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Brief communication: On the potential of dual-coil frequency-domain electromagnetic (FDEM) systems to detect frozen layers in mountain permafrost environments

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Abstract. Frequency Domain Electromagnetic (FDEM) methods are still rarely applied in mountain permafrost environments, such as rock glaciers. Here, we test a separable dual-coil FDEM system at four mountain permafrost sites and compare the results with Electrical Resistivity Tomography (ERT), the most commonly geophysical method applied in these environments. The comparison shows that FDEM can reproduce key subsurface features identified by ERT and highlights the potential of separable dual-coil FDEM systems for a straightforward, preliminary, first-order assessment of subsurface structures in mountain permafrost environments.

1 Introduction

Rock glaciers are widespread landforms in Alpine regions and can be used as proxies for the presence of mountain permafrost. Their internal structure is typically highly complex and heterogeneous, consisting of varying proportions of ice, liquid water, coarse blocks and debris, finer sediments, and air-filled void, which challenges subsurface characterization (Phillips et al., 2023). Geophysical methods are commonly used to investigate the internal structure of rock glaciers in a non-invasive manner. Among these, Electrical Resistivity Tomography (ERT) is the most widely employed technique due to its sensitivity to frozen ground and ice-rich layers (Herring and Lewkowicz, 2022). However, ERT surveys in rock glacier environments are often logistically demanding, time-consuming, and prone to issues with electrode-ground galvanic contact, particularly in coarse-blocky terrains (Pavoni et al., 2022). These limitations motivate the exploration of alternative geophysical methods that are better suited for rapid and preliminary subsurface mapping and characterization.

Frequency Domain Electromagnetic (FDEM) technique is commonly used in near-surface geophysics to easily and rapidly map subsurface electrical properties (Boaga, 2017). However, its application in mountain permafrost environments remains limited due to specific methodological uncertainties and challenges, first and foremost the difficulty in inducing secondary eddy currents in highly resistive layers, i.e., frozen ground and dry rock (Hauck & Kneisel, 2008). Recently, FDEM has been applied by Boaga et al. (2020) and Pavoni et al. (2021) to estimate the active layer thickness of rock glaciers and by Pavoni et al., (2023) to investigate the internal structure of the Calderone glacieret, even if strong limitations in the quantitative characterization of the electrical resistivity of the investigated frozen subsurface remain.

This study investigates the applicability of a separable dual-coil FDEM system at four Alpine sites characterized by different permafrost-related morphologies, with the aim of assessing its potential for reconstructing subsurface structures. The FDEM results are compared with ERT profiles acquired at the same locations. The findings demonstrate the effectiveness of the dual-

https://doi.org/10.5194/egusphere-2026-1264
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coil FDEM system as a reliable and logistically efficient approach for preliminary subsurface evaluations and for identifying frozen layers within mountain permafrost environments, highlighting perspectives and limitations.

2 Sites description

We tested the FDEM method in different sites close to the Flüela Pass (Grisons, Switzerland) and the Stelvio Pass (Central Alps, Italy). The active rock glacier at Flüela Pass has a surface of heterogeneous metamorphic blocks and debris, mainly amphibolites and paragneisses, with patches of finer sediments. Measurements were carried out in the central area previously investigated by Bast et al. (2024), using a 94 m ERT profile with 48 electrodes at 2 m spacing and a 50 m dual-coil FDEM transect with 10 points (Fig. 1a).

The active rock glacier at Stelvio Pass is composed mainly of metamorphic blocks (orto- and paragneiss) and scree deposits with subordinate ablation till. Past geophysical studies (e.g., Cannone et al., 2003; Etzelmüller et al., 2020) suggest the presence of a massive ice core. In this study, ERT was acquired with 48 electrodes at 5 m spacing, and FDEM measurements were performed at 16 regularly spaced points along a 140 m profile (Fig. 1b).

At Le Rese di Scorluzzo, close to the active rock glacier at Stelvio Pass, a slightly lower altitude south-facing slope hosts an inactive rock glacier and, a few meters east, an inactive protalus rampart (Guglielmin and Tellini, 1992). ERT transects were acquired with 48 electrodes at 3 m spacing, while FDEM measurements with 6 m point spacing practically covered the ERT lines (Figs. 1c–d).

3 Method: Frequency Domain Electromagnetic (FDEM)

The FDEM technique, based on Maxwell's electromagnetic induction equations, allows estimation of subsurface electrical resistivity without direct galvanic contact with the ground. FDEM systems consist of a transmitter coil generating a time-varying magnetic field, which induces eddy currents in the subsurface; these in turn produce a secondary magnetic field recorded by a receiver coil. Under the low-induction-number approximation, the quadrature component of the secondary-to-primary field ratio is directly related to apparent resistivity (McNeill, 1980). Investigation depth and spatial resolution depend on transmitted frequency, coil separation and orientation, and subsurface conductivity. Lower frequencies and larger spacings increase sensitivity to deeper layers, while higher frequencies and shorter spacings improve near-surface resolution (Pavoni et al., 2023). Horizontal coplanar (HCP) and vertical coplanar (VCP) configurations probe different depths, and highly conductive conditions reduce effective penetration due to signal attenuation (Boaga, 2017). Finally, apparent resistivity measurements at each location are converted into vertical resistivity profiles via inversion, iteratively adjusting the model until calculated responses match observed data within an acceptable error threshold (Wagner and Uhlemann, 2022).

4 Data acquisition and processing

Electrical Resistivity Tomography surveys were carried out using a Syscal-Pro (Iris Instruments) resistivity meter. Data were acquired using a hybrid acquisition scheme combining dipole–dipole and multi-gradient multi-skip arrays (Pavoni et al., 2025). Measurements were stacked three times, and all quadrupoles were acquired in direct and reciprocal configuration for reliable data quality assessment (Binley and Slater, 2022). In the blocky rock glaciers of Flüela Pass and Stelvio Pass, textile electrodes (Bast et al., 2025) and steel-net electrodes (Pavoni et al., 2025), wetted with salt water, were used. In the Le Rese di Scorluzzo sites, characterized by finer-grained surface sediments, traditional steel-spike electrodes were used.

A dataset-specific filtering procedure was applied to each ERT survey. Quadrupoles with stacking and/or reciprocal errors above 5% were removed, and the same value was used as the expected data error in the inversion process. Inversion modelling was performed using the open-source Python software ResIPy (Blanchy et al., 2020). All models reached a final RMS misfit

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Preprint. Discussion started: 27 March 2026

close to 1 in a few iterations, indicating a good fit between observed and calculated apparent resistivities. Model sensitivity was used to define the lateral and vertical limits of the presented resistivity models, with low-sensitivity areas indicating portions of the model mainly constrained by regularization rather than by data (Fig. S2 in Supplementary Materials).

FDEM measurements were collected using a separable dual-coil CMD-DUO system (GF-Instruments). The instrument operates at a frequency of 925 Hz and allows data acquisition with three different coil spacings (10, 20, and 40 m). Operatively, receiver and transmitter coils are connected by a thin (3 mm) cable. At each site, measurements were manually acquired using the HCP configuration over the entire length of each FDEM transect (see Fig. 1), while the VCP configuration was tested at only a few selected points. Measurement errors were assessed through signal stacking, and the position of each measurement point was approximated as the midpoint between the two coils, corresponding to the location of the data logger equipped with an integrated GPS (Fig. S1, Supplementary Materials). It should be noted that, for the profiles acquired on the active rock glaciers at Flüela Pass and Stelvio Pass (Figs. 1a and 1b), the FDEM transects do not cover the full length of the corresponding ERT lines. This is due to difficulties in optimally positioning the coils, particularly for the longer spacing configurations (20 and 40 m), because of the highly irregular topography and/or steep slopes.

For each site and HCP configuration (10, 20, and 40 m coil spacings), the raw FDEM apparent resistivity data were smoothed using a one-dimensional Gaussian filter ($\sigma = 2$) to reduce high-frequency noise while preserving the main lateral variations. The inversion modelling was performed using the open-source Python software EMagPy (McLachlan et al., 2021), employing a 10-layer model of regular thickness extending to 24 m depth. The model depth was defined based on the sensitivity analysis of the surveys (Fig. S3 in Supplementary Materials). While a sensitivity threshold of 70% is commonly adopted for the largest coil spacing (van't Veen et al., 2022), a higher value of 80% was used in this study due to the challenging field conditions and the high-resistivity subsurface, which limit the induction of secondary eddy currents. A linearized inversion with L-BFGS-B regularization was employed to iteratively update the model and minimize the misfit between observed and predicted apparent resistivities. The optimal regularization parameter was defined using the L-curve method, and the quality of the final model was evaluated using the Root Mean Square Percentage Error (RMSPE). Although RMSPE values below 5% are generally considered acceptable, in this study a threshold of 10% was adopted to account for the high-resistivity environment, the measurement stacking errors of approximately 10%, and the practical difficulties in optimally positioning the coils during data acquisition due to rough surface conditions and complex topography.

6 Results

Figure 2 shows the ERT resistivity models at the survey sites. At the active Flüela rock glacier (Fig. 2a), a shallow high-resistivity layer (~60–80 kΩ·m, ~5 m depth) extends from the upper (southern) section toward the frontal zone (north), with a thickness of ~10 m that gradually thins toward the front and a discontinuity at ~45 m along the profile. A comparable structure is observed at the active Stelvio Pass rock glacier (Fig. 2b), with higher resistivity values and thickness (>100 kΩ·m and 15–30 m, respectively). In both cases, the morphology and the presence of a high-resistivity layer suggest the occurrence of ice-bearing permafrost. At the Le Rese di Scorluzzo sites, despite morphology and vegetation suggesting the possible absence of permafrost, resistivity models reveal a markedly different scenario, with high-resistivity layers characteristic of a frozen subsurface. In the inactive rock glacier (Fig. 2c), in the easternmost area, the top of the high-resistivity layer lies very close to the surface, making it difficult to distinguish from the overlying air-filled material, while the boundary with the underlying low-resistivity unfrozen sediment is clearly identifiable. In the inactive protalus rampart (Fig. 2d), a discontinuous high-resistivity layer is detected at 5–10 m depth in the central area, likely corresponding to a frozen layer, and a superficial high-resistivity zone at the northern margin corresponds to coarse, air-filled deposits observed in the field.

Figure 3 shows the results of the FDEM data inversions. The pseudo-2D models were obtained by interpolating (kriging method) the 1D vertical resistivity profiles inverted at each measurement location (orange circles in Figs. 2 and 3). At all sites,

https://doi.org/10.5194/egusphere-2026-1264
Preprint. Discussion started: 27 March 2026

the FDEM models reproduce the same resistivity patterns observed in the ERT results, although absolute resistivity values are, as expected, systematically lower. At the active Flüela Pass and Stelvio Pass rock glaciers (Figs. 3a–b), a more resistive layer (~500–1000 Ω·m) is clearly identified between two less resistive layers (~100–300 Ω·m) and, as in the ERT models, progressively thins and disappears toward the frontal zone. At Flüela Pass, the same discontinuity detected in the ERT model is evident at ~45 m along the profile. Similarly, at the Le Rese di Scorluzzo sites (Figs. 3c–d), the FDEM-derived resistivity structures closely mirror those obtained from ERT, indicating the presence of high-resistivity layers and suggesting a discontinuous frozen layer at both sites.

In all resistivity models (Figs.2 and 3), the boundaries of the frozen layer were interpreted from resistivity values and gradients, placing limits where the variation (increase at the top, decrease at the base) is steepest (Herring and Lewkowicz, 2022).

7 Discussion and conclusions

The results demonstrate that a separable dual-coil FDEM system with at a signal frequency of ~1 kHz, with coil spacings between 10 and 40 m and HCP orientation, can reconstruct a reliable subsurface structure in mountain permafrost environments. The FDEM-derived resistivity models consistently reproduce the main patterns observed in the ERT results, despite systematically lower absolute resistivity values. This discrepancy is attended, given the tendency of electromagnetic fields to propagate preferentially within more conductive media (Boaga, 2017), the 10 kΩ·m instrumental sensitivity limit of the FDEM device (Gf-instrument datasheet), the limited ability to resolve fine spatial heterogeneities (Carrera et al., 2024), and the results of synthetic modelling studies. In this context, Pavoni et al. (2023) demonstrated that the separable dual-coil FDEM system has a limited capability to accurately reproduce absolute resistivity values in high-resistivity frozen-layer settings, although it is still able to capture the overall subsurface structure.

The measurements performed using the VCP configuration yielded poor results, characterized by anomalous responses, including very high stacking errors, apparent resistivities up to one order of magnitude lower than those obtained with the HCP configuration, and strongly negative in-phase values. These effects are likely related to signal quality, as the orientation of the primary magnetic field in the VCP configuration is less favourable for subsurface penetration compared to the HCP configuration, where the primary field is more efficiently coupled with the ground, facilitating the induction of eddy currents. Similar limitations of VCP-oriented FDEM measurements in rock glacier environments were previously reported by Pavoni et al. (2021) during active-layer investigations. Necessarily, the exclusion of the VCP configuration reduces the number of apparent resistivity measurements at each measured station, resulting in a loss of vertical resolution. However, given the consistently poor data quality obtained with VCP measurements and the cost of doubling survey time, the effort of acquiring this configuration does not appear justified. Instead, survey efficiency can be improved by focusing exclusively on the HCP configuration and increasing the number of measurement locations, thereby enhancing lateral resolution.

Although continuous FDEM acquisition could accelerate data collection further and yield very dense datasets, this approach is difficult to implement in rock glacier environments due to the irregular surfaces and complex topography that prevent stable antenna positioning during measurements. Consequently, static dual-coil FDEM acquisition in HCP configuration, with antennas placed directly on the ground as illustrated in Fig. S1, represents the most practical and robust strategy.

From a logistical perspective, the relatively low weight of the separable dual-coil FDEM system components (~5 kg per antenna, ~1 kg for the data logger, and ~5 kg for connecting cables) allows deployment by small teams (2–3 operators) without the relevant physical and logistical effort required for ERT surveys.

Overall, considering the limited logistical effort required for transport and data acquisition, the relatively straightforward data processing and interpretation, the proposed separable dual-coil FDEM system represents a highly promising tool for preliminary investigations, including remote areas, and for large-scale mapping of mountain permafrost distribution.

https://doi.org/10.5194/egusphere-2026-1264
Preprint. Discussion started: 27 March 2026

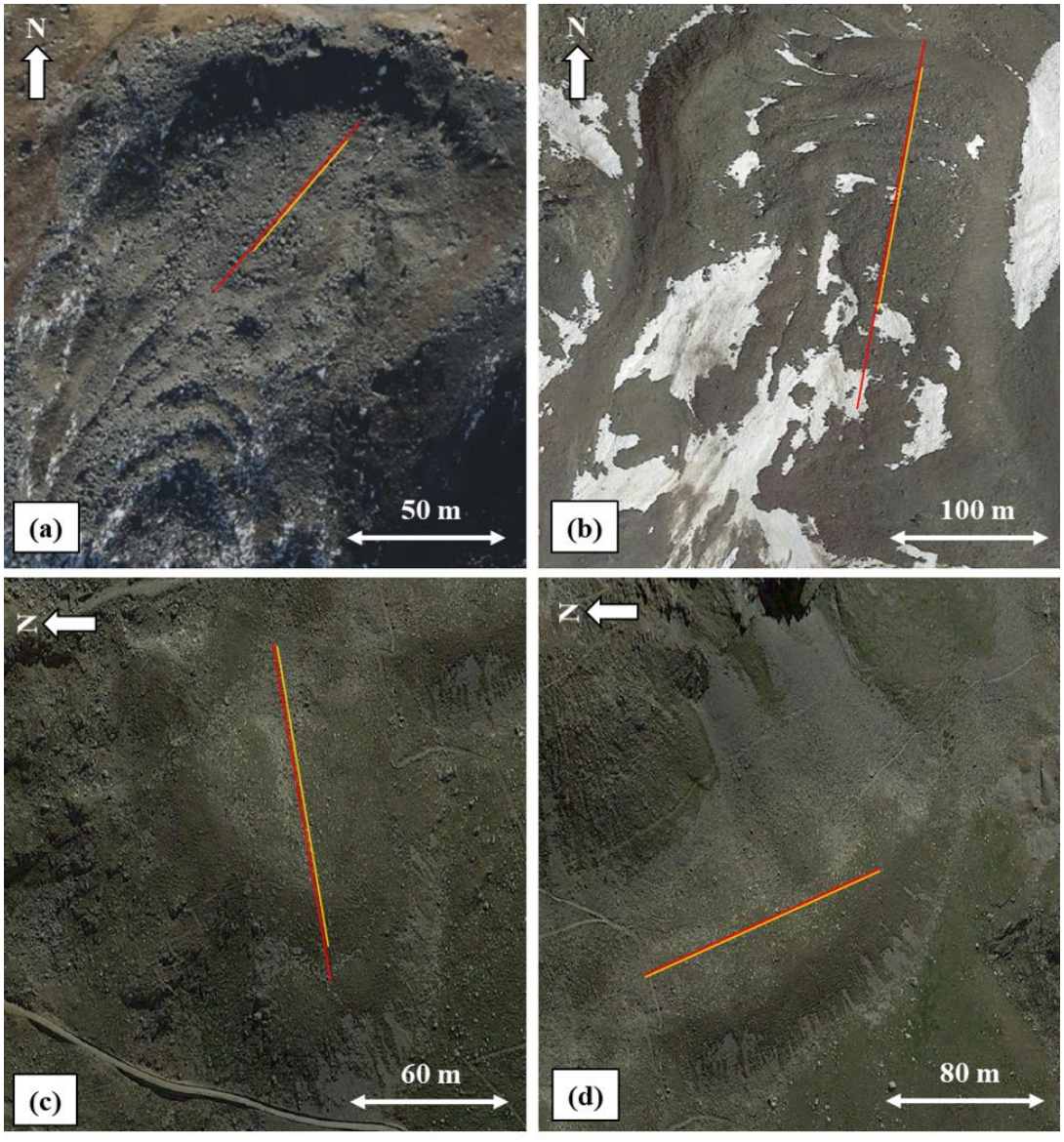

Figure 1. Satellite images of the study sites (Background imagery from Google Satellite; accessed via QuickMapServices in QGIS; Imagery © Google; map data © Google) showing the ERT (red lines) and FDEM (orange lines) survey profiles. (a) Active rock glacier at Flüela Pass (Switzerland; 46.746° N, 9.951° E). (b) Active rock glacier at Stelvio Pass (Italy; 46.527° N, 10.441° E). (c) Le Rese di Scorluzzo inactive rock glacier at Stelvio Pass (Italy; 46.531° N, 10.420° E). (d) Le Rese di Scorluzzo inactive protalus rampart at Stelvio Pass (Italy; 46.530° N, 10.421° E).

https://doi.org/10.5194/egusphere-2026-1264
Preprint. Discussion started: 27 March 2026

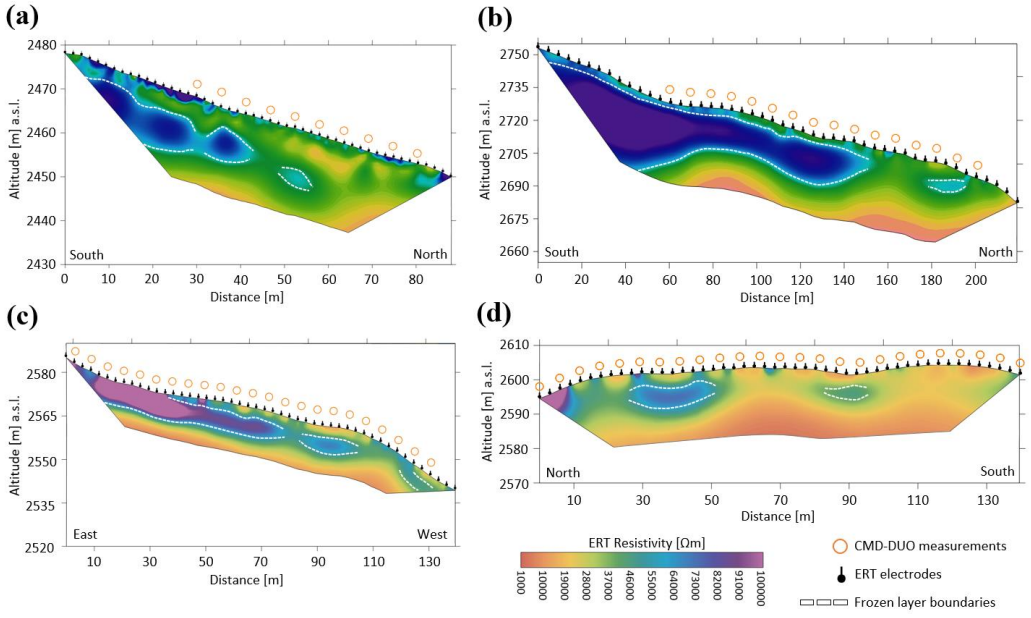

Figure 2. Inverted resistivity models obtained from ERT measurements at (a) the active rock glacier at Flüela Pass, (b) the active rock glacier at Stelvio Pass, (c) Le Rese di Scorluzzo inactive rock glacier, and (d) the Le Rese di Scorluzzo inactive protalus rampart at Stelvio Pass. The positions of the ERT electrodes (black point marker with stem) along the transects and the measurement points acquired with the CMD-DUO FDEM system (orange circle) are shown. The white dashed line indicates the interpreted boundary of the inferred frozen layer.

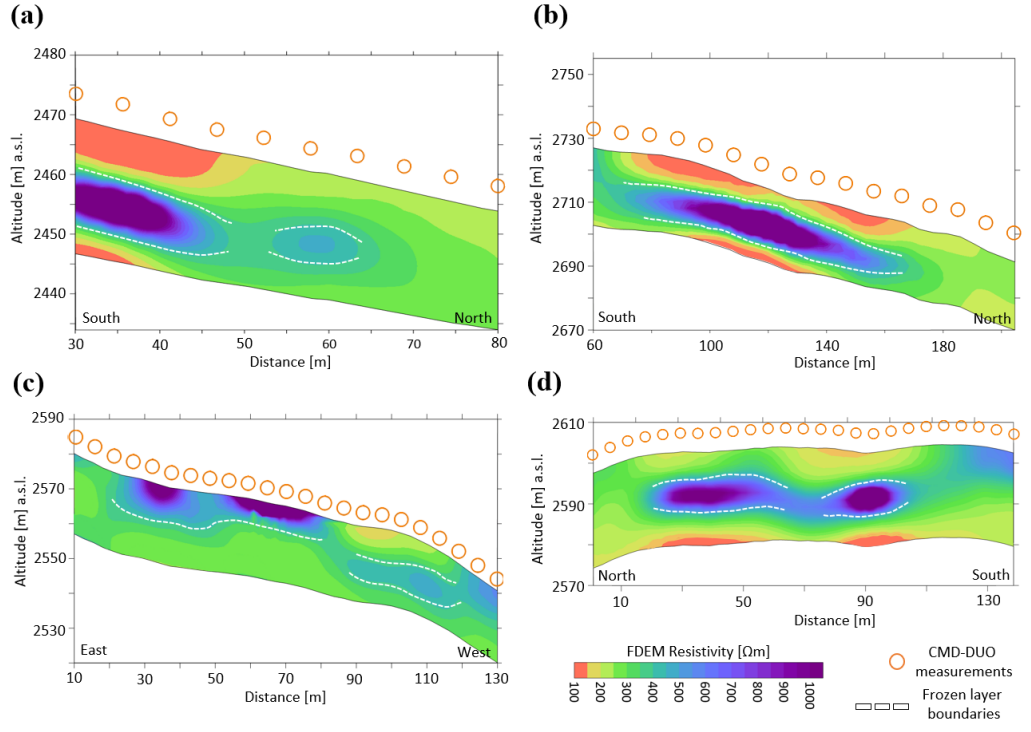

Figure 3. Pseudo-2D inverted resistivity models obtained from FDEM data acquired with the CMD-DUO in HCP configuration at the sites of (a) active rock glacier at Flüela Pass, (b) active rock glacier at Stelvio Pass, c) Le Rese di Scorluzzo inactive rock glacier, and (d) the Le Rese di Scorluzzo inactive protalus rampart at Stelvio Pass. The positions of the measurement points are marked with orange circles, and the white dashed line indicates the inferred boundary of the frozen layer.

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Data Availability Statement. The datasets will be available upon request from the authors

Author contributing. MP, MG, EF, JB developed the concept of the study; MP, AB, MG, SPo, JB were involved in the data acquisition; MP performed the data processing; all authors contributed to the writing and editing of the manuscript.

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