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Thermal conductivity characterization of vegetated and bare soils for enhanced Soil–Vegetation–Atmosphere interaction modelling in landslide-prone regions

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ABSTRACT: Soil thermal properties play a pivotal role in controlling the energy fluxes within the Soil–Vegetation–Atmosphere, SVA, domain, since they concur to determine the evapotranspiration fluxes which have key relevance with reference to climate-induced landslide activity. The study investigates the topsoil thermal behaviour, in a field test located in the South-eastern Apennines of Italy (the Pisciolo hillslope), which represents a prototype of the landslide mechanisms often occurring in that area. The field test consists of two different areas: one vegetated, seeded and cultivated in 2019 as part of a nature-based solution (NBS) for mitigating landslide risk and one defined as a bare area. Temperature measurements were collected at multiple depths, along with heat flux data. The in-situ thermal conductivity was estimated through the extended Fourier's law of heat conduction, allowing for a comparison between rooted (vegetated) and non-rooted (bare) topsoil under varying volumetric water content and temperature. To complement the investigation, laboratory thermal conductivity tests with a custom-needle probe were also conducted. Field and laboratory data were cross analyzed to assess the impact of root systems and moisture variation on the heat transfer processes. The findings contribute to the improved parameterization of SVA models by integrating soil- and vegetation-specific thermal behaviours. This knowledge is essential for predicting the energy and water balances under climate variability and can inform the design of NBS strategies for sustainable and resilient landslide risk mitigation.

Keywords: Soil–Vegetation–Atmosphere interaction; nature-based solutions; landslide risk mitigation; in-situ monitoring; soil thermal properties; laboratory testing

1 INTRODUCTION

In most of the energy processes characterizing the soil-vegetation-atmosphere, SVA, interaction, the dominant heat transfer mechanism in geo-materials is thermal conduction. In this respect, soil thermal conductivity, λ, is the key parameter governing this process. Owing to the complexity of soils, λ varies with their physical and chemical properties and soil state, such as water content, porosity, mesofabric, and mineralogy.

Rooted soils add complexity, as the presence of roots alters the soil thermal and hydraulic behaviour in multiple ways. Root systems reinforce soil structure mechanically, while simultaneously changing porosity, water retention, and heat transfer capacity (Van Der Linden et al., 2022; Stasi, 2024). Evapotranspiration modifies both soil moisture and surface energy partitioning, leading to temporal fluctuations in thermal conductivity and diffusivity. Furthermore, the canopy system acts as a diffusive medium, characterized by its own thermal properties, exerting frequency-dependent damping and phase-shift effects on temperature propagation from the atmosphere to the soil (Van Der Linden et al., 2022). High-frequency temperature fluctuations, such as those caused by cloud cover or wind turbulence, are absorbed by the vegetation canopy, while longer-term cycles, such as seasonal oscillations penetrate deeper, reaching the upper soil layers (Van Der Linden et al., 2022). This frequency-dependent response is often overlooked in land-surface models, where vegetation is simplified as a "skin layer". A better representation of soil thermal conductivity and its dependence on moisture and structural states is therefore fundamental for hydrologic modelling, agricultural planning, environmental management, and geothermal energy analyses.

Many empirical relations have been proposed for λ, most of them derived under controlled laboratory conditions using either steady-state techniques (e.g., the guarded hot plate) or transient methods (e.g., single line heat-source/needle probes and dual-probe heat-pulse tests). In contrast, truthful in-situ estimates of λ are still challenging, as field soils are rarely characterized with a reliable level of confidence due to technical constraints (Peng et al., 2015) and variable climate.

Within this background, the Pisciolo hillslope, located in the Southern Apennines (Italy), has been equipped with a comprehensive monitoring system offering the possibility for investigating coupled thermal and hydro-mechanical processes in clayey soils prone to rainfall-induced landslides (Cotecchia et al., 2014). Selected vegetation has been seeded in the test site since 2019

with the aim of modifying the hydrological balance of the topsoil (Tagarelli & Cotecchia, 2022). A monitoring system has been designed and implemented (Stasi, 2024) to collect continuous measurements of the key variables controlling SVA interaction (Figure 1). In this full-scale "field laboratory", the observation of the thermal behaviour of vegetated vs bare topsoil offers an opportunity to quantify how vegetation and moisture dynamics jointly affect heat transport in clayey soils. By integrating in-situ monitoring and laboratory testing with a needle-probe thermal measurements, the study aims to provide a contribution to advance the parameterization of SVA energy processes and, as long-term objective, to inform the design of nature-based solutions for sustainable landslide risk mitigation.

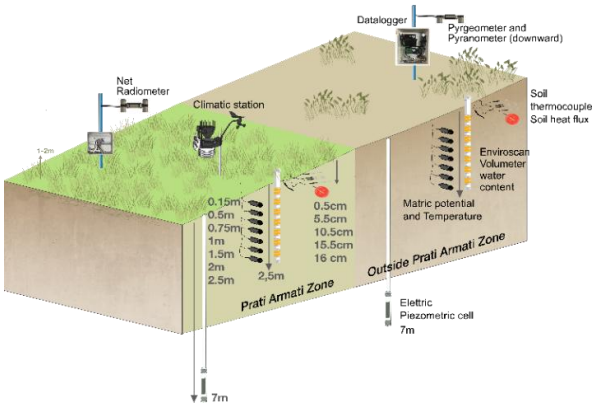


Figure 1. Schematic view of the new monitoring setup inside (1) and outside (2) the vegetated area.

2 MATERIALS AND METHODS

A detailed description of the upgraded monitoring system (Figure 1) is provided by Stasi (2024). In the following, only the sensors providing the data used in this study are presented. The soil temperature has been monitored using thermocouples (TCAV, Campbell Scientific) installed between 2cm and 7cm and Teros21 sensors (Meter Group Inc., USA) at 15cm below ground. Soil heat flux Qz has been measured with a calibrated plate (HFP01, Hukseflux) placed at 8cm depth, i.e., midway between the two temperature sensors to enable gradient-based analysis. Ochsner et al. (2006) reported that plates similar to that here adopted tend to underestimate soil heat flux due to their relatively low conductivity, contact resistance and latent-heat effects. Nevertheless, they remain the standard tool for ground-flux measurements and are widely used in surface energy-balance studies. Volumetric water content, θ, has been measured with a EnviroSCAN™ (Sentek Technologies) between 10-20cm depth. All the data are recorded each 15 mins.

Simultaneous field measurements of soil heat flux and temperature allow to derive the thermal conductivity from the Fourier's law: $Qz=-\lambda\,\partial T/\partial z$. As field data are time-discrete, the vertical gradient can be approximated between two nearby depths z_1 and z_2 as $\partial T/\partial z \approx (T_2-T_1)/(z_2-z_1)$, with the flux plate located at depth z. A direct derivation of λ can, however, become numerically unreal when the temperature gradient or the flux approaches zero. To avoid this, λ has been estimated by using the extended Fourier formulation (Romio et al., 2019):

$$Qz = -\lambda[T2 - T1/z2 - z1] + \varepsilon \qquad (1)$$

where Qz is the soil heat flux at depth z, $T_1=T(z_1)$ and $T_2= T(z_2)$ are the temperatures measured above and below the flux plate, and ε is a constant empirical term that aggregates systematic errors (e.g., errors due to plate–soil contact, plate properties, shallow storage/latent effects). Equation (1) has been fitted with a least square method over the analysis window of 15 min. In this way, the linear regression slope yields λ and its intercept provides ε, thus stabilizing the estimation under weak-gradient conditions while preserving the physical interpretation.

Complementary, laboratory measurements have been conducted on undisturbed soil samples, retrieved from the vegetated area of the Pisciolo slope. These samples have been found to be rooted and, hence, have been subjected to the determination of the Root Length Density (RLD) through the method adopted by Stasi (2024). Thermal conductivity has been determined using a custom-built needle probe, compliant with the ASTM D5334-22 standards. It consists of a stainless needle, containing both a heating element and a resistance temperature detector, placed at the midpoint of its length. During the test, a constant electric current is applied to the heater, generating a uniform heat flux along the probe. The resulting temperature increase in the surrounding soil is recorded over time. The ASTM D5334-22 standard specifies the calculation procedure: the temperature rise ΔT is plotted against the natural logarithm of the elapsed time. The thermal conductivity is obtained from the inverse of the slope of this linear relation, according to Fourier's law for a line heat source:

$$\lambda = \frac{q}{4\pi m} \qquad (2)$$

where q is the heat input per unit length of the probe, and m is the slope of the $\Delta T–ln(t)$ linear portion.

3 RESULTS AND DISCUSSION

Figure 2 reports four complementary views of the dataset: a) the bare and b) the vegetated plot time series; c) cross-site scatterplot comparing thermal conductivity for vegetated vs bare soil; d) laboratory data for a rooted soil undisturbed sample.

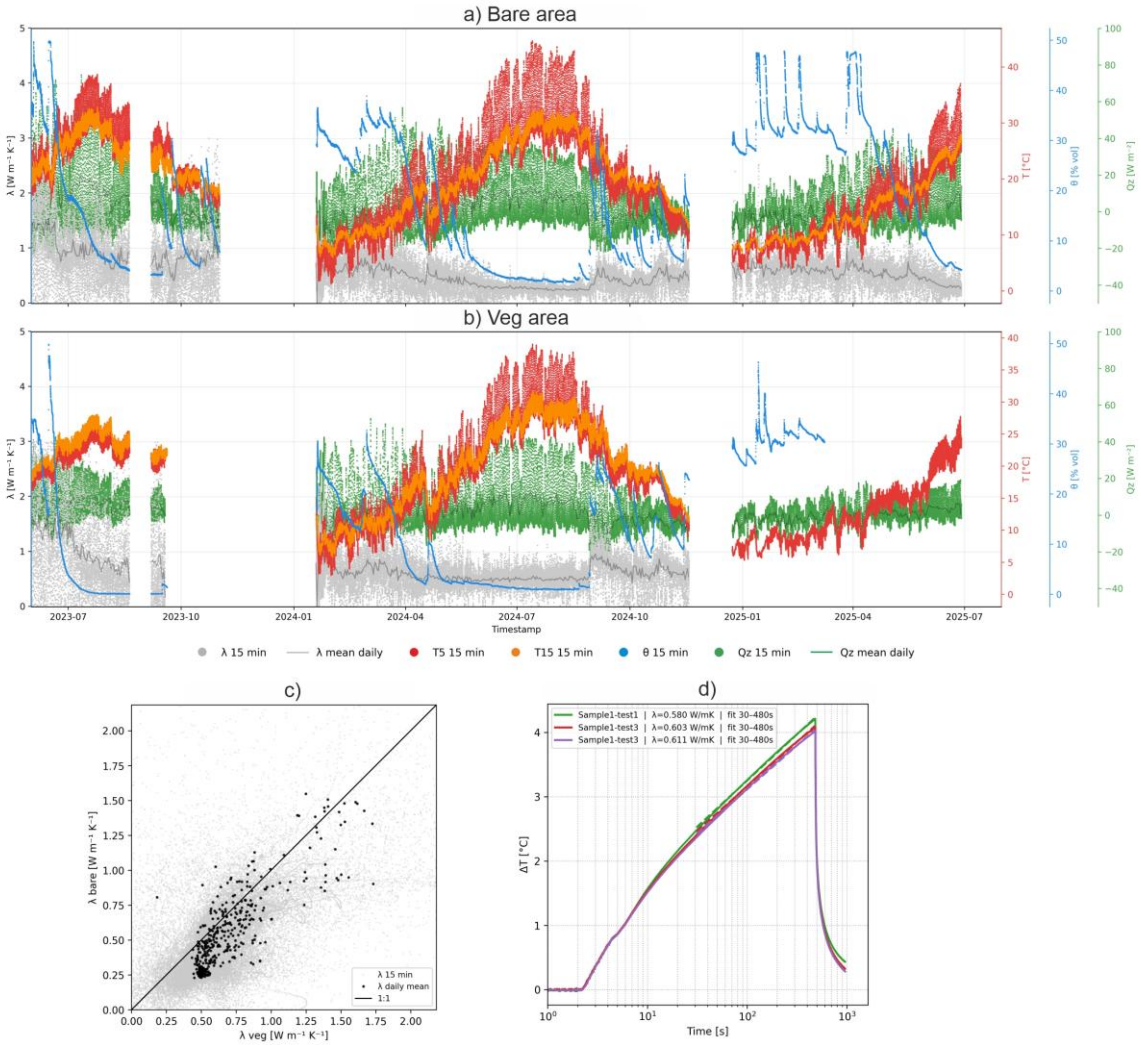


Figure 2. Time series of monitored variables at Pisciolo hillslope for (a) bare and (b) vegetated area: soil temperature at multiple depths together with soil heat flux, volumetric water content and the derived conductivity values; (c) cross-site scatter-plots comparing thermal conductivity for vegetated vs bare soil; (d) laboratory data for an undisturbed rooted sample

Over two years of monitoring (Figure 2a–b), the time series of soil temperature (measured at 5 and 15cm depth), soil heat flux, volumetric water content and thermal conductivity (calculated every 15 min and daily averaged) reveal three clear patterns of behaviour.

Firstly, the vegetation damps the thermal signal so that the diurnal amplitudes of both Qz and $\Delta T/\Delta z$ are smaller in the selected vegetated area than in the bare area. This outcome is consistent with canopy insulation and a different surface-energy partitioning (more shading and altered radiative/aerodynamic conditions, resulting in higher latent heat and lower soil heat flux).

Secondly, the soil water content controls the thermal conductivity: in both areas, λ increases with θ: wet periods exhibit higher λ, while dry ones show lower λ values. This tendency is more evident in the vegetated area, indicating that the root-affected soil responds more rapidly to incremental wetting. Roots enhance liquid-phase connectivity and reduce air-filled porosity, thereby optimizing the contact network soil undisturbed sample.

Finally, the conductivity values differ systematically: despite similar absolute temperatures at the two sites, the vegetated plot shows higher λ for most of the record testifying that the rooted topsoil conducts heat more efficiently at a given moisture state, even though the imposed surface forcing is weaker. To isolate temperature effects, we evaluated λ within narrow θ ranges; within each range, changes in near-surface temperature produced only minor shifts in λ, whereas differences in θ led to much larger contrasts. Thus, moisture dominates the λ changes, with temperature providing only secondary fluctuation of λ. In addition, the vegetation vs bare scatter for λ lies predominantly below the 1:1 line, with $\lambda_{veg} > \lambda_{bare}$ across a wide range of conditions (Figure 2c). The role of roots in increase λ is most pronounced at low-intermediate water contents and tend to decrease at high θ. This reflects a transition from disconnected to connected liquid pathways: once water films coalesce into continuous water bridges, heat transfer becomes dominated by the liquid phase and microstructural contrasts (including root effects) become less important (i.e., $\lambda(\theta)$ steeply rises then levels as saturation increases). In the drier range, rhizosphere processes—notably mucilage and exudates—help maintain water films and root-soil contact, preserving liquid connectivity and effective contact networks that increase λ relative to bare

soil at the same θ. Roots also modify near-surface fabric (porosity, contact area, organic fraction, microcrack closure), often steepening the $\partial\lambda/\partial\theta$ response.

Laboratory observations further show how roots can measurably affect thermal measurements depending on their size and orientation. Accordingly, at a low θ, vegetated soils tend to exhibit higher λ and larger $\partial\lambda/\partial\theta$, while differences narrow at high θ as quasi-saturation or saturation—and hence water-dominated conduction—takes place. Moreover**,** the canopy and litter damp and phase-shift the surface thermal signal, lowering $|\partial T/\partial z|$ and hence $|Qz|$.

The results of three thermal conductivity tests on rooted soil specimens are reported in Figure 2d. The RLD has been measured on various specimens obtained from the tested samples at different depths (0-12cm), at $\theta\approx0.35$ under controlled laboratory conditions (T=25°C). The measured values range from 2.5 to 19.6 cm/cm³, with a mean value of about 11 cm/cm³. The ΔT–time curves show similar trends: the linear fitting in the stationary portion of the semi-logarithmic plot (30–480s) results in thermal conductivity values of λ=0.580–0.611$Wm^{-1}K^{-1}$. These laboratory values fall within the envelope of field-derived λ for the vegetated area, at comparable θ, lending confidence to the in-situ estimates.

Regarding the bare area, no laboratory test has been carried out yet. However, Zizzi et al. submitted manuscript reports that, for non-rooted clayey sample collected from the same site, λ increases with unit weight and degree of saturation, decreases with void ratio and increases with the consistency index, highlighting the roles of structure and mineralogy in heat transfer processes. The results for near-surface bare samples fall within the range of 0.7–1.5$Wm^{-1}K^{-1}$, consistently with those observed in the present work with the field-based observations in bare area.

4 CONCLUSIONS

By comparing vegetated and bare soils in a prototype study area, this work examines how vegetation alters soil thermal response under different volumetric water contents and vegetation conditions. The results show that vegetation affects both the external forcing (temperature gradients and fluxes) and the intrinsic material response, by increasing the effective thermal conductivity of the rooted topsoil. Across different volumetric water contents, the temperature sensitivity of λ remains small to moderate, confirming that soil moisture plays the leading role in controlling the heat transport in geo-materials, even in the absence of an advection component.

The next step of this research program will be to account for the canopy thermal properties directly from field temperature-flux signals, treating the canopy as a diffusive layer to sharpen the upper boundary condition and better capture the energy processes. In parallel, a focused laboratory campaign across root-development stages will quantify how λ evolves with bulk density, saturation and root length density.

The final aim of this research is to assess the impact of vegetation and soil water dynamic on heat transfer processes to refine the parameterization of soil thermal properties in SVA models relevant to slope stability assessments and NBS mitigation techniques, with an approach extendable to different soil and vegetation types.

5 ACKNOWLEDGEMENTS

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