

A simple experiment to characterize evaporation patterns in silty volcanic soils under bare, vegetated and heterogeneous conditions

L. Coppola¹, L. Pagano², A. Reder³, G. Rianna³, A. Tarantino⁴

¹University of Naples Federico II, Department of Civil, Architectural and Environmental Engineering, Naples, Italy – lucia.coppola@unina.it

²University of Naples Federico II, Department of Civil, Architectural and Environmental Engineering, Naples, Italy

³ CMCC Foundation - Euro-Mediterranean Center on Climate Change, Caserta, Italy.

⁴ University of Strathclyde, Department of Civil and Environmental Engineering, Scotland, UK

ABSTRACT: In geotechnical and agricultural problems, estimating the evolution of the hydrological state of the subsoil shallow layers is crucial for addressing stability. In large areas and over long periods, this requires theoretical predictions based on monitoring of weather conditions. In modelling the soil-atmosphere interaction, actual evapotranspiration is often estimated as a fraction of the potential evapotranspiration (computed from a reference potential evapotranspiration -RE- and a crop coefficient), basing on water availability in the topsoil. The paper presents a study aimed at deriving the trend in evaporative process under different crop conditions and the related drying-induced decays for a silty pyroclastic layer. The work is based on an experiment in which small containers, filled with the same silty pyroclastic soil, were prepared with three different crop conditions: bare, grass vegetated, and covered with burnt wood residues. Containers were exposed to dry weather conditions to characterize the different evolution of the evaporation processes, quantified by weighing the containers, and linked to RE by monitoring meteorological variables at the test site. The paper shows that the evolution of evaporation processes differs significantly for bare, vegetated and heterogeneous conditions, allowing quantification of crop coefficient and drying-induced decay for each case.

Keywords: pyroclastic soils; evapotranspiration; vegetation

1 INTRODUCTION

In several geotechnical contexts—such as shallow slopes, shallow foundations, small embankments, and retaining structures—as well as in agricultural and ecological applications, predicting the hydrological evolution of shallow subsoil layers is crucial for addressing issues of stability, efficiency, and environmental health. While local monitoring of water content and/or suction may provide short-term insights, theoretical predictions capable of supporting or replacing monitoring are indispensable for large spatial scales and long-term analyses.

Suction and water content depend on soil hydraulic properties and seepage processes, the latter affected soil-atmosphere interaction in shallow layers. The influence of meteorological forcing on subsurface hydrological states is inherently complex due to the twofold role of meteorological variables. Under dry and hot conditions, soil evaporation is enhanced, reducing soil water content. However, the progressive drying of the surface

layer subsequently reduces evaporation due to diminished water availability. Conversely, when rainfall intensity exceeds the infiltration capacity, infiltration initially raises soil water content, but this increase leads to a reduction in pore-water pressure gradients, thereby limiting further infiltration. Bare soil evaporation can be defined as the transfer of water vapour from the exposed soil surface to the atmosphere (Monteith, 1973; Brutsaert, 1982; Shuttleworth, 1993; Hillel, 2003). This process is regulated by three main factors: (i) the thermal energy supplied to the soil surface, (ii) the vapour pressure gradient between soil and atmosphere, and (iii) water availability in the topsoil. The first two factors determine the so-called Potential Evaporation (PE), i.e., the maximum flux permitted under given atmospheric conditions, while the third defines the soil's capacity to meet evaporative demand, leading to the Actual Evaporation (AE). In the presence of vegetation, the process generalises into Potential Evapotranspiration (PET), typically lower than bare PE, since crops are less efficient at absorbing available energy than bare soil.

The corresponding Actual Evapotranspiration (AET), equal to or lower than PET, is often higher than bare AE during dry periods because vegetation enhances water extraction through root uptake (Foresta et al., 2020; Dias et al., 2022).

The AET is commonly estimated as a reduction of PET, scaled by a reduction coefficient (k_r) that reflects the soil wetting state. Following FAO guidelines (Allen et al., 1998), PET is first derived from the reference evapotranspiration (RE) and adjusted by a crop coefficient (k_{crop}). AET is then obtained by applying k_r to PET, thereby accounting for topsoil water availability.

This study investigates the qualitative change in evaporative (evapotranspirative) phenomenon under different conditions and the associated decay trend induced by soil drying, with specific focus on a silty pyroclastic deposit.

The experimental dataset is generated by exposing silty pyroclastic samples, stored in small containers, to atmospheric conditions under three different surface covers: bare soil, grass vegetation, and wooden ember cover.

2 MATERIALS

Figure 1a illustrates a schematic layout of the experimental activity designed to investigate and characterize the evolution of the evaporation process. Cylindrical small-scale specimens were prepared by pluviation to reproduce three different configurations: i) C1-Bare homogeneous soil condition; ii) C2-Vegetated homogeneous soil condition; iii) C3-Heterogeneous condition.

These three configurations can be found in the same area during the same hydrological year, when vegetation (Pagano et al., 2019) takes over bare conditions (Rianna et al., 2014b), and a wooden ember cover replaces vegetation after a wildfire (Coppola et al., 2023, 2024).

For configurations C1 and C2, the specimens consisted entirely of pyroclastic material, whereas in configuration C3 the same pyroclastic soil was covered with a layer of wooden ember cover (hereinafter WEC). The grain size distribution curves of both materials are shown for comparison in Figure 1b.

The specimens were saturated by capillary rise and subsequently exposed to atmospheric conditions. Evapotranspiration fluxes were quantified by periodically weighing the specimens. Starting from the weight variations, it is possible to calculate the current degree of saturation and the corresponding volumetric water content (θ). Meteorological forcings were measured and recorded at a daily resolution using a weather station.

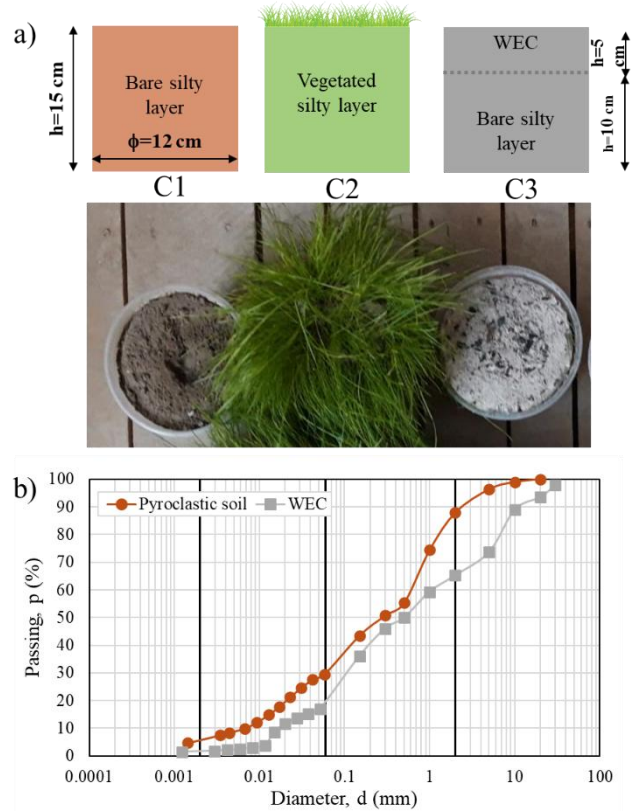


Figure 1. a) schematic layout and photo of the experimental activity; b) grain size distribution of pyroclastic soil and WEC

3 METHOD FOR EVAPORATIVE (EVAPOTRANSPIRATIVE) FLUXES DETERMINATION

According to FAO Guidelines (Allen et al., 1998), AE (AET) can be modelled following the Equation 1:

$$AE = k_r PE = k_r (k_{crop} RE) \quad (1)$$

with RE calculated taking into account Eq. 2:

$$RE = \frac{0.408\Delta \cdot (R_n - G) + \gamma \frac{900}{T_a + 273} u_{2m} (u_{v0}^a - u_v^a)}{\Delta + \gamma(1 + 0.34u_{2m})} \quad (2)$$

RE [$\text{kg m}^{-2} \text{s}^{-1}$] is the potential evaporation rate from a reference surface (hypothetical grass reference crop with prescribed crop height, surface resistance and albedo), T_a [$^{\circ}\text{C}$] is the air temperature, u_{2m} [ms^{-1}] is the wind speed at 2 m above the surface of the ground, Δ [$\text{Pa } ^{\circ}\text{C}^{-1}$] is the slope of the saturation vapour pressure curve at the air temperature T_a , γ [$\text{Pa } ^{\circ}\text{C}^{-1}$] is the psychrometric constant at the air temperature T_a , R_n [W m^{-2}] is the rate of net radiation, G [W m^{-2}] is the soil heat flux.

4 RESULTS

The evaporation (evapotranspiration for C2) process can therefore be effectively described by two coefficients: k_{crop} and k_r . These parameters can be associated with distinct controlling conditions. The former corresponds to an energy-limited condition, where the process is governed by the availability of energy at the soil surface, while the latter represents a water-limited condition, controlled by the actual availability of water within the subsurface. Figure 2 shows the temporal cumulated evolution of the actual evaporation paths for configurations C1, C2, and C3, compared with the evolution of RE. All configurations display four qualitatively similar stages:

- Stage I: characterized by a sharp increase in AE (AET);
- Stage II: exhibiting an almost steady trend;
- Stage III: showing a moderate increase in AE (AET);
- Stage IV: characterized by negligible variations in AE (AET).

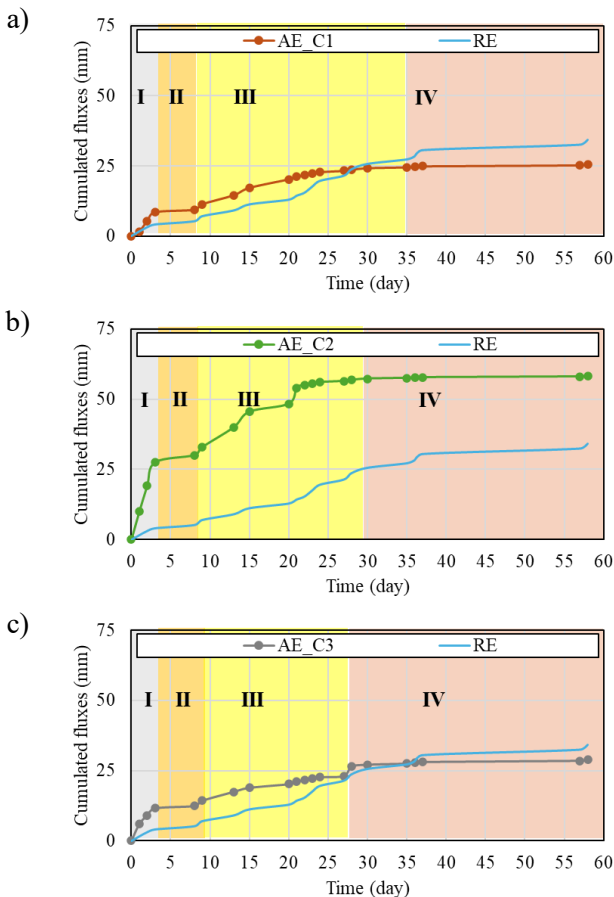


Figure 2. Temporal evolution of actual evapotranspiration (evapotranspiration) for a) C1; b) C2, c) C3

The first three stages represent energy-limited conditions, while the last one corresponds to a water-limited regime. When comparing the evolution of the three configurations during Stage I-II-III, it is evident that configuration C2 exhibits the highest ability to meet

the atmospheric evaporative demand, while configuration C1 shows the weakest response. Figure 3 illustrates the evolution of AE (AET) as a function of the mean volumetric water content. The comparison reveals that the onset of the water-limited regime occurs at different volumetric water contents for each configuration. The highest threshold value is observed for configuration C3, while the lowest corresponds to configuration C2. Consequently, the transition toward the residual condition is more pronounced for configuration C2 and more gradual for configuration C3.

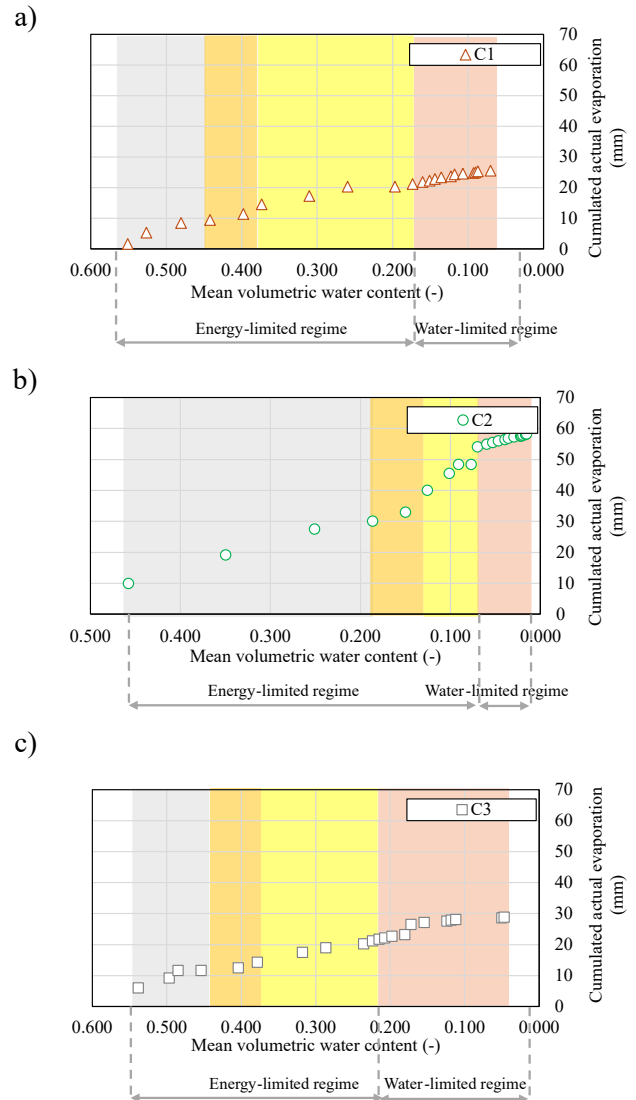


Figure 3. Actual evaporation (evapotranspiration) against mean volumetric water content for a) C1; b) C2, c) C3

5 DISCUSSION

Based on the experimental results, it can be observed that the same material exhibits markedly different evaporation fluxes depending on the configuration taken into account. Under meteorologically limited conditions, the bare surface nearly doubles its evaporative efficiency compared to the standard reference, owing to the dark-brown surface color that enhances net radiation

absorption. Conversely, the tested grass surface exhibits an even more pronounced evaporative response, significantly exceeding that of the reference case, attributable to the leaf length of the sown vegetation and to the presence of roots as well. Finally, the dark-black ember cover, combined with its specific chemical characteristics, further increases the energy absorption capacity, leading to evaporation fluxes up to three times higher than those of the standard configuration. When the evaporative demand persists, water-limited conditions occur at different volumetric water content thresholds for the three crop scenarios. Even the transition toward the residual condition is strongly dependent on the configuration taken into account.

6 CONCLUSIONS

The present study has reported the results of an experimental investigation aimed at improving the understanding of theoretical frameworks for accurately reproducing evaporative and evapotranspirative fluxes. According to FAO guidelines, these fluxes are typically distinguished into potential and actual components. Actual fluxes are generally estimated by reducing potential fluxes through a reduction coefficient (k_r), while potential fluxes are derived from the reference evaporation—governed by meteorological variables—by applying the crop coefficient (k_{crop}). This work has explored the characteristics of evaporative (evapotranspirative) phenomenon under different surface conditions. It has also examined the associated decay trend induced by soil drying, with particular attention to a silty pyroclastic deposit. To this end, small-scale samples reproducing bare soil, vegetated soil, and heterogeneous surface conditions were prepared. Each sample, initially saturated, was exposed to atmospheric conditions and periodically weighed to quantify water loss through evaporation. Experimental results reveal that the same soil material exhibits markedly different evaporation fluxes depending on the surface configuration. Under meteorologically limited conditions, the bare soil nearly doubles its evaporative efficiency compared to the standard reference. The vegetated surface, on the other hand, demonstrates an even stronger evaporative response, significantly exceeding the reference case. Finally, the dark-black ember cover, combined with its specific chemical composition, further increases the surface energy absorption capacity.

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