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Original Article

# Influence of the climate extreme events recorded in 2022 and 2023 on carbon and nitrogen forms in alpine tundra

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**Abstract:** Alpine tundra ecosystems are highly sensitive to climate change, particularly due to their dependence on the duration and timing of snow cover. This study investigated the effects of the climate extreme years 2022 and 2023 on carbon (C) and nitrogen (N) forms in two alpine tundra communities: snowbed (SB) and *Carex curvula* (CC), located at high elevation in the North-West (NW) Italian Alps. During these years, both sites experienced exceptionally low snow cover duration and elevated mean soil temperature during the snow-free season. Dissolved organic carbon (DOC) concentrations significantly increased by +65% in SB and +42% in CC compared to 2016-2021, likely reflecting enhanced microbial decomposition of organic matter. In contrast, soil ammonium and nitrate levels showed no significant changes, indicating differential responses between C and N processes. These findings suggest that DOC is a sensitive (early) indicator of climate-induced shifts in soil functioning. Given the critical role of alpine tundra in global C cycling, understanding DOC dynamics under climate extreme events is crucial to predict future ecosystem feedback to global change.

**Keywords:** Snow drought; Heat wave; Dissolved organic carbon; Alpine soil; Tundra vegetation

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## 1 Introduction

Alpine tundra is a high-mountain environment located above the treeline, which occurs across a wide range of latitudes and landscapes. It represents a fragile and unique ecosystem characterized by harsh environmental conditions such as prolonged snow cover, extended periods with air temperature below freezing and short growing seasons (Freppaz et al. 2019). This ecosystem hosts a wide range of specialized plant species that have evolved complex physiological and morphological traits to thrive under such challenging conditions (Fisk et al. 1998; Carbognani et al. 2014; Körner 2021). One of the most critical factors modulating ecosystem functioning in alpine tundra is snow, which acts as an insulating blanket that buffers soil temperature fluctuations during winter (Brooks et al. 1999; Edwards et al. 2007; Freppaz et al. 2018). Because snow regulates the decomposition of soil organic matter and the release of nitrogen (N) (Walker et al. 1999; Groffman et al. 2001), changes in snow depth and duration can lead to substantial variations in pedoclimatic conditions, nutrient cycling, and the composition of plant communities (Walker et al. 1993; Fisk et al. 1998). Previous studies in alpine regions have demonstrated that earlier snowmelt can accelerate decomposition and nutrient release, while

delayed snowmelt may prolong nutrient limitation, highlighting the sensitivity of alpine tundra ecosystems to interannual variability in snow regimes (Brooks et al. 1999; Venn et al. 2021). Consequently, the duration and timing of snow cover strongly influence soil microbial activity and the biogeochemical dynamics of essential elements such as carbon (C) and N (Broadbent et al. 2021; Pintaldi et al. 2022). Snowmelt timing, in particular, controls soil temperature and moisture availability, as well as the synchrony between plant nutrient demand and microbial activity (Broadbent et al. 2021). Beyond their local importance, alpine tundra soils represent a key component of global mountain ecosystems, sharing features such as shallow and stony profiles, low nutrient availability, and strong coupling between vegetation and belowground processes (Knowles et al. 2015; Körner 2021). In recent decades, climate change has increasingly altered the stability of snow regimes in alpine regions, with implications for ecosystem processes. Warming temperatures have led to earlier snowmelt and reduced snow depth (Beniston et al. 2018), as well as an increase in soil temperature, specifically during summer months (Dorau et al. 2022). Given their sensitivity, changes in C and N cycling in alpine tundra may provide early signals of ecosystem responses to global warming, underlining the importance of long-term monitoring to anticipate their feedback on regional and global biogeochemical dynamics (Pearson et al. 2024).

In the European Alps, the years 2022 and 2023 were particularly anomalous, standing out for their combination of exceptionally low snow accumulation and record-breaking summer heatwaves. Colombo et al. (2023) identified these years as the most extreme of recent decades in terms of snow drought, while several studies reported that the summer air temperatures reached extreme values during both years (Tripathy et al. 2023; Gallo et al. 2024). Such anomalies prompt urgent questions about the potential impacts on soil processes in alpine tundra, especially concerning C and N pools. Here, we aimed to explore whether the climate extremes of 2022 and 2023 influenced C and N forms in alpine tundra soils, focusing on dissolved organic carbon (DOC), ammonium, and nitrate in the topsoil.

## 2 Materials and Methods

The study was conducted in the Long Term Ecological Research (LTER) site Angelo Mosso (https://deims.org/17210eba-d832-4759-89fa-9ff127cbdf6e), located in NW Italy, close to the Monte Rosa Massif (Latitude: 45.871472 - Longitude: 7.867495). The research was performed at two high-elevation sites (2770 and 2840 m a.s.l.), located in the upper part of a glacial plateau, with alpine grasslands belonging to Natura 2000 Habitat 6150 ("Siliceous alpine and boreal grasslands") (Fig. 1). This habitat includes boreo-alpine grassland formations of the highest summits in the Alps and Scandinavia, typically dominated by species of *Juncus sp.*, *Carex sp.*, mosses, and lichens, and including snowbed communities (SB) dominated by *Salix herbacea*. In particular, the first site is a snowbed community belonging to *Salicion herbaceae* alliance, (CORINE Biotopes Code 36.11), characterised by prolonged snow cover and a short growing season. These conditions select for low-stature, cold-adapted species such as *Salix herbacea*, a prostrate woody plant forming dense mats. This species is often accompanied by mosses and lichens, forming a tightly packed vegetation layer that stabilises the substrate and contributes to soil organic matter accumulation. The second site is an alpine grassland of *Carex curvula* (CC) and is part of *Caricion curvulae* alliance (CORINE Biotopes Code 36.34). These communities are primary grassland formations that occur on wind-exposed mountain ridges above the tree line, where harsh climatic and lithological conditions prevent further successional development. Alpine *Carex curvula* grasslands thrive on shallow, stony soils with significant cryoclastic debris and are adapted to short snow cover duration. The species plays a key role in soil stabilisation and nutrient retention in these environments. Soils in the two sites are classified as Skeletic Dystric Regosol (SB) and Skeletic Umbrisol (Arenic) (CC) (IUSS Working Group WRB 2022).

Each site was equipped with dataloggers (HOBO Pro v2 U23-00x) placed within the soil at 10-cm depth for the measurement of hourly soil temperature. These data were used to calculate selected site-specific variables: snow cover duration and mean temperature of soil during the snow-free season, which are among the most important factors influencing C and N dynamics in alpine tundra ecosystems (Schindlbacher et al. 2014). Snow cover duration was calculated according to Danby & Hik (2007), while mean temperature of soil during the snow-free season is the mean daily soil temperature between the end of SCD and the sampling day. Each study site consisted of three plots, each one of 9 $m^2$. Every month in the snow-free season in the period 2016-2023, three topsoil

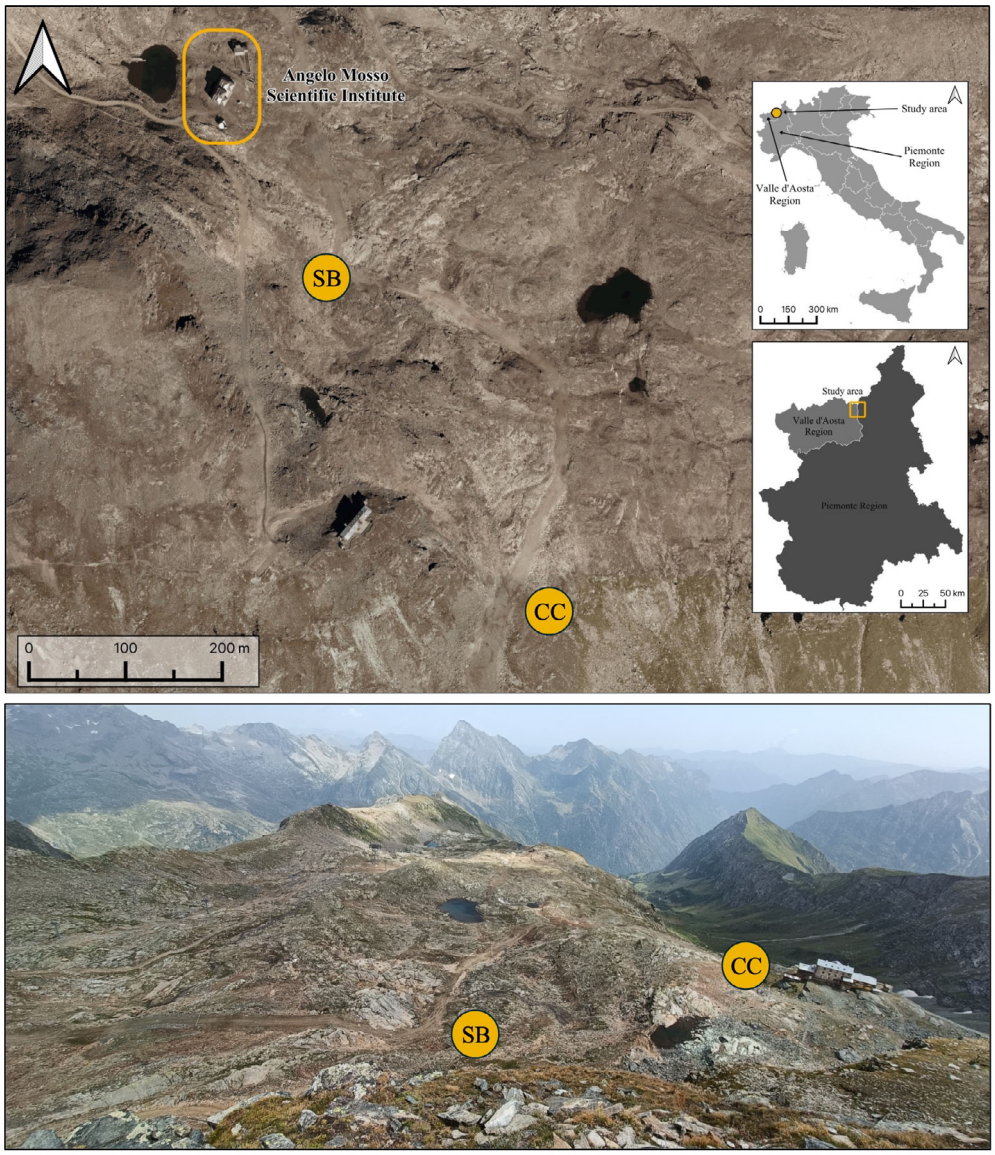



**Fig. 1** Location of the research study area in Italy (upper inset map) and in the northwestern Italian Alps (lower inset map), aerial overview of the study area (upper picture) (orthoimage year 2018; coordinate system WGS84/UTM 32 N), and location of the two plots at the LTER Site Angelo Mosso Scientific Institute (lower picture). SB, snowbed communities; CC, alpine *Carex curvula* grasslands.

samples (A horizon, 0-10 cm depth) were collected, which in turn consisted of three subsamples in each plot. Within 24 h from collection, fresh samples were homogenized by sieving at 2 mm and oven-dried at 105°C for 24 hours to obtain the Gravimetric Water Content. An aliquot of fresh soil was extracted with KCl 1M and then analysed for DOC with a TOC analyzer (Elementar, Vario TOC, Hanau, Germany) after filtration with 0.45 µm nylon membrane filters. Ammonium (extractable N-$NH_4^+$) concentrations in soil extracts were determined spectrophotometrically (U-2000, Hitachi, Tokyo, Japan) by a modified Berthelot method involving reaction with salicylate in the presence of alkaline sodium dichloroisocyanurate (Crooke and Simpson 1971). Nitrate (extractable N-$NO_3^-$) concentrations in soil extracts were determined spectrophotometrically (U-2000, Hitachi, Tokyo, Japan) by the Greiss reaction as described by Mulvaney (1996) and modified by Cucu et al. (2014). Significant differences between sampling sites and years were assessed using a rank-based ANOVA ($p < 0.05$) on ranked data (Conover and Iman 1981), followed by Tukey's HSD test for post-hoc pairwise comparisons. The Standardised Anomaly Index (SAI, which is obtained as $[x - \mu] / \sigma$, where $x$ is the observed value, $\mu$ is the mean, and $\sigma$ is the standard deviation

over the reference period) for snow cover duration and mean temperature of soil during the snow-free season was used to quantify the magnitude of the extreme climatic and pedoclimatic events in our study area in the sampling period.

## 3 Results and Discussion

SAIs revealed that both 2022 and 2023 exhibited extreme climatic and pedoclimatic conditions (Fig. 2). These years showed the lowest snow cover duration since the beginning of observations (SAI SB: -1.2 and -0.7 for 2022 and 2023; SAI CC: -1.3 and -1.1). Simultaneously, mean temperature of soil during the snow-free season was higher, particularly in 2023, which experienced the warmest summer on record for the sites (SAI SB: +1.0 and 1.5 for 2022 and 2023; SAI CC: +1.5 in both years). These findings confirm that our study site mirrored the broader climatic anomalies reported in the Alps (Colombo et al. 2023; Tripathy et al. 2023). Despite the short snow cover durations and the high mean temperatures of soil during the snow-free season, both sites showed no anomalies regarding gravimetric water content, presenting values within the historical range (SB: 13%-25%; CC: 18%-46%).

In parallel with these climatic and pedoclimatic extremes, soil DOC concentrations increased in both SB (+65% for the years 2022-2023 compared to 2016-2021) and CC (+42%) communities (Fig. 3a). This response was consistent across sampling months and was most pronounced in 2023. The observed DOC pulse likely reflects enhanced microbial decomposition driven by elevated soil temperatures and extended snow-free periods, as documented in other alpine and arctic environments (Evans et al. 2006; Pearson et al. 2024). Warmer soils can accelerate microbial activity, organic matter decomposition rate and therefore enhance DOC production in the soil (Kalbitz & Kaiser 2008; Xue et al. 2016). Enhanced temperatures have been shown to increase heterotrophic respiration, indicating a sustained increase in microbial decomposition of soil organic matter under elevated temperatures (Wang et al. 2014). In addition, increased and prolonged photosynthetic activity under warmer conditions may further contribute to DOC through enhanced root exudation during the growing season (Heinzle et al. 2023; Ren et al. 2025). Temperature is a key abiotic driver of root and whole-plant physiology: warming can stimulate root growth

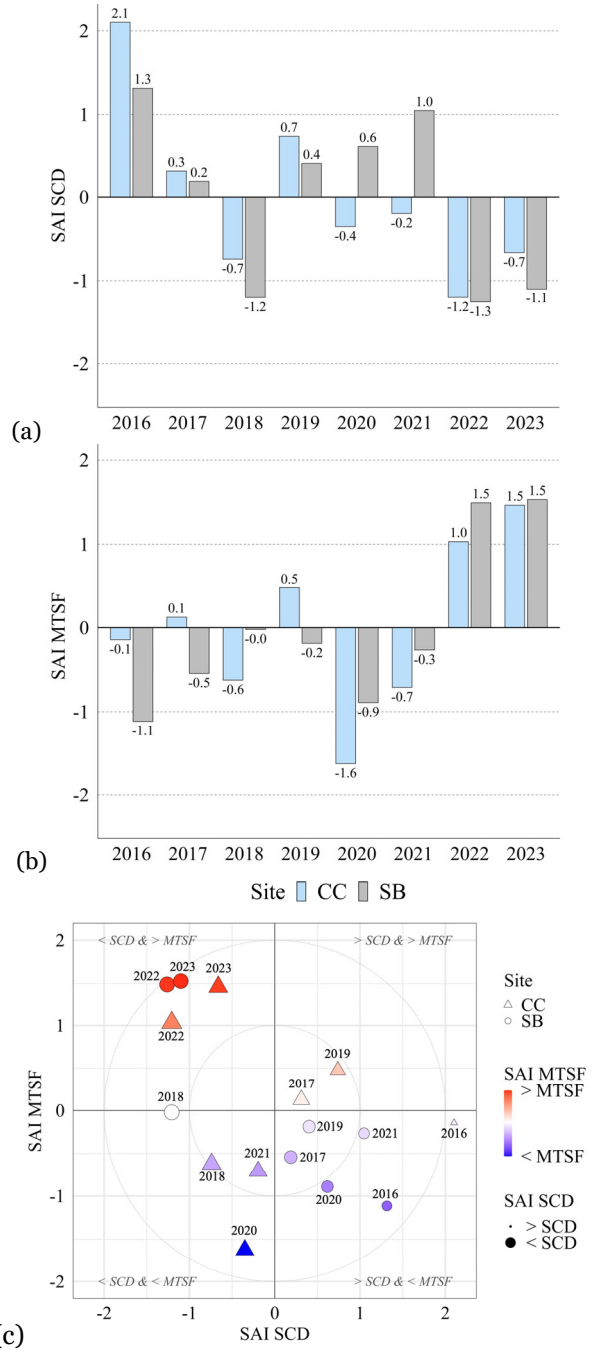



**Fig. 2** Standardised Anomaly Index (SAI) of snow cover duration (SCD) (a) and SAI of mean temperature of soil during the snow-free season (MTSF) (b) in SB and CC from 2016 to 2023. Positive values indicate above-average conditions, while negative values indicate below-average conditions. Scatterplot (c) combining the two SAIs for each year and site. MTSF SAI is shown using a colour scale, from blue (negative SAI) to red (positive SAI). SCD SAI is shown using a dimension scale, from small (positive SAI) to large (negative SAI). Inside and outside circles show 1 and 2 isoradial coordinates, respectively. SAIs of SCD and MTSF, represented in the scatterplot in Fig. 1c, are not correlated ($p > 0.05$).

directly or indirectly by increasing belowground C allocation, thereby promoting greater rhizodeposition and the release of labile C compounds into the soil (Bai et al. 2010). Such combined microbial and plant-mediated processes are likely to be particularly relevant in alpine tundra soils, where shorter snow cover duration and higher summer soil temperatures can intensify belowground C cycling. Interestingly, as shown in Fig. 4a, the DOC response was similar in magnitude across the two vegetation types. This occurrence indicates that both ecosystems were comparably sensitive to the climate anomalies, specifically to the combination of short snow cover duration and warm mean temperature of soil during the snow-free season, thus indicating a convergent response irrespective of vegetation cover. This finding suggests that DOC might be a reliable (early) indicator of climate-induced shifts in soil functioning, highlighting that alpine tundra soil DOC dynamics are highly responsive to short-term climate extremes. This has important implications for the C balance of high-elevation ecosystems, especially under scenarios of continued warming and declining snowpack. Even short-term events like those observed in 2022 and 2023 can alter microbial activity and organic matter turnover, potentially affecting long-term soil C storage and nutrient dynamics (Gavazov 2010; Schindlbacher et al. 2011). Alpine ecosystems are integral components of global C cycling and changes in DOC dynamics in alpine tundra do not only reflect local shifts but may also have cascading effects on broader biogeochemical cycles (Pearson et al. 2024). Therefore, understanding how extreme climatic events affect DOC release is essential to predict future feedback between mountain ecosystems and the global climate system.

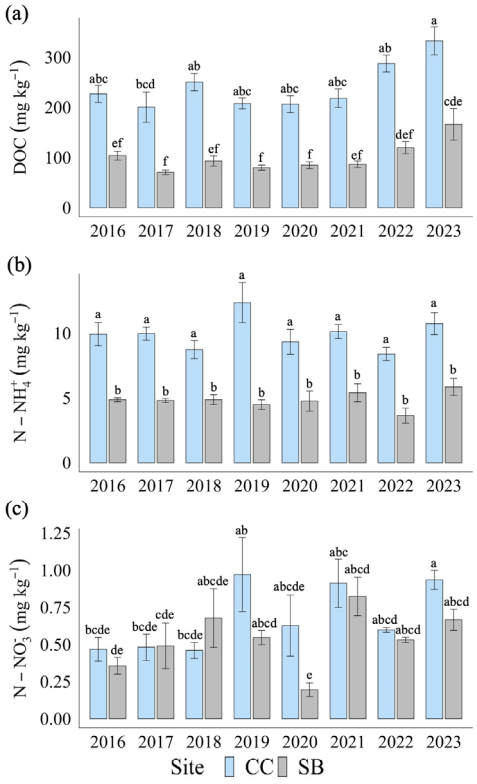



**Fig. 3** Interannual variability of DOC (a), N-$NH_4^+$ (b), and N-$NO_3^-$ (c) in SB and CC, collected in the snow-free season from 2016 to 2023. Different letters indicate significant differences ($p$<0.05) between sites and years. Error bars represent the standard deviation ($n$ = 9).

Despite the strong DOC response, no significant variations were observed for soil ammonium and nitrate concentrations during the same period (Fig. 3b,3c, and Fig. 4b,4c). This decoupling may reflect differential control mechanisms for soil C and N cycling. While DOC is largely governed by microbial decomposition and leaching processes, mineral N dynamics are strongly influenced by multiple drivers such as atmospheric N deposition, microtopography, plant uptake, microbial immobilization, and nitrification/denitrification processes, which may hide short-term climatic perturbations. Indeed, several studies in alpine and

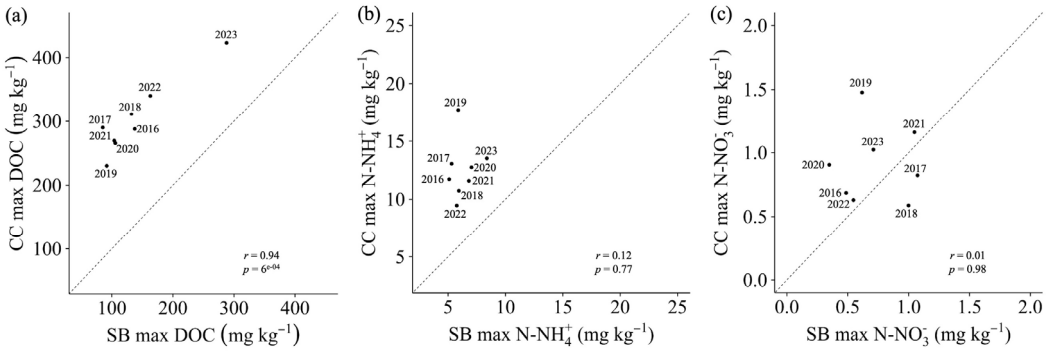



**Fig. 4** Scatterplots showing the maximum values of DOC (a), N–$NH_4^+$ (b), and N–$NO_3^-$ (c) for each year (2016–2023) in SB ($x$ axis) and CC ($y$ axis). Each point represents the annual maximum concentration for a given site and year. The dashed line indicates the 1:1 relationship. Pearson correlation coefficients ($r$) and associated $p$-values are reported in each panel.

Arctic environments have reported heterogeneous responses of soil inorganic nitrogen to climate variability and snow cover (e.g., Brooks et al. 1999; Freppaz et al. 2019; Pintaldi et al. 2022). This reflects the fact that soil ammonium and nitrate are regulated by multiple interacting factors which can therefore mask or attenuate short-term climatic effects.

## 4 Conclusions

Our study addressed the sensitivity of alpine tundra ecosystems to climate extremes, focusing on the effects of the anomalous years 2022 and 2023 on soil C and N forms. We analysed eight consecutive years of field data from two contrasting alpine vegetation communities, SB and CC, to test whether extreme reductions in snow cover and elevated soil temperatures altered soil C and N dynamics. Our results revealed a strong DOC increase during 2022–2023 (+65% in SB and +42% in CC compared to 2016-2021), while ammonium and nitrate showed no significant changes. This indicates a clear decoupling between soil C and N dynamics under climate extremes. The enhanced DOC response highlights the vulnerability of alpine tundra soils to short-term climatic anomalies, with potential consequences for long-term soil C storage and nutrient availability. The contrasting stability of soil mineral N suggests that multiple processes, including plant uptake and microbial immobilisation, buffer short-term changes in nitrogen pools. Future research should integrate long-term observations with modelling approaches that account for vegetation distribution, soil properties, and snow dynamics, in order to upscale local findings to the whole Alps region. Such efforts are crucial to anticipate how increasing frequency of climate extremes will influence ecosystem functioning at broader spatial scales.

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## Author Contributions

BENECH Andrea: Writing - original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. PINTALDI Emanuele: Writing - review & editing, Methodology, Investigation, Conceptualization, Data curation. COLOMBO Nicola: Writing - review & editing, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. FREPPAZ Michele: Writing - review & editing, Methodology, Conceptualization, Funding acquisition, Supervision.

## Ethics Declaration

**Availability of Data/Materials:** Data supporting this research article are available from the corresponding author on request.

**Conflict of Interest:** The authors declare no conflicts of interest.

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