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Soil Organic Matter Dynamics in the Ericaceous and Afroalpine Belts of the Bale Mountains, Ethiopia: Influence of Vegetation, Fire, and Topographic Factors

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Abstract

Soil organic matter (SOM) dynamics in high-altitude tropical ecosystems are poorly understood, yet critical for predicting carbon-climate feedbacks. We characterized SOM pools in the Bale Mountains National Park (Ethiopia) across vegetation types (Ericaceous belt, fragmented Ericaceous belt, Afroalpine heathland, giant Lobelia area), fire histories (recently burned, 10–25 years post-fire, unburned >25 years), and topographic positions. Using physical fractionation, we separated coarse (149–2000 μm) and fine (53–149 μm) particulate organic matter (POM) and mineral-associated organic matter (MAOM, <53 μm). Particulate organic matter dominated the SOM pool (>99%), with C representing only 0.05–0.07% of total organic carbon. The Ericaceous belt had the highest coarse POM (11.38 g kg^{-1}), while the fragmented Ericaceous belt showed the lowest (8.96 g kg^{-1}, $p = 0.042$). Intermediate fire disturbance (10–25 years) increased coarse and fine POM by ~12–13% compared to recently burned or long-unburned sites. Topographic position significantly influenced POM fractions, with northern slopes accumulating the highest amounts ($p < 0.05$). Cation exchange capacity was strongly positively correlated with POM fractions ($r = 0.86$, $p < 0.001$), while elevation showed a negative relationship ($r = -0.38$, $p = 0.04$). The extremely low proportion of MAOM suggests limited long-term stabilization capacity, making these soils vulnerable to warming-induced decomposition. Our results demonstrate that fire history, vegetation, and topography interact to control SOM dynamics, and that conservation strategies should prioritize minimizing anthropogenic disturbance to preserve SOM inputs and ecosystem resilience.

Keywords: Bale Mountains; carbon fractions; Ericaceous and Afroalpine; fire disturbance; soil organic carbon; soil organic matter; vegetation

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1. Introduction

Soils are fundamental components of terrestrial ecosystems and act as critical reservoirs for soil organic carbon (SOC), positioning them as key players in the global carbon cycle [1,2]. A deep understanding of SOC dynamics is essential for characterizing soil biochemical composition and remains a major focus in soil research [3,4]. Maintaining soil quality requires comprehensive

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knowledge of the drivers that influence SOC storage across scales and site characteristics [5]. However, traditional soil conservation approaches often depend exclusively on bulk SOC data, which can mask the subtle contributions of different SOM fractions and fail to capture indicators of ecosystem resilience, carbon storage, and nutrient supply [6,7].

To address these shortcomings, detailed SOM fractionation is vital for achieving a thorough understanding of SOM properties and carbon dynamics [8,9]. This process divides SOM into pools based on particle size or density, providing finer-grained insights into carbon cycling [8,10]. Physical fractions are operationally defined and result from fragmentation processes that form distinct SOC pools with different turnover potentials [11,12]. Understanding the controls over these fractions is particularly important in regions where SOC is vulnerable to land-use and climate change.

Research on SOM decomposition processes is central to advancing sustainable soil management [13,14]. The impact of physical SOM fractions on decomposition varies with ecological contexts, microclimates, and vegetation types [15–18]. Plant traits, such as lignin and wax content, affect decomposition rates; for example, the elevated lignin and leaf-wax-derived *n*-alkanes in Afroalpine woody plants like Erica result in slower litter decay [19]. Thus, plant physiological and biochemical traits substantially modify SOM fraction composition and ecosystem nutrient cycling [20–22].

In addition to biological influences, environmental and edaphic factors strongly regulate SOM dynamics. Soil surface temperature affects decomposition rates and OM integration into different pools [23,24]. Warmer environments typically accelerate nutrient cycling and SOM oxidation [6,13]. Physical soil properties, including density, texture, and moisture availability, control OM development within fractions [17,25]. Attributes like particle size distribution and clay content serve as key indicators for OM allocation [26,27]. Sandy soils may hinder aggregate stability by limiting binding sites [28–30]. Soil chemical properties, such as pH, exchangeable acidity (EA), and cation exchange capacity (CEC), also critically influence SOM formation and fractional distribution [20,22,31–33].

In the Ethiopian highlands, the degradation of SOM compromises soil aggregate stability, increasing the risk of soil erosion and landslides. This loss of SOM also diminishes the soil's capacity for water infiltration and retention [34]. Bale Mountains National Park (BMNP) is renowned for its rich biodiversity [35]. Spanning altitudes from 3200 m to 4377 m, the park encompasses diverse habitats supporting varied fauna and flora, including Ericaceous and Afroalpine vegetation [36,37]. Research in BMNP reveals that over 40% of SOC stocks are in the organic surface soil layers, with variations mainly driven by topography, vegetation, and land use [19,38].

Despite the region's ecological importance, detailed knowledge of SOM fractional distribution and its controlling factors remains limited. Prior studies often overlook comprehensive accounts of SOM fractional properties and shifts across site factors, particularly in disturbed settings [39]. This study aims to fill this gap by providing the first detailed physical fractionation analysis of SOM in mineral topsoils of the BMNP. Our specific objectives are: (1) to characterize the physicochemical properties of surface soils across different site conditions; (2) to delineate the distribution of SOM fractions under diverse vegetation covers and fire regimes; (3) to explore the environmental and edaphic factors correlated with SOM dynamics; and (4) to discuss the implications of SOM fractionation for ecosystem resilience and carbon management.

2. Materials and Methods

2.1. Study Area

Bale Mountains National Park (BMNP) is situated between 6°30′–7°00′N and 39°30′–39°55′E in southern Ethiopia (Figure 1). It is Ethiopia's largest mountain range and the most extensive Afroalpine region above 3000 m altitude [40]. The central section of the Afroalpine region comprises plateaus and mountain peaks, with Tulu-Dimtu (4377 m a.s.l.) as the nation's second-highest summit [41].

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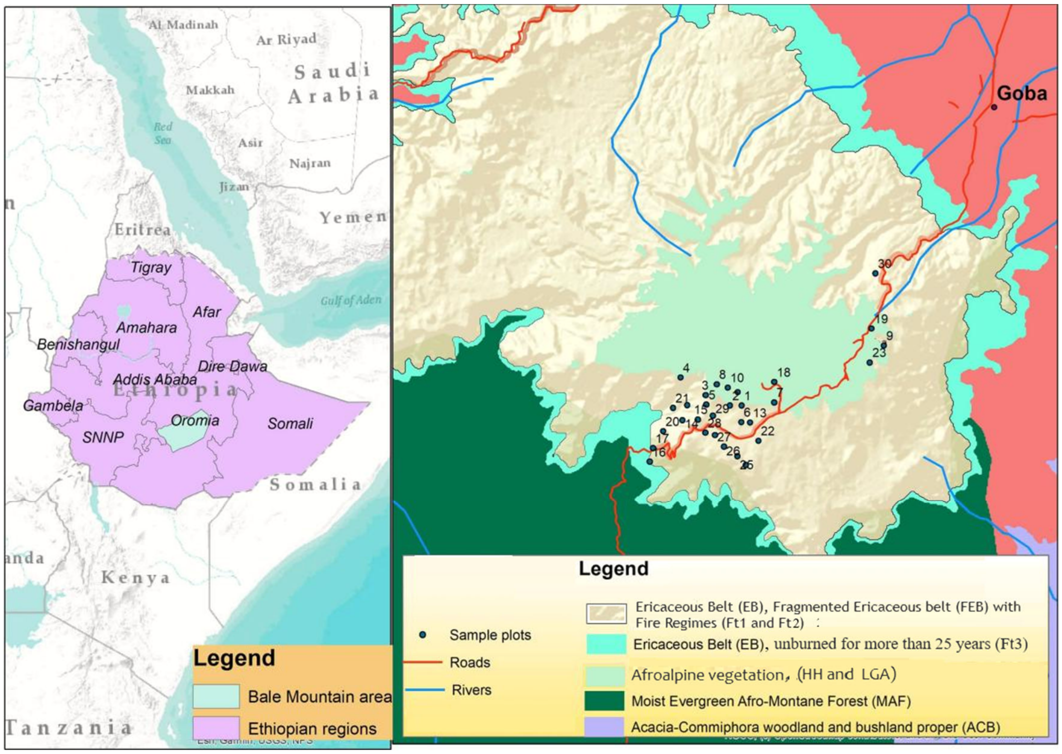

Figure 1. Map of the Bale Mountains National Park showing the three main topographic zones (northeastern face, central Sanetti Plateau, and southwestern face) and the distribution of sampling plots across four vegetation types (EB, FEB, HH, LGA).

The climatic conditions of the BMNP exhibit a north-to-south variance, attributable to the topographic characteristics and geographical position of the mountain range within the tropical region [42]. This area is strongly influenced by the seasonal migration of the intertropical convergence zone, the interaction of dry northeasterly and wet southeasterly trade winds, and the convergence of atmospheric currents from the Atlantic and Indian Ocean, modulated by the Congo Air barrier [43,44]. Average annual rainfall ranges between 1150 and 1740 mm, with the southern side receiving 1000–1500 mm and the northern side 800–1000 mm.

Annual average temperatures across the north, south, and Sanetti plateau range from 8.6 to 13.4 °C, 9.7 to 15.2 °C, and 2 to 7.5 °C, respectively [34,45].

Soils of the Bale Mountains mainly originate from Mesozoic sediments comprising basalts and agglomerates derived from volcanic materials, yielding rocky and shallow Andosols [46]. They are often characterized by low pH values, notable water retention capacity, and prevail as the predominant soil type in the BMNP [47,48]. With ascending elevation, soils become enriched in OM, exhibiting distinct humus layers according to varying site factors, land uses, and vegetation types [34,39].

The vegetation of the BMNP exhibits a pronounced elevational zonation, transitioning from Afromontane forest to extensive Afroalpine ecosystems. The most extensive biome is the Ericaceous belt, spanning 3200–3800 m a.s.l. and forming a near-continuous canopy dominated by *Erica arborea* L. and *Erica trimera* (English) Beentje [46]. About 3800 m a.s.l., the *Erica* canopy becomes fragmented, marking the transition into the Afroalpine zone. The upper boundary of this belt (~3800 m) is a sharp ecotone where climatic stress and fire disturbance create a fragmented Ericaceous belt, with remnants of *Erica* embedded within expanding grasslands of the Afroalpine zone [46,49]. The Sanetti Plateau represents the core of the Afroalpine ecosystem, characterized by a low cover of tussock-forming grasses and sedges, iconic giant rosette (*Lobelia rhynchopetalum*), and dwarf shrubs and forbs, including *Helichrysum splendens* Sims, *Helichrysum citrispinum* Delile, *Helichrysum cymosum* (L.)

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D.Don., *Alchemilla abyssinica* Fresen., *Alchemilla rothii* Oliv., and *Geranium* spp. [44]. The ecological integrity of this fragile ecosystem is increasingly influenced by anthropogenic activity, including expanding settlement, intensification of fire and livestock grazing, which influences vegetation cover, species diversity, and enhances soil erosion [49].

2.2. Sampling Design

2.2.1. Vegetation and Site Sampling

Based on preliminary reconnaissance surveys and existing vegetation maps [41,46], the study area was stratified into four primary vegetation classes:

(i) The Ericaceous belt (EB): characterized by *Erica* spp. forming a nearly-continuous canopy.
(ii) Fragmented Ericaceous belt (FEB): the upper edge of EB characterized by fragmented landscape of EB and small *Erica* patches dispersed on the Sanetti Plateau.
(iii) Herbaceous and heathland (HH): Afroalpine dominated by tussock grasses, sedges, and heathland.
(iv) Giant Lobelia growing area (LGA): Afroalpine ecosystem characterized by giant Lobelia vegetation.

The study area was further stratified by topographic position to capture landscape-scale variation. The area encompasses an elevation gradient from 3200 to 4400 m a.s.l. and includes three main topographic positions: the northeastern slopes (N), the southwestern slopes (S), and the central Sanetti Plateau (P).

Thirty plots of 20 m × 20 m each, strategically located at intervals of 200 m, were surveyed to sample vegetation data, including species composition, vegetation cover, and fire history. Fire history was classified into three classes based on park records and field observations: Ft-1 (burned within the last 10 years), Ft-2 (burned between 10 and 25 years ago), and Ft-3 (unburned for more than 25 years).

2.2.2. Soil Sampling

To investigate the effects of topography, vegetation, fire, and altitude on the fractional distribution of SOM, topsoil samples were collected using a soil auger (5 cm diameter) to a depth of 10 cm from each 20 m × 20 m plot. Within each plot, five subsamples were collected in a square pattern (one from the center and four from opposite corners). These five subsamples were thoroughly homogenized in the field to create a single composite sample representative of each plot. The composite samples were air-dried at ambient room temperature prior to analysis.

2.3. Soil Laboratory Analyses

2.3.1. Physicochemical Properties

Air-dried soil samples were sieved (2000 μm) to remove roots and stone debris. Soil texture was determined via the pipette method [50]. Soil pH was measured in a 1:2.5 soil-to-H_2O suspension. Cation exchange capacity (CEC) and exchangeable acidity (EA) were determined using standard protocols [51].

2.3.2. Soil Organic Matter Fractionation

We employed a comprehensive physical fractionation method adapted from de Figueiredo et al. [52] and Vågen and Winowiecki [53], with methodological enhancements following Tobiašová et al. [9] and Trigalet et al. [30] to ensure reproducibility and standardization. A 20 g subsample of air-dried soil (<2000 μm) was dispersed in 70 mL of sodium hexametaphosphate solution (5.0 g L^{-1}) by shaking for 15 hours at 130 oscillations per minute using an orbital shaker. This extended dispersion period ensures complete disaggregation of soil particles while maintaining the integrity of organo-mineral complexes [30].

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The dispersed slurry was wet-sieved through a 53 μm mesh under gentle water flow to minimize mechanical disruption of organic particles. The material retained on the 53 μm sieve was dried at 50 °C and subsequently dry-sieved through a 149 μm mesh. This procedure yielded the coarse particulate organic matter (cPOM, 149–2000 μm), representing fresh plant debris and partially decomposed OM with rapid turnover, and the fine particulate organic matter (fPOM, 53–149 μm), consisting of fine particulate OM with intermediate turnover potential. The material passing through the 53 μm sieve (mineral-associated organic matter, MAOM, <53 μm) represents OM that is physically protected within aggregates or bound to mineral surfaces, typically associated with longer mean residence times [9].

Additionally, we analyzed total organic carbon (TOC) in the <149 μm fraction (sum of fPOM and MAOM). Organic carbon (OC) and total nitrogen (N) content of each fraction were determined using a volumetric method [50]. The MAOM-to-TOC ratio (MAOM/TOC) was calculated as an indicator of the relative proportion of mineral-associated OM. All fractionation procedures were conducted in triplicate for quality assurance, with coefficient of variation <10% for all measurements.

2.4. Data Analysis

Statistical analyses were performed using R for Windows (version 3.5.2). Descriptive statistics (mean and standard deviation) were used to summarize site and soil properties and SOM fractions. Analysis of variance (ANOVA) was used to test the significance of differences in vegetation classes, fire histories, topography, and soil properties for any of the SOM fractions. Pearson correlation analysis explored relationships between soil parameters, topographic variables, and vegetation metrics. Multiple linear regression models identified significant predictors of SOM fractions. Principal Component Analysis (PCA) was employed on standardized SOM fraction data (cPOM, fPOM, TOC, MAOM, MAOM/TOC) to elucidate multivariate relationships. Redundancy Analysis (RDA) examined the constrained variation in SOM fractions explained by key soil and site variables. A significance level of $p < 0.05$ was used for all tests.

3. Results

3.1. Physicochemical Properties of Surface Soils

The dominant soil texture across the study area was sandy loam (50.0%), followed by loam (30.0%) and silty loam (16.7%) (Figure S1). Texture varied with elevation, with sandy loam predominant at 3200–3800 m a.s.l. and loam more prevalent above 3800 m a.s.l. (Table 1). Sand content showed moderate variation across vegetation classes: EB (560 ± 105 g kg^{-1}), FEB (440 ± 168 g kg^{-1}), HH (468 ± 85 g kg^{-1}), and LGA (485 ± 74 g kg^{-1}). Silt content was highest in FEB (433 ± 132 g kg^{-1}) and lowest in EB (307 ± 110 g kg^{-1}). Clay content was relatively uniform across EB (133 ± 45 g kg^{-1}), FEB (126 ± 42 g kg^{-1}), and HH (120 ± 56 g kg^{-1}), but significantly lower in LGA (88 ± 12 g kg^{-1}; Tukey HSD, $p = 0.03$).

Table 1. Physicochemical properties of topsoils across different vegetation classes (means ± SD).

Vegetations	pH (H_2O)	CEC (cmolc kg^{-1})	EA (cmolc kg^{-1})	Clay (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})
EB	5.90 ± 0.32	527.4 ± 151.1	4.3 ± 1.4	133 ± 45a	560 ± 105	307 ± 110
FEB	6.15 ± 0.26	380.6 ± 132.0	3.7 ± 1.6	126 ± 42a	440 ± 168	433 ± 132
HH	5.95 ± 0.33	449.1 ± 132.5	7.0 ± 4.9	120 ± 56a	468 ± 85	412 ± 32

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LGA	6.21 ± 0.23	475.2 ± 66.6	5.2 ± 2.9	88 ± 12b	485 ± 74	425 ± 77
F-value	1.97	1.6	2.84	3.42	1.89	2.14
p-value	0.144	0.214	0.058	0.032	0.156	0.121

Note: Different superscript letters indicate significant differences (Tukey HSD, $p < 0.05$).

The mean soil pH (H_2O) was 6.00 ± 0.31 (range: 5.24–6.50). Cation exchange capacity (CEC) was notably high (mean: 483.8 ± 140.4 cmolc kg^{-1}), particularly in sandy loams (mean: 534.8 cmolc kg^{-1}). EA was consistently low (mean: 4.74 ± 2.45 cmolc kg^{-1}). Key physicochemical properties varied across the vegetation classes (Table 1). While one-way ANOVA revealed no statistically significant differences for pH (F = 1.965, p = 0.144) or CEC (F = 1.596, p = 0.214), distinct trends were observable. Soil texture showed dominance of sandy loam in the EB (56.00 ± 10.54% sand), transitioning to loamier profiles in LGA (42.54 ± 7.73% silt). EA was elevated in HH soils (7.0 ± 4.9 cmolc kg^{-1}), potentially due to post-fire effects. Soils of the EB had the lowest mean pH (5.90 ± 0.32) and the highest CEC (527.4 ± 151.1 cmolc kg^{-1}).

3.2. Distribution of Soil Organic Matter Fractions

Physical fractionation revealed that particulate organic matter pools were the dominant form of organic carbon (OC). The cPOM fraction represented a substantial pool, with approximately 57% of the total measured OC retained in this fraction. In contrast, the MAOM fraction had the lowest concentration (<0.07%). The distribution of OC fractions varied by vegetation class (Table 2). The highest cPOM was found in EB (11.38 ± 3.87 g kg^{-1}), while the lowest was in FEB (8.96 ± 3.28 g kg^{-1}). fPOM was highest in EB (12.91 ± 3.41 g kg^{-1}) and LGA (12.71 ± 1.48 g kg^{-1}), and lowest in HH (12.57 ± 1.17 g kg^{-1}). TOC was highest in FEB (8.74 ± 3.40 g kg^{-1}) and LGA (8.46 ± 2.46 g kg^{-1}), while lower values were recorded in HH (8.25 ± 2.78 g kg^{-1}). The MAOM/TOC ratio was marginally higher in FEB (0.008 ± 0.003), suggesting a slight increase of mineral-associated OM in these disturbed Ericaceous areas.

Table 2. Distribution of SOC fractions across vegetation classes in BMNP (means ± SD, g kg^{-1}).

Vegetation	cPOM (g kg^{-1})	fPOM (g kg^{-1})	MAOM (g kg^{-1})	TOC (g kg^{-1})	MAOM/TOC
EB	11.38 ± 3.87$_a$	12.91 ± 3.41$_a$	0.06 ± 0.04	7.95 ± 3.61	0.007 ± 0.004
FEB	8.96 ± 3.28$_b$	11.23 ± 2.24$_b$	0.07 ± 0.03	8.74 ± 3.40	0.008 ± 0.003
HH	9.68 ± 3.31a$_b$	12.57 ± 1.17$_{ab}$	0.06 ± 0.03	8.25 ± 2.78	0.006 ± 0.003
LGA	10.91 ± 2.65a$_b$	12.71 ± 1.48$_{ab}$	0.05 ± 0.02	8.46 ± 2.46	0.006 ± 0.002
F-value	3.12	2.98	1.24	0.89	1.56
p-value	0.042	0.048	0.312	0.458	0.221

Note: Different superscript letters indicate significant differences (Tukey HSD, $p < 0.05$).

Fire history modulated SOM fractions in a non-linear response (Table 3). The highest mean TOC (8.9 ± 3.5 g kg^{-1}) and total organic nitrogen (TON, 0.78 ± 0.33 g kg^{-1}) were recorded in soils unburned for more than 25 years (Ft-3). These values were significantly higher than in Ft-2 (TOC: 7.2 ± 3.0 g kg^{-1}, TON: 0.64 ± 0.28 g kg^{-1}). Fire-impacted soil with Ft-2 history showed the highest concentrations of particulate fractions, including fPOM (13.51 ± 1.96 g kg^{-1}), fPOM-N (1.26 ± 0.28 g kg^{-1}), cPOM (12.11 ± 2.6 g kg^{-1}), and cPOM-N (1.02 ± 0.21 g kg^{-1}), alongside the highest CEC (547 ± 118 cmolc kg^{-1}) and sand content (532 ± 82 g kg^{-1}). This pattern suggests that fire acts as a physical perturbation, fragmenting litter into particulate pools that initially boost CEC but may not lead to long-term MAOM formation (Figure S2).

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Table 2. Distribution of SOC fractions across vegetation classes in BMNP (means ± SD, g kg⁻¹).

Fire regime	cPOM (g kg⁻¹)	cPOM-N (g kg⁻¹)	fPOM (g kg⁻¹)	fPOM-N (g kg⁻¹)	TOC (g kg⁻¹)	TON (g kg⁻¹)	MAOM (g kg⁻¹)	MAOM-N (g kg⁻¹)	MAOM /TOC
Ft-3 (>25 yr)	10.00 ± 3.57b	0.87 ± 0.30b	11.60 ± 2.89b	1.00 ± 0.25ab	8.9 ± 3.5a	0.78 ± 0.33a	0.072 ± 0.039a	0.006 ± 0.003a	0.008 ± 0.003a
Ft-2 (10–25 yr)	12.11 ± 2.60a	1.02 ± 0.21a	13.51 ± 1.96a	1.26 ± 0.28a	7.1 ± 3.0b	0.64 ± 0.28b	0.050 ± 0.038b	0.0047 ± 0.003b	0.006 ± 0.003b
Ft-1 (<10 yr)	9.87 ± 4.00b	0.85 ± 0.35b	12.55 ± 3.16ab	1.03 ± 0.32ab	8.5 ± 3.0ab	0.77 ± 0.25a	0.050 ± 0.033b	0.0044 ± 0.003b	0.0055 ± 0.0029b
F-value	4.23	3.89	3.45	4.12	3.78	4.56	3.21	4.89	5.12
p-value	0.025	0.032	0.046	0.028	0.036	0.019	0.054	0.015	0.013

Note: Different superscript letters indicate significant differences (Tukey HSD, $p < 0.05$).

Site variation analysis revealed significant differences in OC fractions among northern slope, southern slope, and Sanetti plateau (P) areas (Table 4). The fPOM and cPOM fractions showed significant differences ($F = 6.3$, $p = 0.002$ and $F = 10.8$, $p = 0.001$ respectively), while TOC showed no significant variation ($F = 2.4$, $p = 0.1$) across topographic positions.

Post-hoc comparisons revealed that northern mountain slopes differed most from plateau sites for particulate fractions (mean difference = 2.97 g kg⁻¹), while southern slopes and plateau sites showed a significant but smaller difference in cPOM (mean difference = 0.7 g kg⁻¹, $p < 0.05$).

Table 4. Distribution of SOM fractions across topographic positions (means ± SD, g kg⁻¹).

Fraction	North	South	Plateau	F-value	*p*-value
fPOM (g kg⁻¹)	13.8 ± 2.8	12.1 ± 1.5	10.8 ± 2.8	6.3	0.002
cPOM (g kg⁻¹)	12.2 ± 3.2	9.6 ± 3.2	9.0 ± 3.5	10.8	0.001
TOC (g kg⁻¹)	6.9 ± 3.5	9.7 ± 1.3	8.9 ± 3.4	9.2	0.1

Note: $p < 0.05$ indicates significant differences among positions.

3.3. Relationships Between Soil, Site, and SOM Fractions

Pearson correlations revealed that cPOM was strongly and positively correlated with CEC ($r = 0.86$, $p < 0.001$) (Figure 2). Conversely, cPOM was negatively correlated with elevation ($r = –0.38$, $p = 0.04$). MAOM was negatively correlated with cPOM ($r = –0.44$, $p = 0.02$).

Principal Component Analysis (PCA) showed that the first two components explained 87.77% of variance in surface soil organic matter fractions (Figure 3).

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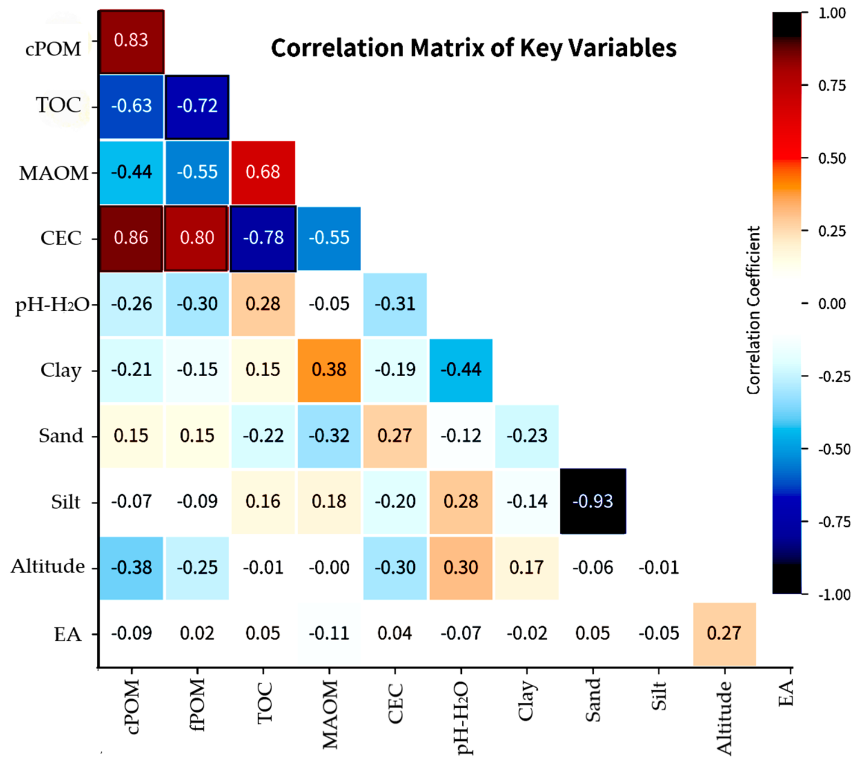

Figure 2. Correlation analysis of soil properties and SOM fractions.

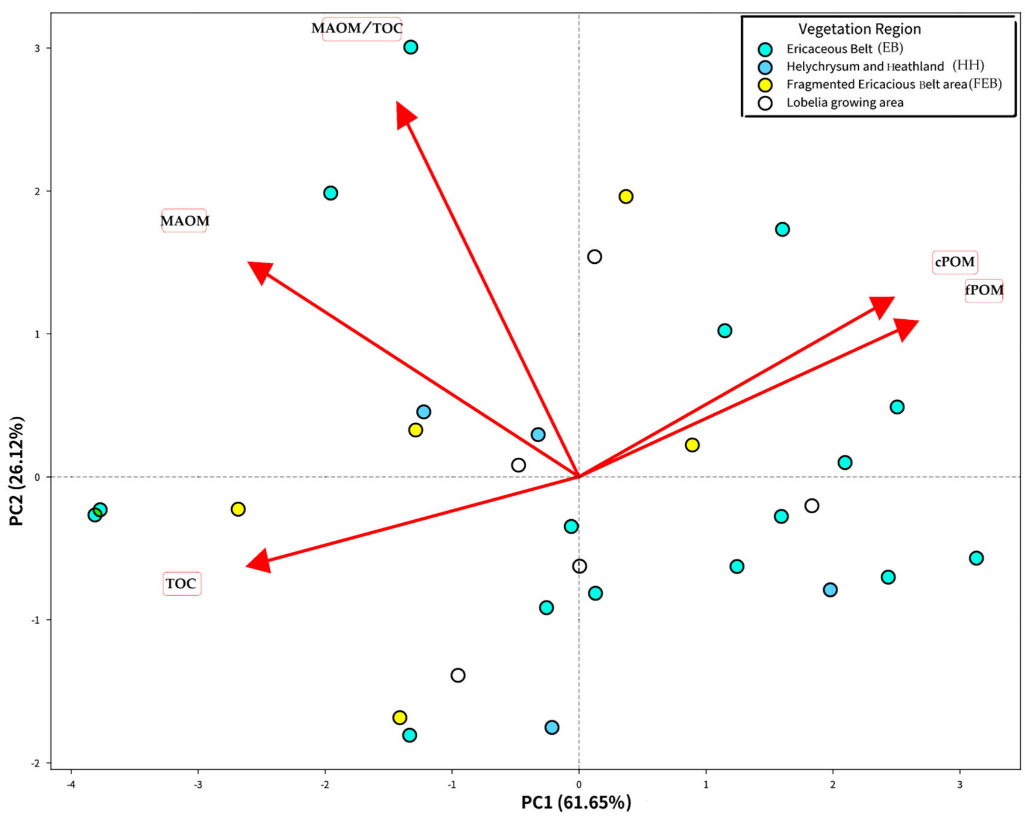

Figure 3. Principal Component Analysis (PCA) biplot of SOM fractions. PC1 contrasts particulate (cPOM, fPOM) versus total and mineral-associated (TOC, MAOM) fractions. PC2 is associated with the MAOM/TOC ratio. Sample points are colored by vegetation region.

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PC1, accounting for 61.65% of the variance, represented a gradient from particulate-dominated SOM (high positive loadings for cPOM and fPOM) to MAOM-dominated SOM (high negative loadings for TOC and MAOM). PC2, explaining 26.12% of the variance, was associated with the relative proportion of MAOM, characterized by high loadings for MAOM/TOC ratio and MAOM content. Soils in EB with longer fire-free intervals (Ft-3) clustered with positive PC1 scores (mean PC1 = 1.24 ± 0.56), indicating particulate-dominated SOM, while Ft-1 and FEB exhibited negative PC1 scores (mean PC1 = –0.89 ± 0.62), suggesting a shift toward more MAOM-depleted SOM.

Redundancy Analysis (RDA) confirmed a significant relationship between soil and site factors with SOM fractions ($F = 7.40$, $p = 0.002$). CEC was strongly and positively associated ($r > 0.8$) with the particulate fractions (cPOM, fPOM), while pH, silt, and clay content were more closely aligned with the distribution of MAOM and total fractions (Figure 4). The RDA ordination explained 89.49% of the variance in SOM fractions explained by soil/site properties, providing strong evidence for the mechanistic links between soil chemistry, texture, and organic matter dynamics.

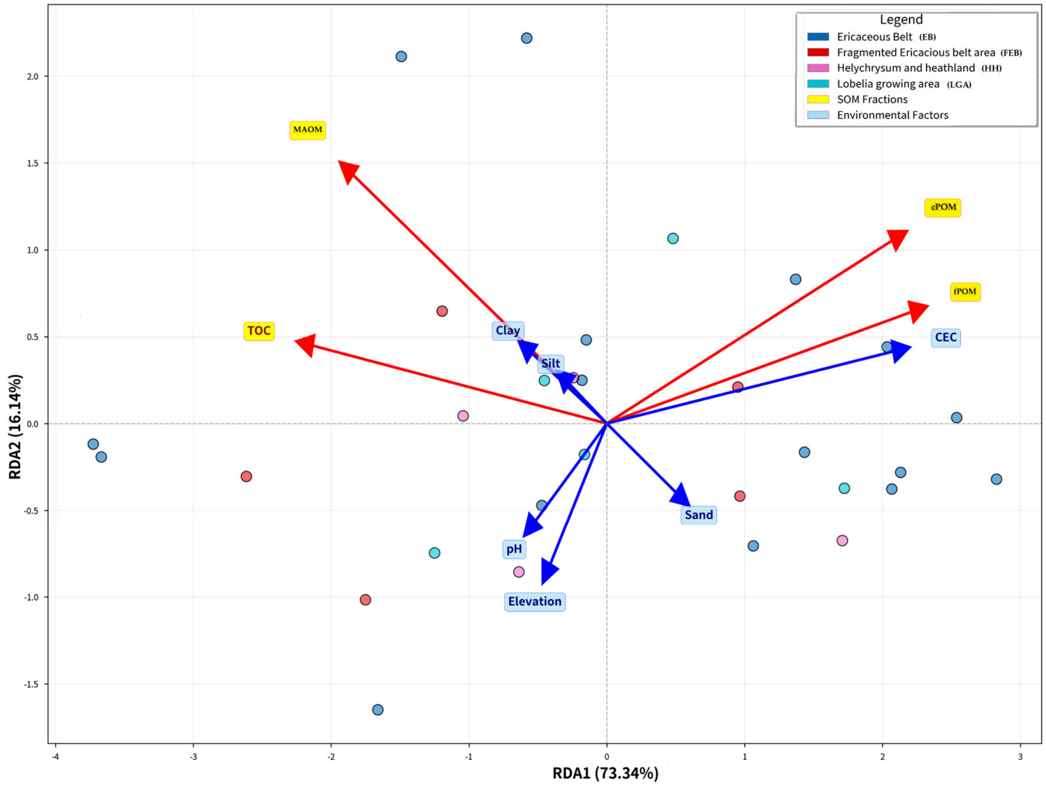

Figure 4. Redundancy analysis (RDA) triplot showing the relationship between soil/site factors (blue arrows) and SOM fractions (red arrows). The color of the samples indicates the vegetation where samples were collected.

4. Discussion

4.1. Topsoil Properties as a Function of Ericaceous and Afroalpine Belts

This study highlights a robust connection between topsoil physicochemical properties and typical environmental proxies in the BMNP. The prevalence of sandy loam and loam textures, which vary with altitude, underscores the impact of parent material and varying weathering intensity, typical in alpine environments [54]. The transition to finer soil textures at elevations above 3800 m is likely attributed to frequent frost events that accelerate physical weathering and facilitate the breakdown of rock and the buildup of fine silt and clay particles [47,55]. Elevated variability of silt contents, especially in the EB, indicates that vegetation cover substantially influences soil formation, potentially by capturing aeolian deposits or modulating microclimatic weathering [37,56–58].

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The slightly acidic pH (mean: 6.0) and remarkably high CEC (mean: 48.38 cmolc kg^{-1}) are characteristic of these organic-rich soils covered by *Erica* and Afroalpine vegetation. Their increased acidity likely reflects the breakdown of acidic *Erica* litter mainly by fungi and intense rainfall causing leaching of base cations [59,60]. The high CEC, particularly in sandy loams where the relatively low surface area of mineral particles results in a minimal contribution to the overall CEC, is primarily linked to abundant SOM in particulate fractions [9,39]. This shows the crucial role of SOM in pH buffering and nutrient retention [60,61]. Low EA further indicates that, despite acidity, these soils are non-toxic and offer a fertile base for adapted vegetation [55].

4.2. Dominance of Particulate Organic Matter and Its Drivers

A key outcome of this research is the predominant role of particulate fractions (cPOM and fPOM) within the total SOM pool. This suggests that OC cycling in these Afroalpine topsoils involves the potential for rapid turnover, with much of the OC stored in minimally processed organic matter [62,63]. This pattern differs from many temperate or tropical forest soils, where mineral-associated OC is the primary reservoir [64,65]. The geographic heterogeneity reflects the interaction of topographic position, microclimate, and disturbance history in shaping SOM dynamics across the study area. The dominance of particulate OC likely results from the cool, humid climate that retards decomposition, coupled with the recalcitrant chemical properties of *Erica* litter [66–69].

The results also indicate that in the BMNP, fire disturbance is a primary regulator of particulate SOM dynamics. The observed increase in cPOM and fPOM in soils with Ft-2 suggests that fire acts as a significant physical perturbation [44]. This process involves potential CO_2 release through combustion and thermal fragmentation of surface litter, transforming it into cPOM that is readily incorporated into the mineral soil [70,71]. While this mechanism can lead to a short-term increase in the pools of particulate OC, it may accelerate microbial decomposition and mineralization, increasing the potential for OC release to the atmosphere, thereby altering the long-term trajectory of carbon sequestration [72,73]. Conversely, higher TOC and enhanced MAOM proportion in Ft-3 sites indicate the value of prolonged disturbance-free conditions for developing more stabilized SOM [6,38,72,74].

4.3. Interpreting Physical Fractions: Operational Pools vs. Inherent Stability

A critical point that emerged from this study is the need to interpret physical fractions with caution. The operational fractions we separated—cPOM, fPOM, and MAOM—are not direct measures of biological or chemical stability. While MAOM is often considered more stable than POM due to protection by mineral surfaces, recent research has shown that MAOM can turn over rapidly under certain conditions, especially when it is not physically protected within stable aggregates or when mineralogy does not favor strong sorption [75,76]. In our soils, the extremely low MAOM/TOC ratio (0.006–0.008) indicates that only a tiny fraction of OC is associated with mineral surfaces. This is likely due to the sandy texture and relatively low clay content, which limit the total reactive surface area available for OM stabilization [77,78]. Even though the Andosol mineralogy (allophane, imogolite) theoretically promotes organo-mineral complexation [79], the physical constraints of low clay and high sand content appear to override this potential.

Therefore, while we use the term "mineral-associated" to describe the <53 μm fraction, we do not equate this with long-term stability. Instead, we interpret the low MAOM/TOC ratio as an indication that the capacity for physical and chemical stabilization is limited, leaving most SOC in forms that are more vulnerable to decomposition if environmental conditions change. This interpretation aligns with the contemporary understanding that SOM persistence is controlled by a combination of mineral protection, aggregate occlusion, and microbial accessibility, rather than by intrinsic recalcitrance alone [80,81].

4.4. Mechanistic Pathways of SOM Stabilization: Physical Protection and Mineral Association

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Applying the aggregate hierarchy model [65] reveals why particulate OM dominates in BMNP soils. According to this model, SOM stabilization progresses from free particulate OM into microaggregates (53–250 μm), incorporation into macroaggregates (>250 μm), and eventually into mineral associations. Our data show that most OC remains in the free particulate fraction (cPOM: 8.96–11.38 g kg^{-1}), with minimal progression into MAOM (0.05–0.07 g kg^{-1}). This arrested stabilization sequence suggests that aggregate formation is impeded, likely due to the sandy loam texture (50%) and low clay content (88–133 g kg^{-1}), which limit the binding agents necessary for aggregate stability [82,83].

The Lehmann and Kleber [80] organo-mineral interaction framework provides further mechanistic insight. Stable SOM formation depends on mineral surface area and reactivity, organo-mineral binding strength, and spatial accessibility of OM to mineral surfaces. In our soils, despite the presence of reactive allophane, the low clay content restricts total reactive surface area, limiting the formation of stable organo-mineral complexes [39,79].

The strong positive correlation between CEC and particulate fractions (cPOM: $r = 0.86$, $p < 0.001$; fPOM: $r = 0.80$, $p < 0.001$) suggests a critical feedback mechanism governing nutrient availability in the Afroalpine ecosystem. The CEC in these soils is largely derived from organic matter rather than clay minerals, consistent with the low clay content. Higher SOM content increases CEC through the contribution of organic colloids, which enhances nutrient retention and supports further primary productivity and formation of particulate pools [84]. The contrasting negative correlations between TOC and CEC ($r = -0.78$) and MAOM ($r = -0.55$) reveal a fundamental trade-off: as MAOM accumulates and forms thick coatings on minerals, the measured CEC of the soil complex decreases.

4.5. Interplay of Biotic and Abiotic Factors in SOM Dynamics

Multivariate analyses effectively identified the main drivers of SOM dynamics. The robust positive correlation between CEC and particulate OC fractions (cPOM and fPOM) suggests a positive feedback loop. In this mechanism, greater SOM inputs enhance CEC, which improves the soil's nutrient retention, thus supporting higher plant growth and labile SOM inputs to the soil [85,86]. Redundancy analysis (RDA) distinctly differentiated biologically mediated processes from mineral-related factors, such as clay, silt, and pH, traditionally tied to enduring stabilization. This implies a dual control framework in the BMNP: biological activity and disturbance patterns dictate the magnitude and cycling of the particulate OM pool, whereas soil mineralogy establishes the foundation for the smaller yet persistent MAOM pool [39,80].

The inverse relationship between particulate and mineral-associated fractions signals a potential efficiency trade-off [60]. Ecosystems that rapidly accumulate a particulate OC pool may be less efficient at physically protecting and chemically transferring that carbon into MAOM [13,87]. This inefficient stabilization pathway makes the substantial OC stocks of the BMNP vulnerable to environmental changes.

4.6. Climate Change Vulnerability and Carbon-Climate Feedbacks

The dominance of particulate SOM fractions in BMNP soils creates particularly high vulnerability to climate change through temperature-sensitive decomposition processes. Using the Q_{10} framework, where Q_{10} represents the factor by which reaction rates increase with a 10 °C temperature rise, particulate OM typically exhibits Q_{10} values of 2–3, indicating that decomposition rates double to triple with each 10 °C warming [13]. Under projected climate scenarios for the Ethiopian highlands, where temperatures are expected to increase by 2–4 °C by 2080 [14], this translates to a 15–30% change in decomposition rates for the particulate fractions.

The implications of this temperature sensitivity are accompanied by the low MAOM proportion observed in our study. With MAOM/TOC of 0.006–0.008, a large percentage of SOC exists in forms susceptible to rapid mineralization under warming conditions [88]. Conservative meta-analyses suggest that a 2 °C increase in global mean temperature could reduce the labile SOC pool by 20–25%

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over the next 50–80 years [89]. This process could result in a net release of approximately 2–3 Mg C ha^{-1} yr^{-1} from topsoils alone [90].

This dynamic creates a positive feedback loop with the global climate system: warming stimulates microbial respiration, accelerates the decomposition of particulate SOC, and increases CO_2 release to the atmosphere, which subsequently reinforces atmospheric warming [2,91]. This feedback is not uniform and is moderated by factors such as soil moisture, nutrient availability, and potential microbial thermal adaptation [72,92]. Nevertheless, this feedback contributes substantially as a source of uncertainty in climate projections and is a key component of the carbon cycle reported by the IPCC [90].

The carbon-climate feedback models developed by Jones et al. [93] and refined by Friedlingstein et al. [14] indicate that such particulate-dominated soils contribute uncertainty to carbon-climate feedback. In the context of the BMNP ecosystem, this feedback is particularly attention-demanding, given that the region is projected to experience above-mean temperature increases. In addition to temperature effects, climate change is expected to change fire regimes in the BMNP, with increased fire disturbance intensity driven by drier conditions [37]. Our results show that fire disturbance already determines SOM distribution, with Ft-1 showing altered SOM dynamics. Under intensified fire regimes, the current 10–25-year recovery cycles (Ft-2 and Ft-3) may be altered, preventing the stabilization of SOM. This pattern indicates that ecosystem recovery requires substantial time to rebuild SOC stocks and to develop efficient stabilization mechanisms [88,94].

The regional carbon budget implications are substantial. BMNP represents one of Africa's largest high-altitude OC stores and could significantly impact regional atmospheric CO_2 concentrations. Unlike MAOM, the particulate-dominated fractions in BMNP soils provide low climate buffering potential [83].

4.7. Comparative Context: Afroalpine SOM Dynamics in a Global Mountain Perspective

The SOM dynamics observed in the Bale Mountains exhibit both similarities and striking contrasts with other global mountain ecosystems, highlighting the unique characteristics of repeated high-intensity fire regimes and distinct volcanic parent material [39]. Comparative analyses with the Andes, Himalayas, and European Alps reveal distinctive patterns that underscore the importance of fire regimes and volcanic mineralogy in shaping SOC cycling [55,95,96].

In mountain ecosystems studied by Feyissa et al. [97], elevation gradients similarly influence SOM distribution, with higher altitudes promoting OM buildup due to reduced decomposition rates. A key distinction lies in the fire history: Andean páramo ecosystems typically experience lower fire regimes, promoting the development of deep, OM-rich soils with highly efficient stabilization mechanisms. MAOM constituted a much larger fraction of TOC in Andean soils, indicating significantly more efficient stabilization mechanisms in non-fire-prone Andean ecosystems [97].

Himalayan mountain soils, as characterized by Gnanavelrajah et al. [27], demonstrate the influence of monsoonal climate patterns on SOM dynamics. The intense wet-dry cycles promote different decomposition and stabilization pathways compared to the more consistent moisture regimes of the Bale Mountains. Gnanavelrajah et al. [27] found that seasonal moisture variability enhanced physical protection of OM within aggregates, leading to higher proportions of intermediate-stability fractions. This contrasts sharply with Bale Mountain soils, where consistent moisture combined with fire disturbance maintains carbon predominantly in particulate pools [35].

European Alpine systems provide perhaps the most instructive comparison, as documented by de Oliveira Marques et al. [23] and Zielonka et al. [98]. These temperate alpine soils, developing under minimal fire pressure and on predominantly crystalline parent materials, show markedly different SOM stabilization patterns. Zielonka et al. [98] reported that in European Alpine soils, 40–60% of SOC exists in the MAOM fraction, compared to <1% in Bale Mountain soils. These Afroalpine ecosystems operate under a distinct set of biogeochemical constraints where fire disturbance is the primary driver of SOC stocks, a pattern that contrasts sharply with less fire-impacted systems like the Andes, Himalayas, and European Alps [5,95,96].

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While our study indicates that high-intensity fire regimes affect the MAOM relative to less fire-impacted ecosystems like the Andean páramo, fire simultaneously acts as a driver of a different, very stable OC pool: pyrogenic carbon (Black Carbon). In the volcanic Andosols of the BMNP, this black carbon can become further stabilized through physical and chemical interactions with high-surface-area minerals like allophane and ferrihydrite, forming persistent BC-organo-mineral complexes [39]. Fire acts as a transformative agent, shifting the dominant stabilization pathway from one reliant on mineral protection of native SOM to one dominated by the inherent chemical recalcitrance of fire-derived BC [99]. The net effect on the total OC stock depends on the balance between the carbon lost through complete combustion and the carbon sequestered as BC [82,100]. The low MAOM/TOC observed in our study arguably indicates that the current fire regime results in a net carbon loss, even as it fundamentally alters the long-term stability and chemical nature of the remaining carbon pool [26,101].

The specific patterns of SOM dynamics in the BMNP result from three factors. Firstly, the volcanic Andosol mineralogy creates soils with high water holding capacity and high CECs but with low clay content for organo-mineral complexation; in addition, frequent anthropogenic disturbances limit the SOM stabilization potential [77,102]. Secondly, Ericaceous vegetation produces decomposition-resistant litter, largely from *Erica* spp. with high lignin content (>30%) and complex polyphenolic compounds [19,58]. However, rather than contributing to MAOM formation, this litter accumulates as a poorly decomposing dry humus layer that remains vulnerable to fire-induced mineralization [66,87,103]. Thirdly, the fire-driven turnover operates on a 10–25-year period (Ft-3) that is too frequent to allow complete humification and stabilization processes to occur [69,104].

The carbon cycling observed in our study represents an adaptation of BMNP soils to anthropogenic fire disturbance rather than an optimal carbon storage strategy. This fire-driven turnover fundamentally distinguishes Afroalpine ecosystems from temperate alpine systems [5]. The soils under study exemplify how disturbance regimes can override climatic and edaphic factors favorable to carbon sequestration. While the cool, moist climate and high litter inputs should theoretically promote carbon sequestration, the anthropogenic fire maintains these soils as dynamic carbon cycling systems rather than as stable carbon sinks.

4.8. Implications for Ecosystem Resilience and Management

The relationship between Ericaceous vegetation and the particulate SOM pools has significantly influenced ecosystem resilience. A thick Ericaceous vegetation ensures steady litter inputs that maintain the particulate OM pool and soil fertility [105]. Yet, this is challenged because dense, undisturbed *Erica* is highly endangered by fire and overgrazing that affect vegetation, litter inputs, and particulate OM pools, and thus might reduce productivity [60,106]. The decreased cPOM content in soils of the FEB exemplifies this trend (see Table 2).

These results indicate that the existing land management in the BMNP may undermine long-term ecological stability. Conservation strategies should prioritize safeguarding SOM inputs and stabilization mechanisms, including systematic anthropogenic fire control and overgrazing management [107]. Preserving these vulnerable topsoils is crucial not only for OC sequestration but also for biodiversity, land, and water management [73,108].

5. Conclusions

This study provides a detailed characterization of SOM dynamics in the fire-prone Ericaceous and Afroalpine belts of the BMNP, Ethiopia, focusing on SOC cycling and stabilization mechanisms. We demonstrate that particulate OM fractions (cPOM and fPOM) are the primary SOM pools. Despite the favorable Andosol mineralogy, the process of SOM stabilization is severely constrained by limited physical protection within aggregates and insufficient organo-mineral complexation. The extremely low MAOM/TOC ratio and high cPOM and fPOM content reflect a poor stabilization efficiency, where SOC remains in particulate forms rather than being transformed into mineral-associated OM.

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This pattern contrasts with results from temperate mountain ecosystems and highlights the unique impact of fire-driven turnover on carbon cycling pathways.

Climate change vulnerability analysis indicates that projected warming of 2–4 °C could accelerate decomposition of particulate fractions, contributing to positive carbon-climate feedback. The strong positive relationship between CEC and particulate fractions underscores the significance of the nutrient cycling capacity in maintaining SOM stocks, while the negative relationship with altitude reflects temperature constraints on litter decomposition. Fire history significantly determines SOM distribution, with intermediate disturbance enhancing particulate pools, while long-term fire absence promotes increase of TOC and its stabilization, indicating that fire management is critical for carbon conservation.

Conservation strategies should prioritize minimizing anthropogenic disturbances, particularly fire frequency and grazing pressure, to maintain vegetation cover and SOM inputs essential for ecosystem resilience. Future research should extend to deeper soil profiles, incorporate microbial community analyses, and develop fire management protocols that balance ecosystem processes with carbon conservation. Such knowledge is critical for developing effective management strategies that preserve both biodiversity and carbon sequestration functions in these fragile high-altitude ecosystems under accelerating global environmental change.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Figure S1: Bale Mountains soils texture distribution; Figure S2: Relations between Soils carbon fractions and litter cover (%).

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