the THM processes for different weather and vegetation conditions.

2 MATERIALS AND METHOD

The geological and geotechnical properties of the soils forming the Pisciolo topsoil are extensively presented in Stasi (2024). The selected plant of Prati Armati® employed at the test site consists of a mix of Gramineae species. The monitoring system has been specifically designed to measure all the variables required to compute both the hydraulic and the energy balance. The monitoring system includes a comprehensive and advanced network of sensors (more than 40) installed along verticals within both the Prati Armati® (V) area and the bare area (B), along with a weather station (Stasi 2024), as shown in Figure 1. Only part of the recorded data are discussed in this study, in particular those logged through: i) soil

suction and temperature sensors (Teros 21, METER Group Inc., USA), suitable for fine-grained soils (i.e. high suctions); ii) volumetric water content, VWC, sensors (EnviroSCAN™, Sentek Technologies), installed at the same depths as the Teros 21; iii) a meteorological station recording air temperature at 2 m above ground level (a.g.l.) and rainfall. The sensors are located at 15, 50, 75, 100, 150, 200, and 250 cm depth, in both the vegetated and the bare area, enabling a direct comparison of the THM response of rooted and non-rooted topsoil.

In addition to time-series analyses of temperature, suction, and VWC, further data processing was carried out to highlight specific aspects of the SVA interaction. Soil temperature records at different depths were transformed into the frequency domain using Fast Fourier Transform (FFT), which revealed dominant periods in the thermal regime (daily and seasonal cycles) and their attenuation with depth. For brevity, FFT plots are not presented here, although their interpretation is discussed.

To characterize soil water retention behavior in situ, suction and VWC data collected at the same depth were plotted against each other, deriving depth-specific soil water retention curves, SWRCs, for both B and V profiles (Stasi, 2024). These curves provide field-based evidence of the modifications to the soil hydraulic state induced by the roots. Indeed, th root profile was derived using the Root Length Density (RLD) index, which ranged from 18 cm cm^{-3} near the surface to nearly zero at 75–100 cm depth. This vertical gradient reflects root-induced changes in soil structure and porosity, which in turn affect water retention behavior (Stasi, 2024).

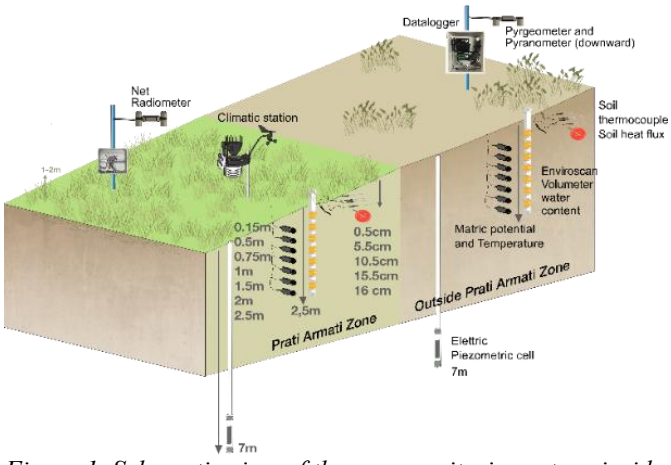


Figure 1. Schematic view of the new monitoring set-up inside (a) and outside (b) the vegetated area

3 RESULTS AND DISCUSSION

The monitoring dataset is plotted in Figure 2, which shows, for both the B and the V area, the time evolution of: soil temperature at multiple depths (top plot, Fig. 2a), together with air temperature; of soil suction (middle plot, , Fig. 2b), plotted on a logarithmic scale to capture the wide suction range; the corresponding VWC (bottom plot, , Fig. 2c) and rainfall data. Interruptions in data logging were due to occasional datalogger malfunctioning. Figure 1d shows three typical stages of vegetation development during the year (Early, Mid, and Late), providing visual support for the interpretation of soil THM behavior in the V area.

Over the two-year monitoring period, clear differences emerged between B and V profiles. Although in the bare area sparce wild vegetation occurs, the scale of influence of vegetation was larger in the V profile, where it consistently buffered the soil thermal regime compared to the more variable conditions observed in the B profile. The most pronounced differences in daily mean soil temperature occurred in the upper 100 cm. At 15–50 cm depth, bare soil is up to 3–5 °C warmer than vegetated soil during summer peaks, while in winter the vegetated profile remains slightly warmer (by 0.5–1 °C), owing to canopy and litter isolation. At greater depths (200–250 cm), the difference is smaller (1–2 °C), but a persistent cooling effect under vegetation is still evident.

At shallow depths (15–100 cm), the temperature signal was strongly modulated by both diurnal and seasonal cycles, with daily fluctuations visible year-round and seasonal amplitudes exceeding 15 °C. In deeper layers (>150 cm), the fluctuations were attenuated and phase-shifted, as expected, leaving a dominant seasonal signal and only weak daily oscillations.

Soil suction evolution also differs markedly between B and V profiles. During dry periods, the vegetated area experiences sharper suction increases, consistently with root water uptake extending to ~1 m depth (Stasi, 2024). Suction peaks in the vegetated profile persist longer, whereas in the bare profile the suctions are generally higher and penetrate deeper, with stronger variation driven by direct atmospheric boundary conditions. This suggests that vegetation accelerates near-surface drying while buffering deeper layers, thereby mitigating sharp and extreme fluctuations that could otherwise lead to desiccation cracking, often occurring in the bare area.

Similarly, VWC reduces more rapidly and to lower values in the vegetated profile, particularly within the 0–100 cm root horizon. In contrast, bare soil retains higher moisture for longer, with slower depletion during drought. This contrast testifies the role of vegetation in reducing infiltration through canopy interception, surface protection and evapotranspiration fluxes.

The thermal dataset was further analyzed in the frequency domain using Fast Fourier Transform (FFT). Although spectra are not shown here, their analysis revealed that under bare soil the diurnal (24 h) cycle was detectable down to ~100 cm, whereas under vegetation it decayed rapidly below 50 cm.

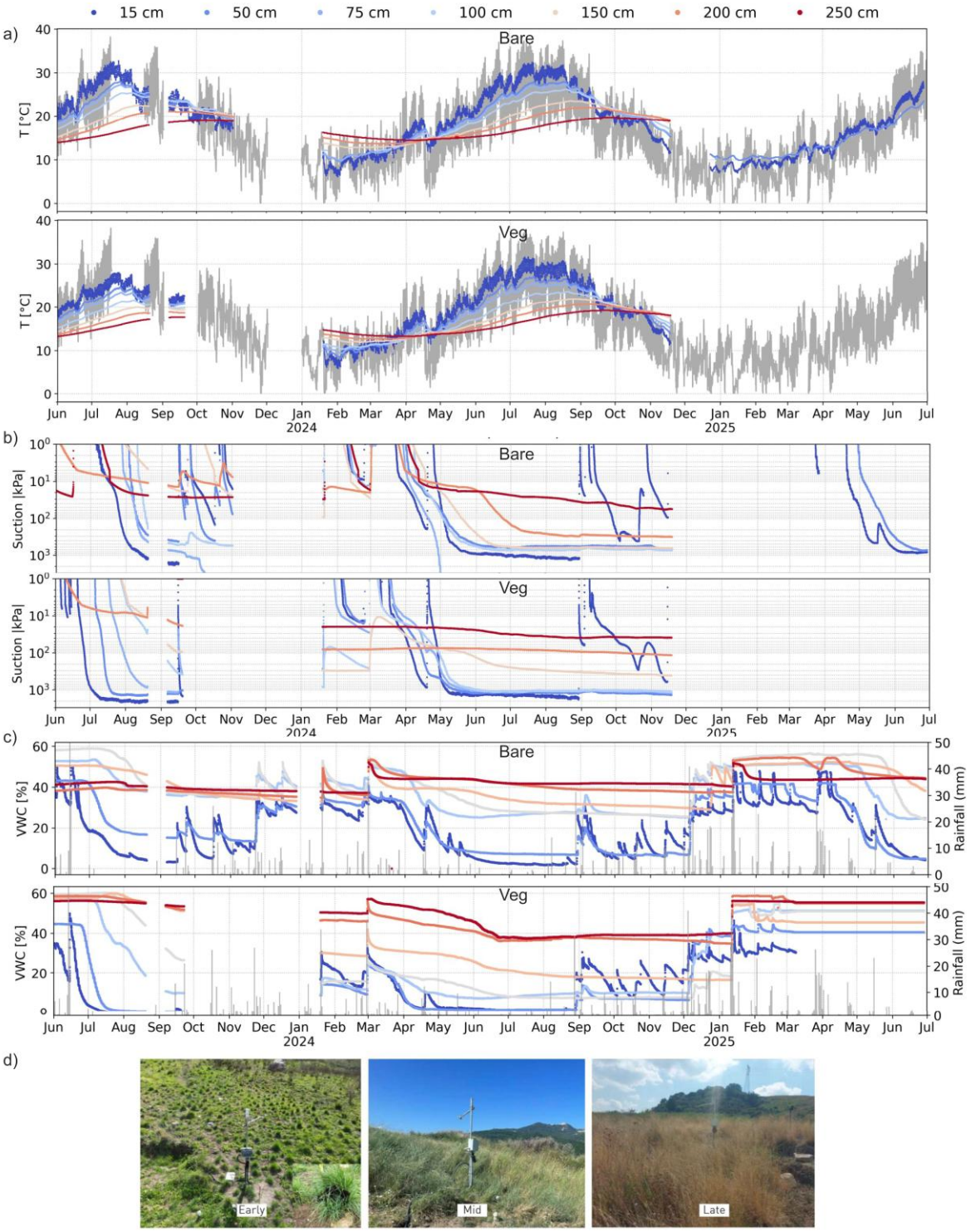


Figure 2. Time series of monitored variables at Pisciolo hillslope for the bare area and the vegetated area:(a) soil temperature at different depths together with air temperature (top panels); (b)soil suction (middle panels); (c) volumetric water content (VWC) with rainfall (bottom panels). (d) photographs of the three characteristic stages of vegetation development in 2024

Interestingly, the V profile exhibited a stronger semi-diurnal (12 h) component at 15 cm, suggesting canopy–soil interactions modulate sub-daily variability. In both profiles, long-term oscillations dominated the deeper layers, with semi-annual amplitudes of 3.9 °C (B) and 3.2 °C (V) at 15 cm, persisting at ~1 °C even at 250 cm depth. Overall, vegetation strongly dampened its propagation to depth. These patterns reflect the combined effects of shading, root-zone water dynamics, and altered soil thermal conductivity.

Figure 3a–b shows the in-situ soil water retention curves (SWRCs), reconstructed as previously described, only for the March–August 2024 drying period, highlighting systematic differences between B and V profiles with depth.

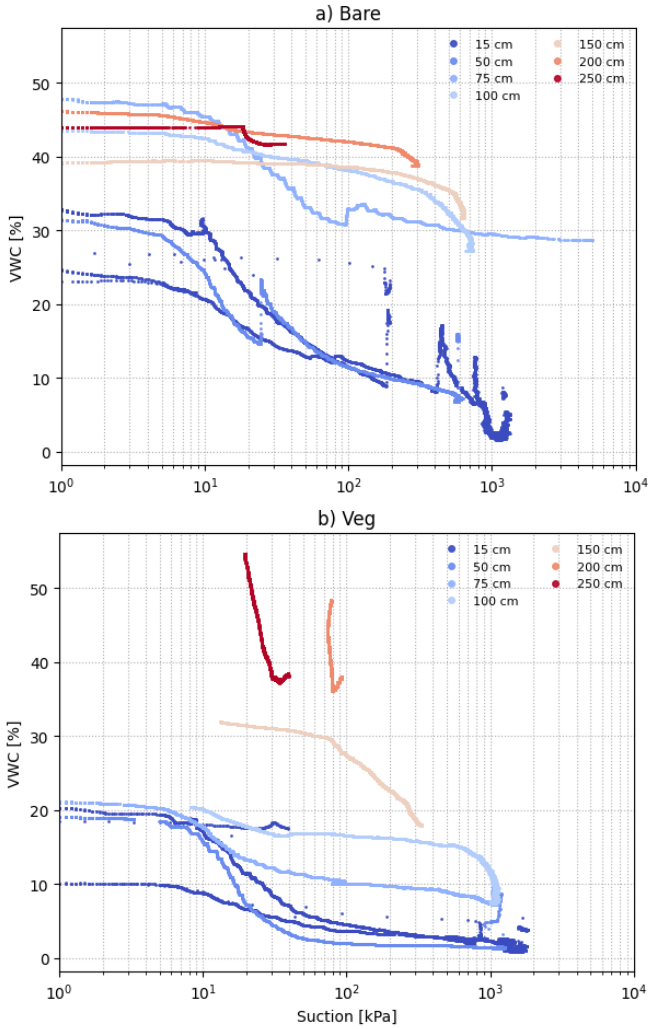


Figure 3. In-situ soil water retention curves (SWRCs) reconstructed from coupled suction and VWC measurements for the bare (a) and vegetated (b) profiles. Curves are reported for multiple depths (15–250 cm)

In the bare soil (Fig. 3a), the curves at shallow depths (15–100 cm, blue tones) start from different VWC (≈26–48%), reflecting the absence of canopy interception and direct exposure to atmospheric conditions. The drying paths extend to very high suctions (up to 10^3–10^4 kPa), with steep main drying curves typical of clayey soils. Notably, at 75 cm depth the suction probe recorded the highest values during May, most likely associated with cavitation phenomena maybe due to the development of desiccation cracks. At deeper levels (150–250 cm, indicated by red tones), the bare profile maintained higher volumetric water content (≈40–50%) and exhibited flatter retention curves up to the air-entry value, suggesting limited surface evaporative demand.

In the vegetated soil (Figure 3b), shallow layers (15–100 cm) displayed low initial VWC compared to the bare profile, possibly reflecting the root water uptake within the rooted zone. Indeed, these profiles experienced suction decrease more rapidly, with the air-entry value, AEV, shifted towards lower suctions up to 150cm. This possibly testifies that the root system modifies pore structure and increases the continuity of finer pores, thereby anticipating air entry. Below 150 cm, SWRCs remained close to saturation with high VWC values, suggesting that the soil is unaffected by root uptake. Moreover, the nearly vertical WRC curves (Fig. 3b) may be attributed to the presence of coarse-grained inclusions within the soil matrix.

4 CONCLUSIONS

The monitoring results highlight the role of vegetation in controlling the thermo-hydro-mechanical behavior of clayey topsoil in interaction with the atmosphere. Although these results should be interpreted considering the partially bare control area and the lack of replicated measurements, thermal analyses demonstrate that vegetation dampens the propagation of high-frequency (daily) temperature oscillations while maintaining the persistence of seasonal signals, a response consistent with diffusive heat transfer modulated by canopy shading, moisture-dependent conductivity, and root-zone processes.

The in-situ SWRCs provide field-based parameterization of rooted soils for THM modeling, revealing root-induced changes in hydraulic behavior. Reduced fluctuations in VWC and suction contribute to slope stability by limiting infiltration and enhancing root water uptake. Vegetation may decouple the upper soil layers from direct atmospheric forcing, effectively redefining the top boundary condition and reducing piezometric pressures at depth, thereby reducing piezometric loads within the soil profile over time. As a result, the factor of safety conceptually increases, since pore pressure reductions enhance slope stability.

5 ACKNOWLEDGEMENTS

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