

WOODY PLANT SPECIES DIVERSITY AND COMMUNITY TYPES ALONG ENVIRONMENTAL GRADIENTS IN DAMOTA FOREST PATCHES IN MELOKOZA DISTRICT, SOUTH ETHIOPIA

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ABSTRACT

Forests are dynamic systems, where structure, composition, and ecological function emerge from the complex interplay of altitude, soil, and biological interactions. Although the forests in the region are central to biodiversity conservation and local livelihoods, they remain poorly documented, especially in terms of ecological community structure. To address this gap, we classified the forest's woody plant communities and identified the environmental gradients that govern their distribution. Vegetation data were collected from 120 systematically arranged 20 m × 20 m quadrats placed along five transects. Species composition, abundance, and cover were quantified and analyzed using cluster analysis, canonical correspondence analysis, and standard diversity measures. A total of 60 woody species belonging to 55 genera and 33 families were recorded, with shrubs (35 species) more numerous than trees (25 species). The analyses revealed four distinct community types. The forest exhibited high overall diversity (Shannon $H' = 3.5$) and a well-balanced distribution of species (evenness $J = 0.93$). Variation in altitude, aspect, soil pH, available phosphorus, and sand content emerged as the principal factors explaining differences in community composition ($p < 0.05$). These findings show that the Damota Forest is strongly structured by topographic and edaphic gradients and retains considerable woody-species diversity despite ongoing human pressure. Strengthening conservation efforts, restoring degraded sites with native indicator species, and aligning local forest management with climate- and carbon-focused initiatives such as Ethiopia's Green Legacy Programme are essential steps toward securing the forest's long-term resilience.

Keywords: Damota Forest, Environmental Gradients, Plant Community Structure, Species Diversity

INTRODUCTION

Forests are dynamic ecosystems whose structure, composition, and function are shaped by multiple interacting forces. Their ecological roles ranging from climate regulation to soil fertility enhancement and hydrological stability have long been recognized (FAO, 2020). In tropical regions, particularly in sub-Saharan Africa, rapid forest fragmentation has altered

landscape structure and disrupted ecological processes, leading to shifts in species assemblages and losses of biodiversity (Haddad *et al.*, 2015; Newbold *et al.*, 2020). These changes underscore a central question in contemporary ecology, how environmental gradients and human disturbance interact to structure plant communities, and how these interactions influence the persistence of forest ecosystems in changing landscapes.

Plant community composition is not randomly assembled; rather, it reflects a combination of ecological filters, species interactions, and historical contingencies. Environmental gradients such as altitude, slope, soil characteristics, and moisture availability act as filters determining which species are able to establish and dominate in a given site (Bruehlheide *et al.*, 2018; Whittaker *et al.*, 2021). Disturbance particularly when chronic or anthropogenic represents a parallel axis of influence, reshaping competitive hierarchies, altering recruitment niches, and shifting successional routes (Fahrig *et al.*, 2019; Chetan *et al.*, 2022; Teshome *et al.*, 2023). Understanding these mechanisms is central to current discussions on community assembly, biodiversity environment relationships, and ecosystem resilience. Consequently, research that links floristic and community patterns with environmental drivers contributes not only to local conservation needs but also to broader ecological theory concerning environmental filtering and disturbance-mediated assembly processes (Zhu *et al.*, 2024; Caishuang *et al.*, 2024; Qian *et al.*, 2024; Huang *et al.*, 2025).

In Ethiopia, the southern and southwestern highlands are known for their ecological heterogeneity and high species endemism (Friis *et al.*, 2010; Gole *et al.*, 2021). Nevertheless, many forest patches in this region, including the Damota Forest in Melokoza District, remain poorly studied despite facing escalating pressures from agricultural expansion, logging, and unregulated grazing (Tadesse *et al.*, 2022; Fisseha & Demissew, 2022; Eshete *et al.*, 2023). These pressures are altering vegetation structure and may be reshaping community assembly processes in ways that are not yet documented. The absence of systematic ecological assessment limits the capacity to evaluate how environmental gradients and disturbance jointly structure species communities in these forests. It also restricts meaningful comparisons with other systems where similar mechanisms have been examined.

The Damota Forest Patch represents an ecologically significant but scientifically under-characterized fragment of the Southwest Ethiopian Highlands. No formal classification of its plant community types currently exists, and the manner in which altitude, slope, edaphic factors, and disturbance shape these communities remains unknown. This lack of baseline ecological information poses obstacles for forest conservation, restoration efforts, and integration of local forest patches into national biodiversity planning frameworks (Government of the Federal Democratic Republic of Ethiopia, 2020; Gebrehiwot & Kassa, 2021). More importantly, it prevents researchers from testing whether established ecological theories such as environmental filtering across elevational gradients, or disturbance-mediated shifts in community composition hold true in this understudied landscape.

Given these gaps, this study aims to classify the woody plant community types of the Damota Forest Patch and to evaluate the environmental gradients associated with their distribution. By linking floristic patterns with ecological drivers, the study contributes to ongoing theoretical discussions about how community structure emerges in fragmented tropical landscapes. At the same time, it provides applied insights that support Ethiopia's biodiversity conservation and restoration goals, including commitments under the 2022 Kunming-Montreal Global Biodiversity Framework and the Ethiopian National Biodiversity Strategy and Action Plan (NBSAP). Through this dual theoretical and applied framing, the study addresses both scientific and management needs for one of Ethiopia's understudied forest ecosystems.

Research Questions

How does the community composition and diversity of woody species change with altitude and different soil characteristics in Damota Forest?

Among the topography, soil properties, and disturbance, which environmental factors have the greatest impact on the structure of woody plant communities?

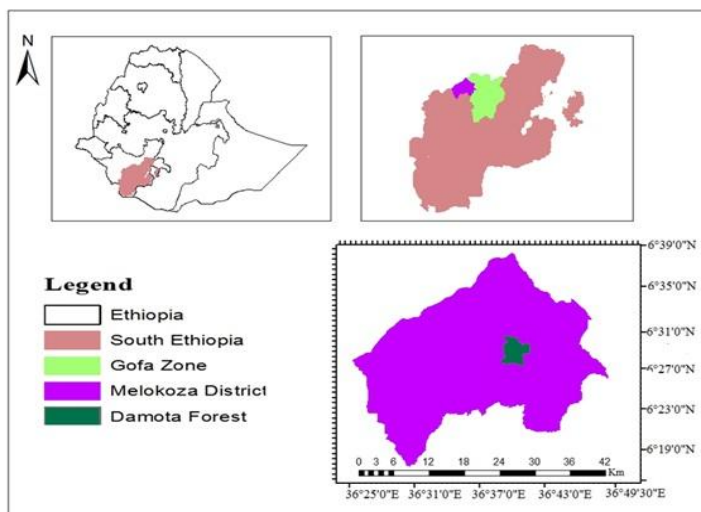
In what ways does human, induced disturbance affect the diversity of woody species?

METHODS

Study area description

The research was carried out in Damota Forest, situated in Melokoza District, South Ethiopia. The study was carried out in the Damota Forest, situated within the Melokoza district of the Gofa Zone in South Ethiopia. Geographically, the area lies between 6°17'00" and 6°39'00" North latitude and 36°25'00" to 36°49'30" East longitude (Fig. 1). The region experiences a temperature range from a minimum of 15.1 °C to a maximum of 27.5 °C, with an average annual temperature of approximately 22 °C. According to the Melokoza Agricultural Office, the district has a population of 152,502 people, the majority of whom rely on agriculture, particularly the cultivation of sesame and maize. The total land area of the district covers 168,180.93 hectares. Of this, 31,884.093 hectares are used for perennial crops, 6,885 hectares for annual crops, 33,687.15 hectares consist of natural forests and 48,620.78 hectares are allocated to various other land uses. Land ownership in the district varies significantly: 20.3 % of farmers own more than two hectares, while 26.7 % possess less than 0.5 hectares. The highland areas are characterized by a rich diversity of vegetation, including woodlands, highland bamboo stands, and moist montane forests. Melokoza is also home to several preserved natural forests, among these notably Sirso Forest (3,501.487 hectares), Zalalo Forest (3,066.556 hectares), Damota Forest (603.275 hectares), Melabungulo Forest (410.928 hectares) and Gudo Forest (250.671 hectares). The district's soils are primarily loam (50 %), followed by sandy loam (35 %) and clay (15 %), supporting a wide range of land uses and vegetation types.

Fig. 1: Study area map.



Sampling Techniques

The study area was purposively selected to represent characteristic forest patches of the Southwest Ethiopian Highlands. Because questions of community assembly and species–environment relationships require sampling designs that capture ecological heterogeneity, a systematic layout was chosen to reduce spatial bias. Five parallel transects were laid out at 300-m intervals, ensuring coverage of topographic and disturbance gradients. Along each transect, 24 quadrats of 20 m × 20 m (400 m²) were placed at 300-m intervals, yielding a total of 120 vegetation plots (5 transects × 24 quadrats).

Data Collection

All woody plant species in each 20 m × 20 m quadrat were recorded, with scientific and local names, abundance, and visually estimated cover. To allow comparison of species dominance patterns in relation to environmental filtering, percentage cover values were converted to the ordinal Braun-Blanquet scale (van der Maarel, 1979; Kent & Coker, 1992): 1 ≤ 0.1 %, 2 = 0.1–1 %, 3 = 1–2 %, 4 = 2–5 %, 5 = 5–10 %, 6 = 10–25 %, 7 = 25–50 %, 8 = 50–75 %, 9 > 75 %. Community names were assigned based on indicator species, species constancy, and fidelity.

Environmental variables relevant to community assembly altitude, slope, aspect, latitude, and longitude were measured for each plot. Altitude and geographic coordinates were recorded using a handheld GPS. Slope was measured with a Suunto clinometer. Aspect was coded following Woldu (2012): N = 0, NE = 1, E = 2, SE = 3, S = 4, SW = 3.3, W = 2.5, NW = 1.3. Disturbance type and intensity were assessed in each quadrat using the scale developed by Leul (2015), ranging from 0 (no indication of disturbance) to 3 (heavy disturbance based on stumps, logs, and fuelwood extraction).

To examine how edaphic factors shape community variation, soil samples (200 g) from 0 – 15 cm and 16–30 cm depths were collected from the four corners of each quadrat using an auger with ‘1–30 cm depths were collected from the four corners and one from the centre of each quadrat using an auger. Samples from each depth were composited, placed in sterile polyethylene bags, and transported to the Arba Minch University soil laboratory. After removing debris and shade drying, samples were analyzed for texture, pH, electrical conductivity (EC), organic matter (OM), and macronutrients (N, P, K) using standard procedures (Nelson & Sommers, 1996).

Data Analyses

Cluster Analysis and Ordination

To identify coherent plant communities and their ecological differentiation, both classification and ordination were applied. Agglomerative hierarchical clustering, using Euclidean distance and Ward’s method, was used to classify plots based on abundance data (Kent, 2012). The optimal number of clusters was determined using the elbow and silhouette criteria.

Ordination was used to link community structure to environmental gradients relevant to filtering processes. Canonical Correspondence Analysis (CCA) was performed using Bray–Curtis dissimilarity to examine species environment relationships and compositional turnover. All analyses were run in R using the *vegan* package (R Core Team, 2016; Oksanen *et al.*, 2019).

Diversity and Similarity

To evaluate how diversity patterns vary along environmental and disturbance gradients, Shannon–Wiener diversity (Shannon & Wiener, 1949) and Pielou’s evenness (Pielou, 1966) were calculated:

$$\text{Shannon diversity index (H')} = -\sum \text{Pi} \ln \text{Pi} \dots\dots\dots (1)$$

Where, $\text{Pi} = \text{Ni}/\text{N}$, Ni = number of individuals of species i ; $\ln$ = natural logarithm, N = total number of individuals of all species.

Evenness was calculated as:

$$\text{Evenness index (E)} = \text{H}'/\ln \text{S} \dots\dots\dots (2)$$

Where, E = evenness index, H' = Shannon diversity index, S = number of species, $\ln$ = natural logarithm. Evenness indicates how even the species are distributed in the forest with values ranging from 0 to 1, where 1 means an equal distribution and values approaching 0 mean unequal distribution.

Sorensen’s similarity coefficient was used to quantify floristic resemblance among communities:

$$\text{Ss} = \frac{2a}{2a+b+c}$$

Where;

Ss = Sorensen’s similarity coefficient; a = number of species common to both communities;

b = number of species in community 1; c = number of species in community 2

These indices were used to assess whether communities with different environmental conditions or disturbance intensities showed predictable differences in richness or even distribution—patterns relevant to biodiversity environment interactions.

Community Classification

To refine vegetation classification and reduce distortion in clustering outcomes, outlier plots were identified and excluded following Kent (2012). A similarity ratio was used as the compositional measure, and Ward’s linkage minimized variance within clusters (Woldu, 2012). A synoptic table was then developed; with synoptic values computed as frequency $\times$ mean cover, enabling clear identification of dominant or character species for naming the community types.

Ordination of Vegetation and Environmental Variables

To determine the appropriate ordination model for analyzing community–environment relationships, a preliminary Detrended Correspondence Analysis (DCA) was run to estimate gradient lengths (Leps & Smilauer, 2003). Since gradient lengths exceeded 3 SD units, Canonical Correspondence Analysis (CCA) was selected as the primary constrained ordination method (Kent, 2012). Prior to the final CCA, Monte Carlo permutation tests and Adonis analyses identified the environmental variables that significantly explained variation in species composition. The final CCA was based on all 120 plots, 60 woody species, and the measured environmental variables. All ordinations were run in R (version 4.3.0).

RESULTS

Floristic Composition and Species Accumulation Curve

A total of 60 woody species, representing 55 genera and 33 families, were recorded. The Rubiaceae was the richest family (5 species, 8.2 %), followed by Malvaceae (4 species, 6.56 %). Woody vegetation was dominated by shrubs (35 species), while trees accounted for 25 species, indicating a structurally mixed system typical of montane forests under varying disturbance regimes.

Plant Community Structure

Hierarchical cluster analysis resolved the plots into four distinct communities, each supported by Indicator Species Analysis (Fig. 2; Table 1). Clear compositional turnover was observed across the clusters, reflected in several strong indicator species.

Community 1: *Syzygium guineense* – *Schefflera abyssinica* Community

This community (9 plots; 2163–2429 m a.s.l) consisted of 47 species and exhibited $H' = 3.35$ and evenness = 0.86. *Syzygium guineense* (IV = 8.22) and *Schefflera abyssinica* (IV = 5.67) showed high fidelity and abundance.

Community 2: *Myrsine melanophloeos* – *Ekebergia capensis* Community

The largest community (63 plots; 2380–2966 m a.s.l) contained 57 species, with the highest diversity ($H' = 3.81$) and evenness (0.94). *Myrsine melanophloeos* (1.86) and *Ekebergia capensis* (1.00) were the principal indicators.

Community 3: *Hagenia abyssinica* – *Vepris dainellii* Community

Comprising 19 plots (2510–2980 m a.s.l), this community consisted of 37 species, with $H' = 3.28$ and evenness = 0.92. *Hagenia abyssinica* (7.00) and *Vepris dainellii* (1.84) defined this cluster.

Community 4: *Polyscias fulva* – *Dombeya torrida* Community

This community (29 plots; 2605–2983 m a.s.l) supported 35 species, $H' = 3.10$, and evenness = 0.85. High indicator values were recorded for *Polyscias fulva* (8.28) and *Dombeya torrida* (1.97).

Summary statistics for richness and diversity are shown in Table 2.

Table 1: Indicator species values for woody species across four plant communities.

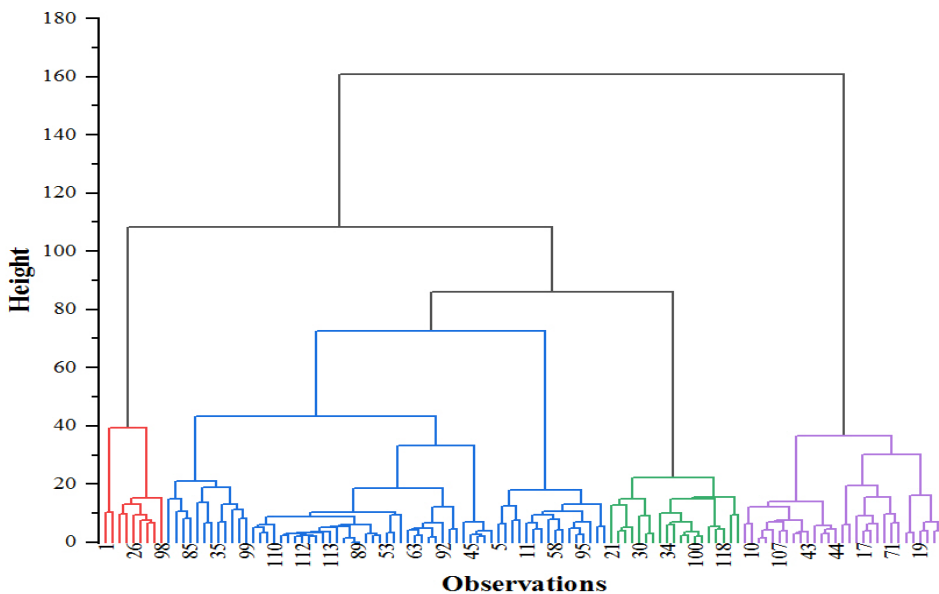
Key: Community 1, 2, 3 & 4. Each community is named by the species with highest values.' with 'Synoptic abundance values of woody species across plant communities in Damota Forest.

Species	Community 1	Community 2	Community 3	Community 4
<i>Syzygium guineense</i> (Willd.) DC.	8.22	0.60	0	0
<i>Schefflera abyssinica</i> (Hochst. ex A.Rich.) Harms	5.67	0.16	0	0
<i>Prunus africana</i> (Hook.f.) Kalkman	4.89	0.17	0	0
<i>Croton macrostachyus</i> Hochst. ex Delile	4.78	0.21	0	0
<i>Millettia ferruginea</i> (Hochst.) Baker	4.67	0	0	0
<i>Cordia africana</i> Lam.	2.56	0.41	0	0
<i>Polyscias fulva</i> (Hiern) Harms	2.33	0.37	0	8.28
<i>Apodytes dimidiata</i> E.Mey. ex Arn.	2.22	0.21	0.58	0
<i>Ekebergia capensis</i> Sparrm.	2	1.00	0.47	1.69
<i>Erythrina brucei</i> Schweinf.	1.56	0.51	0.21	0

<i>Dracaena steudneri</i> Engl.	1.44	0.39	0.37	1.31
<i>Maesa lanceolata</i> Forssk.	1.22	0.49	0.21	0.34
<i>Bridelia micrantha</i> (Hochst.) Baill.	1.11	0.29	0	0
<i>Myrsine melanophloeos</i> (L.) R.Br.	0.89	1.86	0.84	0.79
<i>Hagenia abyssinica</i> (Bruce) J.F.Gmel.	0.78	0.08	7	0
<i>Ilex mitis</i> (L.) Radlk.	0.78	0.57	0.32	1.14
<i>Inga vera</i> Willd.	0.67	0.43	0.16	0.14
<i>Lepidotrichilia volkensii</i> (Gurke) Leroy	0.56	0.11	0.05	0.14
<i>Premna oligotricha</i> (Briq.) C.Y.Wu & B.L.Chen	0.56	0.08	0	0
<i>Sida ovata</i> Forssk.	0.56	0.35	0.21	0.14
<i>Buddleja polystachya</i> Fresen.	0.44	0.02	0	0
<i>Clerodendrum alatum</i> Wall.	0.44	0.17	0.37	0.24
<i>Hypericum revolutum</i> Vahl	0.44	0.27	0.58	0.48
<i>Oxyanthus speciosus</i> DC.	0.44	0.22	0.63	0
<i>Vernonia amygdalina</i> Delile	0.44	0.09	0	0
<i>Agarista salicifolia</i> (Lam.) G.Don	0.33	0.16	0	0
<i>Brucea antidysenterica</i> J.F.Mill.	0.33	0.22	0.05	0
<i>Galineria saxifraga</i> L.	0.33	0.13	0.42	0.34
<i>Murraya koenigii</i> (L.) Spreng.	0.33	0.60	0	0.31
<i>Rhamnus prinoides</i> L Her.	0.33	0.22	0.05	0.28
<i>Triumfetta tomentosa</i> Bojer	0.33	0.22	0.47	0.38
<i>Clausena anisata</i> (Willd.) Hook.f. ex Benth.	0.22	0.32	0.05	0.286
<i>Clutia lanceolata</i> Forssk.	0.22	0.13	0	0
<i>Embelia schimperi</i> Vatke	0.22	0.27	0.11	0.21
<i>Pentas schimperiana</i> (A.Rich.) Vatke	0.22	0.29	0.21	0.31
<i>Phyllanthus sepialis</i> Müll.Arg.	0.22	0.13	0	0
<i>Phytolacca dodecandra</i> L'Hér.	0.22	0.05	0	0
<i>Rhus natalensis</i> Bernh. ex Krauss	0.22	0.02	0	0.10
<i>Solanum torvum</i> Sw.	0.22	0.24	0.26	0.31
<i>Vernonanthura tweedieana</i> (Baker) H.Rob.	0.22	0.09	0	0.24
<i>Vernonia adoensis</i> Sch.Bip. ex Walp.	0.22	0.16	0.26	0.31
<i>Cestrum nocturnum</i> L.	0.11	0.24	0.11	0
<i>Dracaena fragrans</i> (L.) Ker Gawl.	0.11	0.16	0.42	0.31
<i>Rytigynia neglecta</i> (Hiern) Robyns	0.11	0.21	0.21	0.17
<i>Acanthus sennii</i> Chiov.	0	0.14	0	0
<i>Arundinaria alpina</i> K.Schum.	0	0.17	0.47	0.14
<i>Dombeya burgessiae</i> Gerrard ex Harv.	0	0.35	0	1.07

<i>Erica arborea</i> L.	0	0.05	0.05	0.03
<i>Maytenus gracilipes</i> (Welw. ex Oliv.) Exell	0	0.13	0.05	0
<i>Nuxia congesta</i> R.Br. ex Fresen.	0	0.16	0	0
<i>Pavetta abyssinica</i> Fresen.	0	0.27	0.16	0.28
<i>Pouteria adolfi-friederici</i> (Engl.) Baehni	0	0	0.37	1.8
<i>Rhus glutinosa</i> A.Rich.	0	0.13	0.05	0.10
<i>Rubus steudneri</i> Schweinf.	0	0.14	0.11	0.03
<i>Schrebera alata</i> (Hochst.) Welw.	0	0.13	0	0
<i>Sida tenuicarpa</i> Vollesen	0	0.06	0	0.28
<i>Sparrmannia ricinocarpa</i> (Eckl. & Zeyh.) Kuntze	0	0.13	0.37	0.31
<i>Dombeya torrida</i> (J.F.Gmel.) Bamps	0	0.17	0.95	1.97
<i>Tetradenia urticifolia</i> (Baker) Phillipson	0	0	0.11	0.14
<i>Vepris dainellii</i> Pichi-Serm.	0	0.59	1.84	0.59

Fig. 2: Dendrogram generated from hierarchical cluster analysis.



Species Richness, Shannon Diversity, and Evenness

Species richness and diversity varied among communities (Table 2). Community 2 showed the highest richness and diversity, while Community 4 exhibited the lowest richness but maintained relatively high evenness. The overall Shannon diversity of the forest was $H' = 3.50$, with an evenness of 0.93, indicating consistently high species distribution equity across plots. Species richness of woody plant species recorded per plot, values are

summarized as the mean across all plots within each community type for comparative analysis.

Table 2: The communities, plots, mean species richness (S), diversity (H'), and evenness (J).

Community	No of plots	Altitudinal range (m)	Species richness (S)	Shannon diversity (H')	Evenness (J)
1	9	2163–2429	47	3.35	0.86
2	63	2380–2966	57	3.81	0.94
3	19	2510–2980	37	3.28	0.92
4	29	2605–2983	35	3.10	0.85
Overall H'				3.5	0.93

Sorensen's Similarity among Communities

Sorensen's similarity coefficients (Table 3) indicated moderate overlap among communities in Damota Forest. The highest similarity was between Communities 1 and 4 (0.357), suggesting shared species under partially overlapping environmental conditions. The lowest similarity (0.113) occurred between Communities 1 and 2, reflecting marked compositional differentiation along the altitudinal and disturbance gradients.

Table 3: Sorensen's similarity index between communities.

	1	2	3
2	0.1132075		
3	0.3023256	0.2500000	
4	0.3571429	0.2765957	0.1621622

Environmental variables significantly associated with the canonical axes.

Of the 13 variables tested, four were significantly associated with CCA axes (Table 4). Altitude ($r^2 = 0.6367$, $p = 0.001$) exerted the strongest influence, aligning with the primary gradient in species turnover. Disturbance ($r^2 = 0.2756$, $p = 0.001$) also showed clear structuring effects. Calcium (Ca) and potassium (K) were significantly related to secondary axes, indicating contributions of soil chemistry to community differentiation.

Table 4: Correlation of environmental variables with the first two axes (CCA1 and CCA2).

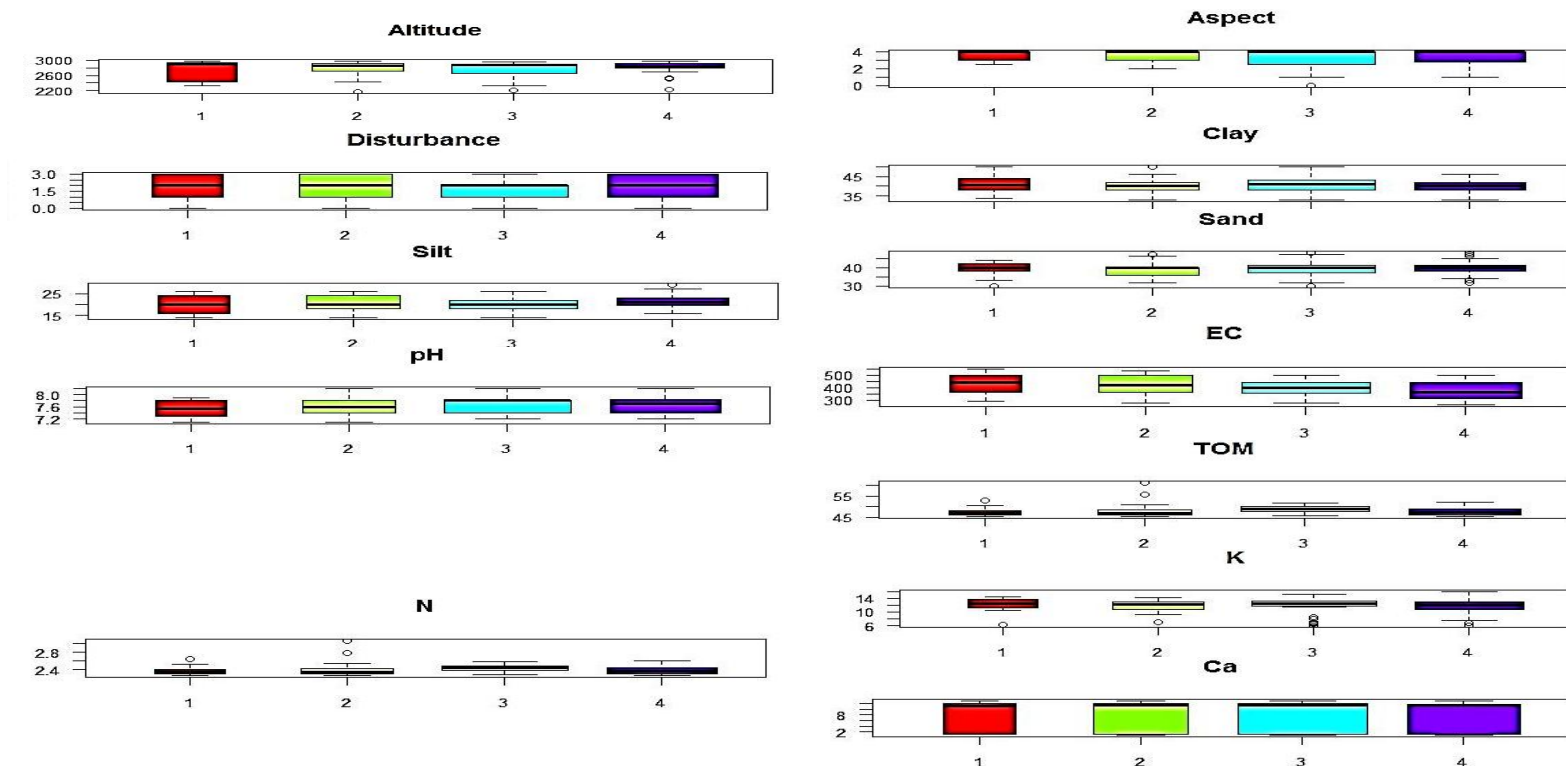
Environmental Variable	CCA1	CCA2	r^2 (Explained Variation)	Significance
Altitude	0.98816	-0.15343	0.6367	$p = 0.001^*$
Disturbance	-0.99811	-0.06150	0.2756	$p = 0.001^*$
Calcium (Ca)	0.58914	0.80803	0.1851	$p = 0.001^*$
Potassium (K)	0.95649	0.29177	0.0608	$p = 0.044^*$

Community-environment variables relationship

The box plots (Figure 3) revealed differences in environmental variables among the four types of plant communities. There was a distinct pattern concerning altitude, with Community 1 found at lower elevations, while Communities 3 and 4 tended to be located at higher altitudes. Levels of disturbance varied between communities, with Community 1 showing notably higher disturbance numbers. On the other hand, the variables related to soil texture (clay, sand, and silt) and aspect displayed only minor variations among the communities. These findings suggest that altitude and soil nutrient variables are crucial in distinguishing the different plant community types, while soil texture and aspect have a lesser impact on community variation.

Fig. 3: Variation of environmental variables among four woody plant community types in Damota forest patches.

The x-axis (1-4) represents community types (Communit1–Communit4). The y-axis represents the measured environmental variables: altitude (m), aspect (°), disturbance index, soil texture components (clay, sand, and silt, %), soil pH, electrical conductivity (EC, $\mu\text{S}/\text{cm}$), total nitrogen (N, %), total organic matter (TOM, %), potassium (K, mg/kg), and calcium (Ca, mg/kg). Boxplots display the median (central line), interquartile range (box), and variability (whiskers and outliers).



DISCUSSION

Floristic Composition and Growth-Form Patterns

The woody flora of Damota Forest includes 60 species across 55 genera and 33 families, a diversity level comparable to other Ethiopian Afromontane forests. Rubiaceae is the most species-rich family, a trend commonly observed in montane systems where ecological breadth, shade tolerance, and flexible regeneration strategies facilitate persistence in heterogeneous microhabitats (Tesfaye *et al.*, 2020; Wondimu *et al.*, 2021). Malvaceae is also well represented, consistent with its broad ecological amplitude in tropical and subtropical regions (Tadesse & Dagne, 2020). The dominance of these families indicates that lineages with broad environmental tolerances and effective dispersal mechanisms are favored under montane climatic variability. The floristic structure, characterized by many families represented by a single species and a few by multiple species, exemplifies a typical tropical pattern of high phylogenetic breadth but uneven species distribution (Aerts *et al.*, 2011; Desta *et al.*, 2023). This skewed representation suggests non-random assembly processes. Community composition is shaped primarily by environmental filtering, where only species with functional traits suited to local climatic and edaphic conditions persist (Keddy, 1992; Kraft *et al.*, 2015).

The distribution of growth forms supports this interpretation. Shrubs are more numerous than trees, a pattern consistent with other Ethiopian mid- and upper-montane forests (Gurmessa *et al.*, 2012; Tadele *et al.*, 2013; Mewded *et al.*, 2021). Shrubs generally demonstrate rapid regeneration, early reproduction, and tolerance to variable light and disturbance. In the presence of canopy gaps, grazing, and selective extraction, shrub dominance reflects resilience driven by specific traits rather than random demographic changes (Mensah *et al.*, 2020; Chala *et al.*, 2022). Collectively, floristic composition and growth-form patterns indicate that trait-based ecological sorting operates across environmental gradients. This observation is consistent with phylogenetic niche conservatism theory, which suggests that evolutionary lineages retain ancestral ecological traits that constrain current distributions (Wiens, 2004; Wiens & Graham, 2005). Damota Forest is therefore structured by both contemporary environmental filters and long-term evolutionary constraints.

Plant Community Classification and Indicator Species

The identification of four woody plant communities: *Syzygium guineense*–*Schefflera abyssinica*, *Myrsine melanophloeos*–*Ekebergia capensis*, *Hagenia abyssinica*–*Vepris dainellii*, and *Polyscias fulva*–*Dombeya torrida* captures a clear ecological gradient primarily structured by altitude and disturbance intensity.

The lower to mid-montane *Syzygium guineense*–*Schefflera abyssinica* community occurs under relatively stable moisture and reduced anthropogenic influence, supporting high richness and evenness. Such conditions favor late-successional, shade-tolerant taxa and reflect strong climatic buffering. The *Myrsine melanophloeos*–*Ekebergia capensis* community, located at mid-altitudes, exhibited peak diversity and evenness. Mid-altitude zones often maximize coexistence because they combine favorable thermal regimes with environmental heterogeneity, facilitating niche partitioning and reduced competitive exclusion (Rahbek, 1995; McCain, 2009). These areas function as ecological transition belts where species from adjacent altitudinal zones overlap.

The upper-montane *Hagenia abyssinica*–*Vepris dainellii* community reflects intensified abiotic filtering. Lower temperatures, reduced atmospheric pressure, and shorter growing seasons impose physiological constraints on plant metabolism, water transport efficiency, and reproductive timing (Korner, 2007; 2021). Only species possessing cold tolerance,

efficient nutrient use, and conservative growth strategies persist, explaining reduced richness. The *Polyscias fulva*–*Dombeya torrida* community is strongly associated with disturbance. Disturbance resets successional trajectories, alters competitive hierarchies, and promotes light-demanding or pioneer species (Connell, 1978; Ahmed *et al.*, 2022). This community, therefore, reflects dynamic equilibrium rather than climatic zonation alone. Together, these communities represent alternative ecological states produced by the interaction of macroclimatic gradients and disturbance-mediated successional dynamics.

Species Richness, Diversity, and Evenness

The unimodal richness pattern peaking at mid-altitude supports both geometric constraints (mid-domain effect) and ecological transition theory. However, purely geometric explanations are insufficient. Mid-altitudes also combine moderate temperatures, adequate moisture, and soil fertility conditions that optimize photosynthesis and nutrient cycling. These conditions reduce physiological stress while maintaining heterogeneity, facilitating species coexistence through niche complementarity. Declines at higher altitudes likely reflect metabolic constraints imposed by lower temperatures and nutrient mineralization rates (Bruun *et al.*, 2006; Korner, 2007). Reduced microbial activity limits nitrogen and phosphorus availability, constraining productivity and competitive diversity. High evenness across communities indicates limited dominance and suggests that resource partitioning rather than competitive exclusion governs species abundances. Such a balance often characterizes systems structured by multiple interacting environmental filters rather than a single overriding gradient.

Floristic Similarity

Low Sorensen similarity values indicate strong species turnover across relatively short distances. High beta-diversity is expected in montane systems where steep altitudinal gradients compress climatic zones spatially (Korner, 2007). Environmental heterogeneity restricts species to narrow realized niches, while limited dispersal connectivity further reinforces compositional differentiation (Leibold *et al.*, 2004). From a conservation perspective, high turnover implies that protecting a single altitudinal band would inadequately capture the forest's functional and phylogenetic diversity. Biodiversity conservation must therefore consider the full altitudinal continuum.

Community–Environment Relationships

CCA results confirm altitude as the dominant structuring variable ($r^2 = 0.64$, $p = 0.001$). Altitude integrates multiple correlated drivers, including temperature decline, changes in vapor pressure deficit, cloud dynamics, and soil development, making it a master environmental gradient (Jenny, 1994; Korner, 2021). Its strong explanatory power reflects cumulative physiological constraints on plant performance across the altitudinal range.

Disturbance ($r^2 = 0.28$, $p = 0.001$) represents a secondary but influential structuring force. By altering light availability, soil structure, and regeneration niches, disturbance modifies competitive hierarchies and recruitment dynamics. This pattern is consistent with intermediate disturbance theory and successional models predicting shifts toward pioneer or stress-tolerant taxa under repeated perturbation (Connell, 1978). Soil variables, including pH, phosphorus, calcium, and potassium, contributed to additional fine-scale differentiation. Soil pH regulates nutrient solubility and microbial activity, thereby influencing nutrient uptake efficiency (Neina, 2019). Phosphorus, frequently limiting in tropical soils, constrains productivity and reproductive allocation. Variation in calcium and potassium availability

provides mechanistic explanations for compositional shifts, given their central roles in structural stability, osmotic regulation, and stress tolerance. A high proportion of constrained variance explained by the first canonical axis indicates deterministic structuring along a dominant environmental gradient rather than stochastic assembly (ter Braak, 1986; Legendre & Legendre, 2012). When a single axis captures a large share of variation, species distributions are interpreted as coherent responses to underlying climatic or edaphic drivers (Borcard *et al.*, 2018). Such axis dominance is characteristic of montane systems structured primarily by altitudinal climatic gradients (Korner, 2007; Sundqvist *et al.*, 2013).

Edaphic Filters

Calcium plays fundamental structural and signaling roles in plant physiology, stabilizing cell walls, maintaining membrane integrity, and mediating stress responses. Variation in Ca availability influences competitive ability and drought tolerance, and in montane systems often reflects differences in parent material and weathering intensity, thereby generating persistent edaphic niches. Potassium regulates stomatal conductance, osmotic balance, and enzyme activation, directly affecting water-use efficiency and photosynthetic performance. Where K is limited, species with conservative growth strategies are favored. Differences in Ca and K availability, therefore, act as physiological filters, sorting species according to nutrient-use strategies and reinforcing niche partitioning at local scales. Nutrient-mediated community differentiation is well established in trait-based ecology, where variation in soil cations shapes plant functional strategies and competitive hierarchies (Chapin *et al.*, 2002; Laliberté *et al.*, 2013). Empirical studies link calcium gradients to shifts in species composition through their effects on structural stability and stress tolerance (White & Broadley, 2003), while potassium availability influences drought resistance via stomatal regulation (Marschner, 2012). Such edaphic filtering mechanisms operate beneath broader climatic gradients, refining community composition through trait-mediated responses (Keddy, 1992; Kraft *et al.*, 2015).

Hierarchical Environmental Filters

Across analyses, a hierarchical filtering framework emerges. Altitude establishes broad physiological limits, structuring macroclimatic constraints. Soil chemistry (Ca, K, P, pH) refines species sorting through nutrient-mediated trade-offs in growth and stress tolerance, while disturbance modulates successional trajectories and competitive hierarchies at local scales. This multi-layered structure aligns with trait-based and metacommunity models of community assembly that emphasize sequential, multi-scale filtering across environmental gradients (Keddy, 1992; Leibold *et al.*, 2004; Kraft & Ackerly, 2010; Kraft *et al.*, 2015; Vellend, 2016). In montane ecosystems, macroclimatic constraints typically dominate broad spatial patterns, whereas soil chemistry and disturbance regulate fine-scale coexistence dynamics (Korner, 2007; Sundqvist *et al.*, 2013; Korner, 2021). Accordingly, biodiversity patterns in Damota Forest are best interpreted as the outcome of interacting, edaphic, and anthropogenic filters operating across spatial scales. The distinct communities, mid-altitude diversity peak, and high beta-diversity collectively indicate deterministic ecological structuring rather than random assembly. The forest's conservation significance, therefore, lies not only in species richness but in maintaining the environmental gradients that sustain functional and phylogenetic diversity across the Afromontane landscape.

Above all, Damota Forest harbors a uniquely diverse and phylogenetically distinctive woody species community shaped by the interplay of altitude, soil chemistry, and disturbance. Mid-altitude zones emerge as biodiversity hotspots where overlapping species pools, trait-mediated niche partitioning, and balanced growth-form distributions maximize

richness and evenness. Hierarchical environmental filtering from macroclimatic constraints to edaphic gradients and local disturbance drives deterministic community assembly, producing high diversity and distinct plant communities across short distances. By integrating floristic, functional, and multivariate environmental analyses, this study provides novel insights into montane community structuring, highlights the forest's ecological uniqueness, and offers actionable guidance for conservation and restoration strategies that preserve both functional and phylogenetic diversity across the Afromontane landscape.

Vegetation patterns in Damota Forest are influenced not only by ecological gradients but also by spatially structured human activities. Each plant community reflects specific land-use pressures along the altitudinal gradient. The findings indicate that fine-scale vegetation classification serves as a direct indicator of human influence, establishing a novel connection between community ecology and applied socioecological processes.

CONCLUSION

This study demonstrates that Damota Forest functions as a well-organized montane system shaped by distinct environmental and ecological gradients, rather than a random assemblage of woody plants. The four community types identified, *Syzygium guineense* – *Schefflera abyssinica*, *Myrsine melanophloeos*–*Ekebergia capensis*, *Hagenia abyssinica*–*Vepris dainellii*, and *Polyscias fulva*–*Dombeya torrida*, represent recurring combinations of species that sort predictably along variations in altitude, soil properties, and disturbance regimes. The dominance of shrub life-forms, together with the clear contrasts in species richness, diversity, and evenness among communities, underscores how differences in life-history traits and environmental constraints jointly influence forest structure. Species richness and diversity were highest at mid-elevations, particularly within the *Myrsine melanophloeos*–*Ekebergia capensis* community. This pattern reinforces the view that mid-altitude zones act as ecological meeting grounds, offering moderate temperatures and favorable soil conditions that allow species with different ecological backgrounds to coexist. At the same time, the strong turnover in species composition across the forest highlights the contribution of local heterogeneity: altitudinal shifts, soil variation, and contrasting disturbance histories each sustain distinct plant assemblages that collectively shape the forest's biodiversity. These findings carry important implications for conservation planning. First, protecting only single altitudinal gradients would risk overlooking the unique species pools maintained in other zones. Second, management strategies must acknowledge fine-scale variation in soils and microhabitats, as these factors help maintain the integrity and resilience of each community. Third, long-term ecological monitoring is essential. Altitudinal change and ongoing anthropogenic disturbances may alter species distributions, shift community boundaries, or disrupt regeneration processes. The patterns documented here provide a baseline against which such changes can be detected, including the potential upward expansion of low-elevation species or the decline of taxa restricted to higher altitudes. Overall, Damota Forest exemplifies how Afromontane vegetation in Ethiopia is shaped by the interaction of environmental gradients such as soil conditions and disturbance history. Conserving this complexity across floristic, functional, and community levels is key for maintaining ecological processes, safeguarding biodiversity, and ensuring the forest's resilience as environmental pressures intensify.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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