Journal homepage: http:/www.indianecol.org

Indian Journal of Ecology

DOI: https://doi.org/10.55362/IJECOL/2026/0125
Article Number: 0000

Functional Group Dynamics and Community Composition of Forests in the Northwestern Himalayan Foothills in Haryana, India

Ravi Kumar[1]*, Kushal[2], Subrata Nandy[3] and Balkar Singh[4]

[1]Department of Botany, S.D. PG College, Panipat - 132 103, Kurukshetra University, Kurukshetra-136 119, India
[2]Department of Botany, Kurukshetra University, Kurukshetra-136 119, India
[3]Indian Institute of Remote Sensing, ISRO, Dehradun- 248 001, India
[4]Department of Botany, Arya PG College, Panipat-132 103, Kurukshetra University, Kurukshetra-136 119, India

* Corresponding Author. Email: ravikumarbotanykuk24@gmail.com

https://orcid.org/0009-0001-3121-9414 (R. Kumar)

Received: April 11, 2026 Revision Submitted: July 02, 2026 Accepted: July 11, 2026

ABSTRACT: Forest ecosystems in the north-western Himalayan Shivalik foothills exhibit high environmental heterogeneity, resulting in complex patterns of species composition, vegetation structure, and ecological functioning. The present study investigated floristic composition, vegetation structure, and functional group dynamics across six forest types in the Yamunanagar (YFD) & Panchkula (PFD) Forest Divisions of Haryana, and assessed species diversity, community organisation, and population structure. A total of 137 plant species belonging to 61 families were recorded. Poaceae was the most species-rich family, followed by Asteraceae and Fabaceae. Dominance–diversity analysis identified *Shorea robusta* C.F. Gaertn. and *Mallotus philippensis* (Lam.) Müll. Arg., *Senegalia catechu* (L.f.) P.J.H. Hurter &Mabb., and *Pinus roxburghii* Sarg. as the dominant tree species across different forest types, while *Lantana camara* L. consistently dominated as the shrub layer. *Heteropogon contortus* (L.) P. Beauv. and *Achyranthes aspera* L. were the most abundant herb species, whereas *Ichnocarpus frutescens* (L.) W.T. Aiton and *Pueraria tuberosa* (Roxb. ex Willd.) DC. predominated among climbers. The Shannon–Wiener diversity index (H′) for trees ranged from 1.237 in subtropical pine forests to 2.510 in mixed deciduous forests of PFD, while Margalef's species richness index varied from 1.744 to 7.440. The concentration of dominance (Cd) ranged from 0.103 to 0.455, with lower values in mixed deciduous forests indicating greater species evenness. Dominance–diversity curves exhibited a log-normal distribution, reflecting balanced niche partitioning. The study demonstrates moderate to high species diversity and considerable compositional heterogeneity among forest types. These findings provide a valuable ecological baseline for long-term biodiversity monitoring, in the north-western Himalayan foothills.

Keywords: Phytodiversity, Community composition, Abundance, Species richness, Diversity indices.

1. INTRODUCTION

Forests are among the richest and most complex terrestrial ecosystems, supporting a variety of life forms and possessing a tremendous intrinsic ability for self-maintenance. Tropical dry deciduous forests occupy approximately 38–41% of total forest area throughout India (Dixit, 1997; ISFR, 2021). Tropical forests are often referred to the most species-diverse terrestrial ecosystems and provide a variety of natural resources to help sustain the livelihoods of local communities (Kumar et al., 2006). These forests are disappearing at alarming rates due to deforestation for the extraction of timber and other forest products (Murphy & Lugo, 1986; Raghubanshi & Tripathi,

Available online: July 22, 2026

2009; Kushwaha et al., 2018; Bhuyan et al., 2025; Mesa-Sierra et al., 2025). However, many of these forests are losing their resilience due to excessive biotic interference, such as anthropogenic disturbances and uncontrolled grazing. India is a large developing country known for its diverse forest ecosystems and biodiversity. According to the Global Forest Resource Assessment (GFRA, 2020) published by the FAO, India is ranked among the top 10 countries in the world in terms of forest area and holds the 3rd position for the highest annual net gain in forest cover between 2010 and 2020 (ISFR, 2023). The floristic composition of vegetation and species diversity reflect the gene pool and adaptation potential of a community (Odum, 1971). Many tropical forests are under great anthropogenic pressure and require management interventions to maintain overall biodiversity, productivity, and sustainability. Understanding species diversity and distribution patterns is important to help managers evaluate the complexity and resources of these forests. Quantitative floristic inventories have been used in recent years to characterize forest vegetation throughout the tropics (Johnston & Gillman, 1995; Kumar et al., 2011; Condit, 1996; Pascal & Pelissier, 1996; Ayyappan & Parthasarathy, 1999; Parthasarathy, 1999, 2001; Phillips et al., 2003; Kushwaha & Nandy, 2012; Mansingh et al., 2025; Chovatiya et al., 2025). Without data, it is impossible to test these competing claims, and it is imperative that tropical forests, which are rich in biological diversity, be studied intensively to investigate the complex interactions between biodiversity and ecosystem functioning.

With nearly 205250 villages classified as forest-adjoining, there is obviously a huge dependence of communities on forest resources (ISFR, 2021). Forest degradation is usually accompanied by species extinction, loss of biodiversity and decreasing primary productivity. Consequently, there is growing interest in quantifying habitat characteristics, i.e. forest structure, floristic composition, and species richness in Indian forests (Kumar et al., 1999, 2001, 2002; Gupta & Kumar, 2014; Singh et al., 2016; Yadav & Yadav, 2005; Chovatiya et al., 2025). In addition to sustaining biodiversity, tropical dry deciduous forests play a crucial role in climate regulation through carbon sequestration. However, anthropogenic disturbances may not only alter species composition but also influence carbon storage and greenhouse gas emissions, thereby linking biodiversity dynamics with climate change processes to develop and implement adaptation strategies both for biodiversity conservation and protection and for safe guarding the livelihoods of forest dependent people (Bonan, 2008; Pan, et al., 2011; Chaturvedi et al., 2011; Fisher et al., 2014; Gupta & Kumar, 2014; IPCC, 2022; Mansingh et al., 2025).

This study presents a detailed analysis of plant species richness, abundance, and diversity across different physiognomic units in the Shivalik landscape of the north-western Himalaya in Haryana, India, based on qualitative and quantitative analyses. The present study focuses specifically on the tropical dry deciduous forests of Haryana, which are a relatively underexplored region in terms of detailed ecological and floristic assessments. It is an effort to go beyond traditional species inventories by linking floristic diversity with functional attributes, thereby contributing to a deeper understanding of how biodiversity influences ecosystem processes and sustainability. In light of increasing anthropogenic pressures and the growing need for sustainable resource management, it is imperative to conduct comprehensive, data-driven studies on tropical forest ecosystems. By integrating floristic diversity, functional attributes, and disturbance dynamics, the present study aims to unravel the complex interactions that govern ecosystem structure and functioning in tropical dry deciduous forests of Haryana. Such insights are essential for developing effective conservation strategies and ensuring the long-term sustainability of these ecologically and economically vital ecosystems.

2. MATERIALS AND METHODS

2.1. Study Area

The study was performed in Shivalik ranges, the foot hills of North-western Himalaya, India located at 30° 00′ 00″ to 30° 30′ 00″N latitude and 70° 00′ 00″ to 77° 00′ 45″E longitudes in forests of Kalesar National Park in Yamunanagar Forest Division (YFD) and between longitude 76° 46′ 40″ to 77° 0′ 33″E and latitude 30° 40′50″ to 30° 54′ 40″N in reserved and protected forests of Panchkula Forest Divisions (PFD) (Figure 1). The altitude varies from 300 to 650 msl at Kalesar forest and 370 to 1100 m at Morni hills. The climate of the area is subtropical monsoonal. Average annual rainfall is1437 mm in Panchkula and 973mm in Yamunanagar district (HARSAC/CRID, Govt. of Haryana 2021a, 2021b). The Shivaliks are composed of alluvial detritus of the solidified and upheaved detritus of the great Himalayan range (Wadia, 1961) in northern India.

2.2. Sampling Design

A vegetation study was conducted in a stratified random manner in six forest types (Champion & Seth, 1968) covering Northern tropical dry deciduous *Shorea robusta* C.F. Gaertn. plain forests, Northern tropical dry deciduous Shivalik *Shorea robusta* C.F. Gaertn. forests, Mixed dry deciduous forests in YFD, Dry deciduous forests, Mixed dry deciduous forests, and Sub-tropical pine forests in PFD.

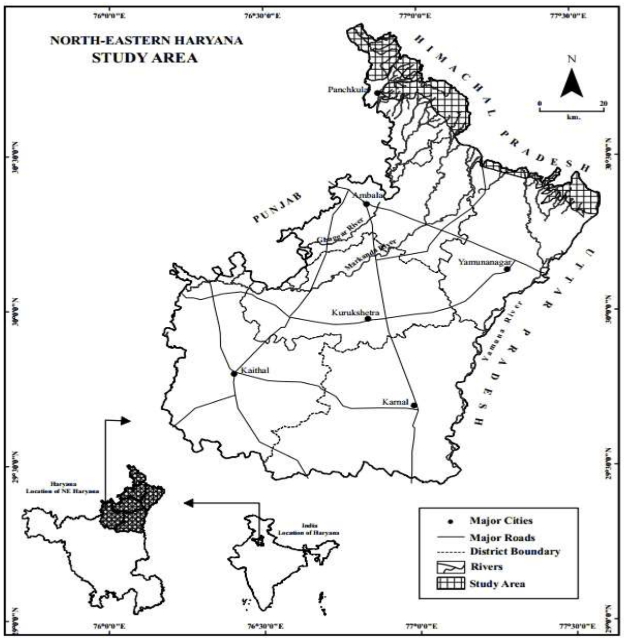

Figure 1. Location of the study site in Haryana. (The map has been prepared using ArcGIS software with appropriate Latitude/longitude demarcation of the studied sites)

Sampling was done in all the strata, i.e., trees, shrubs, & herbs. Twelve plots of 0.1ha for trees in each of the forest types, twenty-four plots of 5×5m for shrubs, and sixty plots of 1×1m for herbs were sampled within each forest type ecosystem using a stratified random sampling approach (Figure 2). Within each plot, saplings and shrubs were identified to species, and the number of individuals of each species was counted.

2.3. Vegetation Functional Group Sampling

The sampling design was to collect field data based on vegetation functional group type strata, i.e., trees, shrubs, herbs, and climbers, to collect macro-habitat-specific relative species abundance information along with other ecologically important variables. Hence, sampling was aimed at addressing the basic issues related to composition, structure, and function through appropriate distribution and intensity across spatial and temporal gradients at the landscape level. For season-specific vegetation, based on the field phenology, sampling was undertaken during rainy, winter, and summer seasons in order to cover the maximum number of occurrences.

2.4. Data Analysis

The collected data were quantitatively analyzed for density, frequency, and abundance according to (Curtis & McIntosh, 1951). Relative frequency, relative density, and relative dominance were calculated following (Phillips, 1959), and the sum of these numbers yielded the importance value index (IVI) of tree species following Curtis (1959). The abundance-to-frequency ratio (A/F) of different species

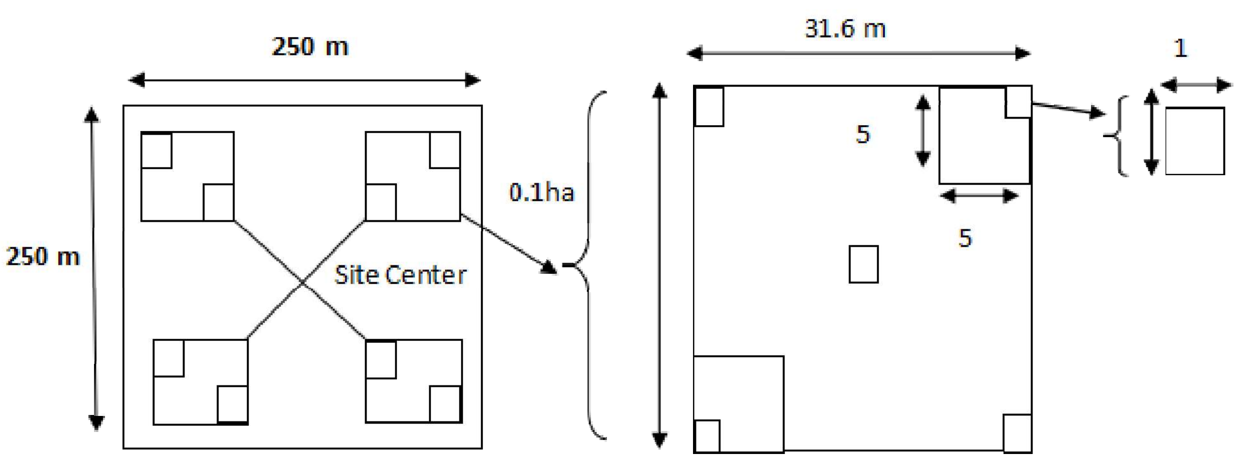

Figure 2. Stratified clustered sampling design. (The figure shows the stratified clustered sampling framework used to ensure representative sampling across different functional groups of the study area)

was computed to assess their distribution pattern of following Whitford (1949). The dominance – diversity curves of species of each site were plotted using log values of IVI and species sequence using Magurran (1988). Shannon-Wiener index of species diversity was computed for various plant species using equation 1. Concentration of dominance (C) was measured using equation 2. Equitability (e) was calculated following equation 3 and Margalef's index of Species richness (d) was calculated using equation 4.

Equation 1: Shannon–Wiener Diversity Index (Shannon & Weaver, 1949)

$$H' = -\sum_{i=1}^{S}\left(\frac{N_i}{N}\right)\ln\left(\frac{N_i}{N}\right)$$

Equation 2: Simpson's Concentration of Dominance (Simpson, 1949)

$$C = \sum_{i=1}^{S}\left(\frac{N_i}{N}\right)^2$$

Equation 3: Pielou's Equitability (Evenness) Index (Pielou, 1966)

$$E = \frac{H'}{\ln S}$$

Equation 4: Margalef's Species Richness Index (Margalef, 1958)

$$D = \frac{S-1}{\ln N}$$

3. RESULTS AND DISCUSSION

3.1. Floristic Composition and Vegetation Structure

The floristic composition and vegetation structure of the studied forest ecosystems, northern tropical dry deciduous plain *Shorea robusta* C.F. Gaertn. forests, northern tropical dry deciduous Shivalik *Shorea robusta* C.F. Gaertn. forests, mixed deciduous forests, dry deciduous forests, and subtropical pine forests revealed considerable spatial heterogeneity across the Yamunanagar Forest Division (YFD) and Panchkula Forest Division (PFD). The vegetation was stratified into four functional layers (trees, shrubs, herbs, and climbers), reflecting the characteristic patterns of tropical and subtropical forests (Figure 3).

A total of 137 plant species were recorded, including 82 species (38 families) in YFD and 111 species (51 families) in PFD, indicating moderately high species diversity (Table 1 & 2). This level of diversity aligns with earlier studies (Dixit, 1997; Kumar et al., 1999, 2001; Murphy & Lugo, 1986; Raghubanshi & Tripathy, 2009) in tropical dry deciduous forests, where environmental heterogeneity and resource variability promote species coexistence.

The dominance of families such as Poaceae, Asteraceae, and Fabaceae highlights the ecological significance of grasses and forbs in ground vegetation, particularly in nutrient cycling and soil stabilisation. The presence of several families represented by a single species suggests niche specialisation and uneven species distribution within these ecosystems. Mixed deciduous forests exhibited the highest species richness in both divisions, supporting the intermediate disturbance hypothesis, which suggests that moderate levels of disturbance enhance species diversity. In contrast, subtropical pine forests showed comparatively lower tree diversity but higher herbaceous diversity, likely

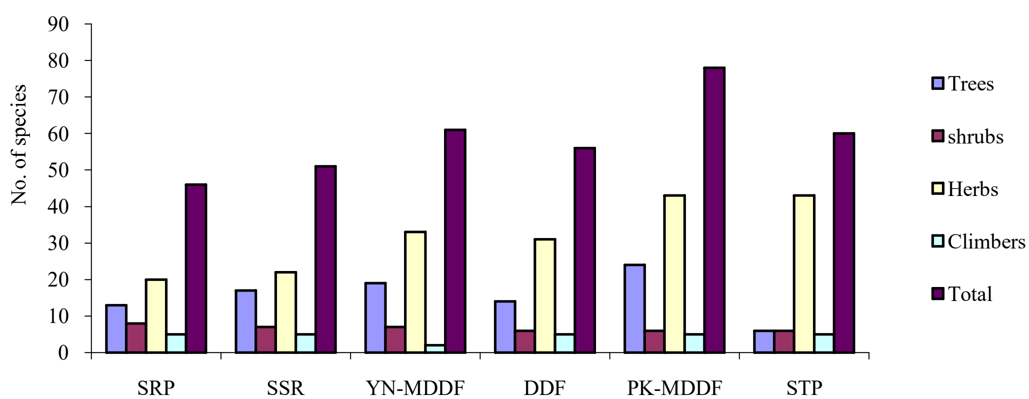

Figure 3. Distribution Patterns of different functional groups in the forests of North-western Himalayan foothills in Haryana. (The figure depicts variation in species richness among functional groups, indicating differential contributions of trees, shrubs, herbs, and climbers to overall forest biodiversity in six types of forest ecosystems studied)

Table 1. Floristic compositions of various functional groups at Yamunanagar Forest Division in Northwestern Himalayan Foothills in Haryana

Plant species	Family	IUCN	SSR	SRP	DDF
Trees					
Senegalia catechu (L.f.) P.J.H. Hurter & Mabb.	Fabaceae	(LC)	-	-	13.47
Aegle marmelos (L.) Corrêa	Rutaceae	(NT)	3.88	1.72	2.54
Terminalia anogeissiana Gere & Boatwr.	Combretaceae	(LC)	-	3.06	29.88
Bauhinia purpurea L.	Fabaceae	(LC)	-	-	6.98
Buchanania lanzan Spreng.	Anacardiaceae	(LC)	2.95	-	-
Casearia tomentosa Roxb.	Salicaceae	(LC)	1.18	3.61	9.28
Cassia fistula L.	Fabaceae	(LC)	9.99	3.51	17.75
Cordia dichotoma G. Forst.	Boraginaceae	(LC)	7.75	3.96	1.42
Diospyros montana Roxb.	Ebenaceae	(LC)	-	-	2.91
Diospyros exculpta Buch.-Ham.	Ebenaceae	(LC)	11.88	-	61.11
Ehretia aspera Willd.	Boraginaceae	(LC)	40.57	50.26	11.28
Ficus racemosa L.	Moraceae	(LC)	1.48	-	-
Ficus religiosa L.	Moraceae	(LC)	-	-	1.58
Garuga pinnata Roxb.	Burseraceae	(LC)	-	-	1.53
Grewia optiva J.R. Drumm. ex Burret	Malvaceae	(LC)	10.95	1.79	-
Holoptelea integrifolia (Roxb.) Planch.	Ulmaceae	(LC)	-	-	18.30
Kydia calycina Roxb.	Malvaceae	(LC)	-	1.80	6.55
Lannea coromandelica (Houtt.) Merr.	Anacardiaceae	(LC)	-	-	29.93
Litsea glutinosa (Lour.) C.B.Rob.	Lauraceae	(LC)	4.17	18.14	-
Mallotus philippensis (Lam.) Müll. Arg.	Euphorbiaceae	(LC)	85.27	74.98	6.04
Ougeinia oojeinensis (Roxb.) Hochr.	Fabaceae	(LC)	2.72	-	-
Catunaregam spinosa (Thunb.) Tirveng.	Rubiaceae	(LC)	7.94	-	52.59
Schleichera oleosa (Lour.) ken.	Sapindaceae	(LC)	7.45	5.61	-
Shorea robusta C.F. Gaertn.	Dipterocarpaceae	(LC)	76.69	127.89	19.94
Sterculia villosa Roxb. ex Sm.	Malvaceae	(LC)	12.18	1.91	2.34
Syzygium namosialangense Widodo & E. Lucas	Myrtaceae	(NE)	-	1.86	5.21
Terminalia elliptica Willd.	Combretaceae	(LC)	12.5	-	-
Shrubs					
Justicia adhatoda L.	Acanthaceae	(LC)	8.76	-	21.26
Callicarpa macrophylea Vahl	Lamiaceae	(LC)	4.13	-	41.42
Clerodendrum infortunatum L.	Lamiaceae	(LC)	-	40.02	-
Colebrookea oppositifolia Sm.	Lamiaceae	(LC)	45.60	54.01	12.83
Lantana camara L.	Verbenaceae	(LC)	158.83	141.65	102.66
Mirabilis jalapa L.	Nyctaginaceae	(NE)	-	-	13.56
Bergera koenigii L.	Rutaceae	(LC)	5.20	7.10	-
Nepeta graciflora Benth.	Lamiaceae	(NE)	72.16	50.51	34.12
Pogostemon plectranthoides Desf.	Lamiaceae	(NE)	-	6.71	-
Azanza lampas (Cav.) Alef.	Malvaceae	(LC)	5.32	-	74.15
Herbs					
Abutilon indicum (L.) Sweet	Malvaceae	(LC)	6.33	-	6.34
Achyranthes aspera L.	Amaranthaceae	(LC)	20.60	11.21	20.60
Adiantum capillus-veneris L.	Pteridaceae	(LC)	10.09	19.76	10.09
Aerva javanica (Burm.f.) Juss. ex Schult.	Amaranthaceae	(LC)	-	12.08	8.56
Ageratum conyzoides L.	Asteraceae	(LC)	8.12	-	4.48

Cont...

Table 1. Floristic compositions of various functional groups at Yamunanagar Forest Division in Northwestern Himalayan Foothills in Haryana

Plant species	Family	IUCN	SSR	SRP	DDF
Lysimachia arvensis (L.) U. Manns & Anderb.	Primulaceae	(LC)	12.20	10.19	-
Barleria cristata L.	Acanthaceae	(LC)	4.48	10.18	4.48
Bothriochloa ischaemum (L.) Keng	Poaceae	(LC)	4.12	15.02	-
Senna tora (L.) Roxb.	Fabaceae	(LC)	4.48	4.84	-
Cenchrus setigerus Vahl	Poaceae	(LC)	-	5.53	-
Enteropogon dolichostachyus (Lag.)	Poaceae	(NE)	7.58	13.16	-
Chrysopogon fulvus (Spreng.) Chiov.	Poaceae	(LC)	9.53	12.91	9.53
Commelina paludosa Blume	Commelinaceae	(LC)	4.05	8.23	-
Cynodon dactylon (L.) Pers.	Poaceae	(LC)	19.12	-	15.50
Cyperus rotundus L.	Cyperaceae	(LC)	17.83	-	15.55
Desmostachya bipinnata (L.) Stapf	Poaceae	(LC)	-	17.75	21.94
Eulaliopsis binata (Retz.) C.E. Hubb.	Poaceae	(LC)	23.56	13.81	2.02
Euphorbia hirta L.	Euphorbiaceae	(LC)	-	20.11	6.48
Heteropogon contortus (L.) P. Beauv.	Poaceae	(LC)	30.99	28.19	30.91
Holarrhena pubescens Wall. ex G. Don	Apocynaceae	(LC)	-	10.80	3.58
Mesosphaerum suaveolens (L.) Kuntze	Lamiaceae	(LC)	-	-	2.02
Indigofera heteracantha Wall. ex Brandis	Fabaceae	(LC)	-	23.11	4.48
Launaea procumbens (Roxb.) Ramayya & Rajagopal	Asteraceae	(LC)	-	-	2.02
Vicia lens (L.) Coss. & Germ.	Fabaceae	(NE)	-	-	2.53
Malvastrum coromandelianum (L.) Garcke	Malvaceae	(LC)	-	-	7.99
Parthenium hysterophorus L.	Asteraceae	(LC)	10	-	4.05
Dicliptera paniculata (Forssk.) I. Darbysh.	Acanthaceae	(LC)	20.91	-	6.82
Phyllanthus amarus Schumach. & Thonn	Phyllanthaceae	(LC)	5.54	-	-
Physalis angulata L.	Solanaceae	(LC)	16.73	-	6.82
Pluchea lanceolata (DC.) C.B. Clarke	Asteraceae	(LC)	-	-	5.54
Pupalia lappacea (L.) Juss.	Amaranthaceae	(LC)	-	-	16.73
Tripidium bengalense (Retz.) H.Scholz	Poaceae	(LC)	28.41	-	26.77
Sida ovata Forssk.	Malvaceae	(LC)	9.32	16.03	5.79
Tridax procumbens L.	Asteraceae	(LC)	-	3.48	3.63
Triumfetta romboides Jacq.	Malvaceae	(LC)	-	-	7.87
Urena lobata L.	Malvaceae	(LC)	4.35	-	4.35
Cyanthillium cinereum (L.) H. Rob.	Asteraceae	(LC)	-	5.18	7.57
Chrysopogon zizanioides (L.) Roberty	Poaceae	(LC)	21.56	18.47	21.56
Climbers					
Phanera vahlii (Wight & Arn.) Benth.	Fabaceae	(LC)	32.21	15.36	-
Stephania rotunda Lour.	Menispermaceae	(LC)	30.90	20.33	-
Coccinia grandis (L.) Voigt	Cucurbitaceae	(LC)	36.85	20.87	-
Ichnocarpus frutescens (L.) W.T. Aiton	Apocynaceae	(LC)	57.52	110.54	250.6
Macuna pruriens (L.) DC.	Fabaceae	(LC)	-	-	49.31
Millettia extensa (Benth.) Baker	Fabaceae	(LC)	125.5	109.22	-
Trichosanthes cucumerina L.	Cucurbitaceae	(LC)	17.11	23.56	-

Details & Abbrevations: SSR= Shivalik *Shorea robusta* Forest; SRP= *Shorea robusta* Plain Forest; DDF= Dry Deciduous Forest; (LC) Least Concern; (NT) Near Threatened; (NE) Not Evaluated

Table 2. Floristic compositions of different functional groups at Panchkula Forest division in Northwestern Himalayan Foothills in Haryana

Plant species	Family	IUCN	DDF	MDDF	STP
Tree layer					
Senegalia catechu (L.f.) P.J.H. Hurter & Mabb.	Fabaceae	(LC)	158.32	-	-
Vachellia leucophloea (Roxb.) Maslin, Seigler & Ebinger	Fabaceae	(LC)	-	1.43	-
Terminalia anogeissiana Gere & Boatwr.	Combretaceae	(LC)	12.01	65.16	-
Azadirachta indica A. Juss	Meliaceae	(LC)	16.24	-	-
Bauhinia purpurea L.	Fabaceae	(LC)	-	1.67	-
Bauhinia variegata L.	Fabaceae	(LC)	-	1.64	-
Casearia tomentosa Roxb.	Salicaceae	(LC)	2.37	3.13	12.30
Cassia fistula L.	Fabaceae	(LC)	13.49	15.04	6.02
Cleome viscosa var. *viscosa*.	Cleomaceae	(LC)	-	7.72	-
Diospyros montana Roxb.	Ebenaceae	(LC)	13.03	-	-
Ehretia aspera Willd.	Boraginaceae	(LC)	-	1.06	-
Flacourtia sepiaria Roxb.	Salicaceae	(LC)	-	3.12	-
Garuga pinnata Roxb.	Burseraceae	(LC)	14.46	-	-
Grewia optiva J.R. Drumm. ex Burret	Malvaceae	(LC)	9.42	-	-
Holoptelea integrifolia (Roxb.) Planch.	Ulmaceae	(LC)	-	10.59	-
Kydia calycina Roxb.	Malvaceae	(LC)	-	10.87	6.79
Lagerstroemia parviflora Roxb.	Lythraceae	(LC)	-	7.37	20.75
Lannea coromandelica (Houtt.) Merr.	Anacardiaceae	(LC)	18.16	62.83	-
Mallotus philippensis (Lam.) Müll. Arg.	Euphorbiaceae	(LC)	-	5.16	9.98
Mitragyna parviflora (Roxb.) Korth	Rubiaceae	(LC)	2.43	16.70	-
Myristica malabarica Lam.	Myristicaceae	(LC)	-	5.17	-
Naringi crenulata (Roxb.) Nicolson	Rutaceae	(LC)	2.05	1.23	-
Nyctanthes arbor-tristis L.	Oleaceae	(LC)	-	-	7.04
Ougeinia oojeinensis (Roxb.) Hochr.	Fabaceae	(LC)	-	1.33	-
Pinus roxburghii Sarg.	Pinaceae	(LC)	-	-	193.41
Catunaregam spinosa (Thunb.) Tirveng.	Rubiaceae	(LC)	6.87	3.19	-
Searsia parviflora (Roxb.) F.A. Barkley	Anacardiaceae	(LC)	-	6.64	17.42
Falconeria insignis Royle	Euphorbiaceae	(LC)	-	5.21	26.29
Sterculia villosa Roxb. ex Sm.	Malvaceae	(LC)	-	1.15	-
Syzigium cuminii (Linn.) Skeels	Myrtaceae	(LC)	20.1	0.18	-
Terminalia elliptica Willd.	Combretaceae	(LC)	-	57.37	-
Terminalia arjuna (Roxb. ex DC.) Wight & Arn.	Combretaceae	(LC)	7.28	-	-
Woodfordia fruticosa (L.) Kurz	Lythraceae	(LC)	-	5.04	-
Ziziphus mauritiana Lamk.	Rhamnaceae	(LC)	4.10	-	-
Shrubs					
Justicia adhatoda L.	Acanthaceae	(LC)	6.38	-	-
Colebrookea oppositifolia Sm.	Lamiaceae	(LC)	-	-	69.46
Carrisa spinarum L.	Apocynaceae	(LC)	3.25	34.6	61.59
Lantana camara L.	Verbenaceae	(LC)	217.17	158	-

Cont...

Table 2. Floristic compositions of different functional groups at Panchkula Forest division in Northwestern Himalayan Foothills in Haryana

Plant species	Family	IUCN	DDF	MDDF	STP
Bergera koenigii L.	Rutaceae	(LC)	60.05	78	55.31
Naringi crenulata (Roxb.) D.H. Nicolson	Rutaceae	(LC)	-	-	9.16
Nepeta graciliflora Benth.	Lamiaceae	(NE)	-	10.30	34.75
Sida cordifolia L.	Malvaceae	(LC)	10.40	-	39.96
Girardinia diversifolia (Link) Friis	Utricaceae	(LC)	-	2.11	3.22
Vitex negundo L.	Lamiaceae	(LC)	-	17.3	-
Ziziphus oenophila (L.) Mill.	Rhamnaceae	(LC)	3.20	-	26.55
Herbs					
Achyranthes aspera L.	Amaranthaceae	(LC)	38.11	28.52	22.80
Adiantum capillus-veneris L.	Pteridaceae	(LC)	-	12.25	29.01
Ageratum conyzoides L.	Asteraceae	(LC)	9.71	11.83	2.33
Alysicarpus bupleurifolius (L.) DC.	Fabaceae	(LC)	-	3.87	5.21
Lysimachia arvensis (L.) U. Manns & Anderb.	Primulaceae	(LC)	-	2.95	-
Argemone mexicana L.	Papaveraceae	(LC)	7.30	1.45	3.40
Arisaema concinnum Schott	Araceae	(LC)	-	-	2.31
Asplinium esculentum Retz.	Athyriaceae	(NE)	-	2.64	25.00
Barleria cristata L.	Acanthaceae	(LC)	-	2.40	4.23
Bergenia pacumbis (Buch.-Ham. ex D.Don) C.Y. Wu & J.T. Pan	Saxifragaceae	(LC)	-	-	3.40
Senna tora (L.) Roxb.	Fabaceae	(LC)	13.95	15.34	-
Enteropogon dolichostachyus (Lag.) Keng	Poaceae	(NE)	4.28	1.99	10.23
Chrysopogon fulvus (Spreng.) Chiov.	Poaceae	(LC)	35.31	17.51	-
Commelina paludosa Blume	Commelinaceae	(LC)	13.06	17.55	4.12
Cynodon dactylon (L.) Pers.	Poaceae	(LC)	10.05	-	-
Cyperus rotundus L.	Cyperaceae	(LC)	26.56	10.53	15.24
Desmodium distortum (Aubl.) J.F. Macbr.	Fabaceae	(LC)	-	-	3.76
Desmostachya bipinnata (L.) Stapf	Poaceae	(LC)	-	5.04	8.11
Eclipta prostata (L.)	Asteraceae	(LC)	-	-	2.56
Eulaliopsis binata (Retz.) C.E. Hubb.	Poaceae	(LC)	26.43	8.37	-
Euphorbia hirta L.	Euphorbiaceae	(LC)	1.56	-	12.25
Euphorbia pulcherrima Willd. ex Klotzsch	Euphorbiaceae	(LC)	-	3.50	1.98
Evolvulus alsenoides (L.)	Convolvulaceae	(LC)	-	-	4.24
Girardinia diversifolia (Link) Friis	Utricaceae	(LC)	-	-	0.93
Glycirrhiza glabera L.	Fabaceae	(LC)	-	-	6.39
Heliotropium bacciferum Forsk.	Boraginaceae	(LC)	-	-	7.61
Heteropogon contortus (L.) P. Beauv.	Poaceae	(LC)	31.31	13.23	1.66
Indigofera astragalina DC.	Fabaceae	(LC)	-	-	6.65
Leonotis nepetifolia (L.) R. Br.	Lamiaceae	(LC)	4.62	10.45	1.62
Indigofera astragalina DC.	Fabaceae	(LC)	-	-	4.98
Leucas biflora (Vahl) Sm.	Lamiaceae	(LC)	2.97	6.01	6.02

Cont...

Table 2. Floristic compositions of different functional groups at Panchkula Forest division in Northwestern Himalayan Foothills in Haryana

Plant species	Family	IUCN	DDF	MDDF	STP
Craterostigma sessiliflorum (Benth.) Y.S. Liang & J.C. Wang	Linderniaceae	(NE)	-	2.81	-
Malvastrum coromandelianum (L.)	Malvaceae	(LC)	4.61	9.74	1.62
Mazus pumilus (Burm. f.) steenis	Mazaceae	(LC)	-	7.22	-
Oplismenus compositus (L.) P. Beauv.	Poaceae	(LC)	8.25	-	10.78
Oxalis corniculata L.	Oxilidaceae	(LC)	3.82	3.92	-
Parthenium hysterophorus L.	Asteraceae	(LC)	3.30	6.04	-
Dicliptera paniculata (Forssk.) I. Darbysh.	Acanthaceae	(LC)	-	8.14	-
Phyllanthus niruri auct.	Phyllanthaceae	(LC)	-	2.89	-
Phyllanthus virgatus G. Forst.	Phyllanthaceae	(LC)	-	2.81	7.18
Physalis angulata L.	Solanaceae	(LC)	-	-	2.63
Polygala arvensis Willd	Polygalaceae	(LC)	-	7.41	14.21
Pupalialappacea (L.) Juss.	Amaranthaceae	(LC)	13.62	16.37	6.52
Rungia pectinata (L.) Nees	Acanthaceae	(LC)	-	4.78	1.98
Selaginella wallichii (Hook. & Grev.) Spring	Selaginellaceae	(LC)	-	5.57	4.19
Jacobaea nudicaulis (Buch.-Ham. ex D.Don) B.Nord.	Asteraceae	(LC)	7.81	-	4.02
Cenchrus americanus (L.) Morrone	Poaceae	(NE)	-	8.84	7.72
Sida orientalis Cav.	Malvaceae	(LC)	1.56	-	4.54
Sida ovata Forsk.	Malvaceae	(LC)	2.17	5.39	-
Sonchus brachyotus DC.	Asteraceae	(LC)	-	-	4.84
Taraxacum sect. *Taraxacum* F.H. Wigg.	Asteraceae	(NE)	-	-	2.98
Themeda arundinacea (Roxb.) A. Camus	Poaceae	(LC)	8.09	5.38	-
Tridax procumbens L.	Asteraceae	(LC)	4.07	4.25	8.29
Triumfetta romboides Jacq.	Malvaceae	(LC)	6.72	9.10	-
Urena lobata L.	Malvaceae	(LC)	2.32	2.12	-
Cyanthillium cinereum (L.) H.Rob.	Asteraceae	(LC)	-	4.67	-
Viola canescens Wall.	Violaceae	(LC)	-	-	10.29
Xanthium strumarium L.	Asteraceae	(LC)	2.78	2.57	-
Climbers					
Phanera vahlii (Wight & Arn.) Benth.	Fabaceae	(LC)	-	70.36	-
Stephania rotunda Lour.	Menispermaceae	(LC)	21.76	67.14	-
Cissus repanda (Wight & Arn.) Vahl	Vitaceae	(LC)	70.35	45.92	37.17
Coccinia grandis (L.) Voigt	Cucurbitaceae	(LC)	45.92	21.37	46.69
Ichnocarpus frutescens (L.) W.T. Aiton	Apocynaceae	(LC)	67.14	94.85	162.15
Pueraria tuberosa (Roxb. ex Willd.) DC.	Fabaceae	(NE)	94.85		
Millettia extensa (Benth.) Benth. ex Baker	Fabaceae	(LC)	-	-	16.62
Trichosanthes cucumerina L.	Cucurbitaceae	(LC)	-	-	37.36

Details & Abbreviations: DDF= Dry Deciduous Forest; MDDF= Mixed Dry Deciduous Forest; STP= Subtropical Pine; LC= Least Concern; NE= Not Evaluated due to increased light penetration and reduced canopy competition, creating favorable microhabitats for understory species (Figure 4). Species dominance patterns based on the importance value index (IVI) varied across forest types and vegetation layers (Table 3). *Shorea robusta C.F. Gaertn.* dominated forests in YFD reflect its strong ecological amplitude and competitive ability under dry deciduous conditions. In PFD, *Acacia catechu* (L.F.) Willd., *Terminalia anogeissiana Gere & Boatwr.* and *Pinus roxburghii* Sarg. dominated respective forest types, indicating adaptation to specific edaphic and climatic conditions.

The shrub layer was largely dominated by the invasive *Lantana camara L.,* which is known to suppress native regeneration and alter vegetation structure. Its widespread dominance across forest types indicates strong ecological plasticity and highlights a major conservation concern. However, *Colebrookea oppositifolia* Sm. dominated in subtropical pine forests, suggesting habitat-specific shrub composition.

The herbaceous layer exhibited high diversity, particularly in open canopy systems, where increased light availability promotes species richness (Figure 4). Dominant herbaceous species included *Heteropogon contortus* (L.) P. Beauv., *Achyranthes aspera* L., and *Adiantum capillus-veneris* L. The dominance of grasses such as *Cenchrus setigerus* Vahl, *Desmostachya bipinnata* (L.) Stapf, and *Saccharum munja Roxb*. underscore their ecological role in soil stabilisation and nutrient cycling. Climber diversity, although relatively low, contributed to vertical stratification and structural complexity, with species such as *Ichnocarpus frutescens* (L.) W.T. Aiton, *Millettia extensa (Benth.) Benth. Ex Baker* and *Pueraria tuberosa* (Roxb. ex Willd.) DC. playing important roles in forest dynamics. Overall, variations in species composition, richness, and dominance patterns reflect the influence of environmental gradients, including soil properties, moisture availability, and topography, as well as anthropogenic pressures. The observed dominance of invasive species such as *Lantana camara* L. poses potential threats to biodiversity and forest regeneration, necessitating targeted management interventions.

3.2. Population Structure and Regeneration Status

The population structure of tree species across forest ecosystems revealed distinct patterns in girth class distribution, providing insights into regeneration dynamics and forest stability (Figure 5-7). In most forest types, a large proportion of individuals were concentrated in lower girth classes, indicating active regeneration and recruitment.

In northern tropical dry deciduous plain *Shorea robusta* C.F. Gaertn. forests, 75.45% of individuals were recorded in lower girth classes (31–90 cm), while only 4.80% occurred in higher girth classes (180–270 cm), suggesting strong regeneration but relatively fewer mature individuals (Figure 8A). Similarly, Shivalik *Shorea robusta* C.F. Gaertn. forests

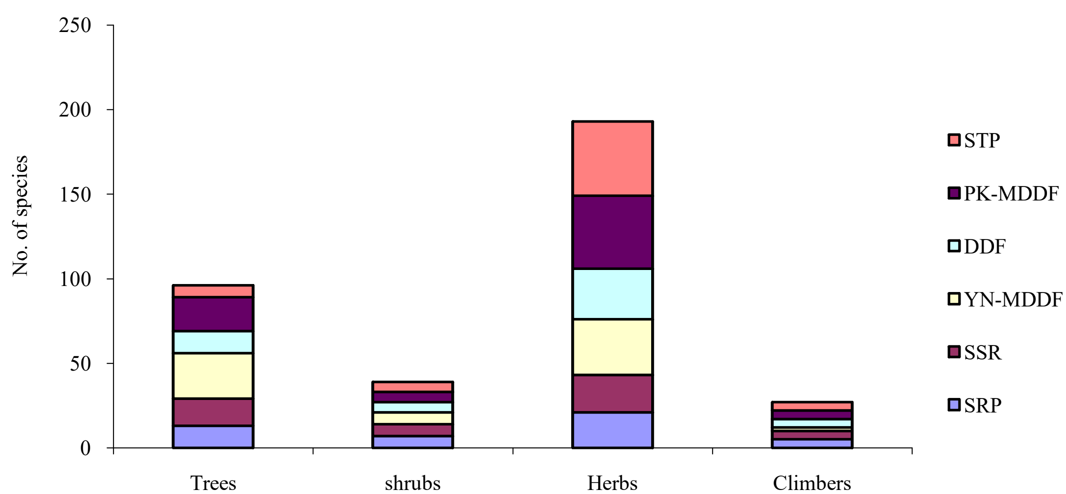

Figure 4. Relative abundance of various functional groups in various forest ecosystems. (The figure shows ecosystem-wise variation in the relative abundance of functional groups, indicating differences in community structure and dominance patterns in six types of forest ecosystems studied)

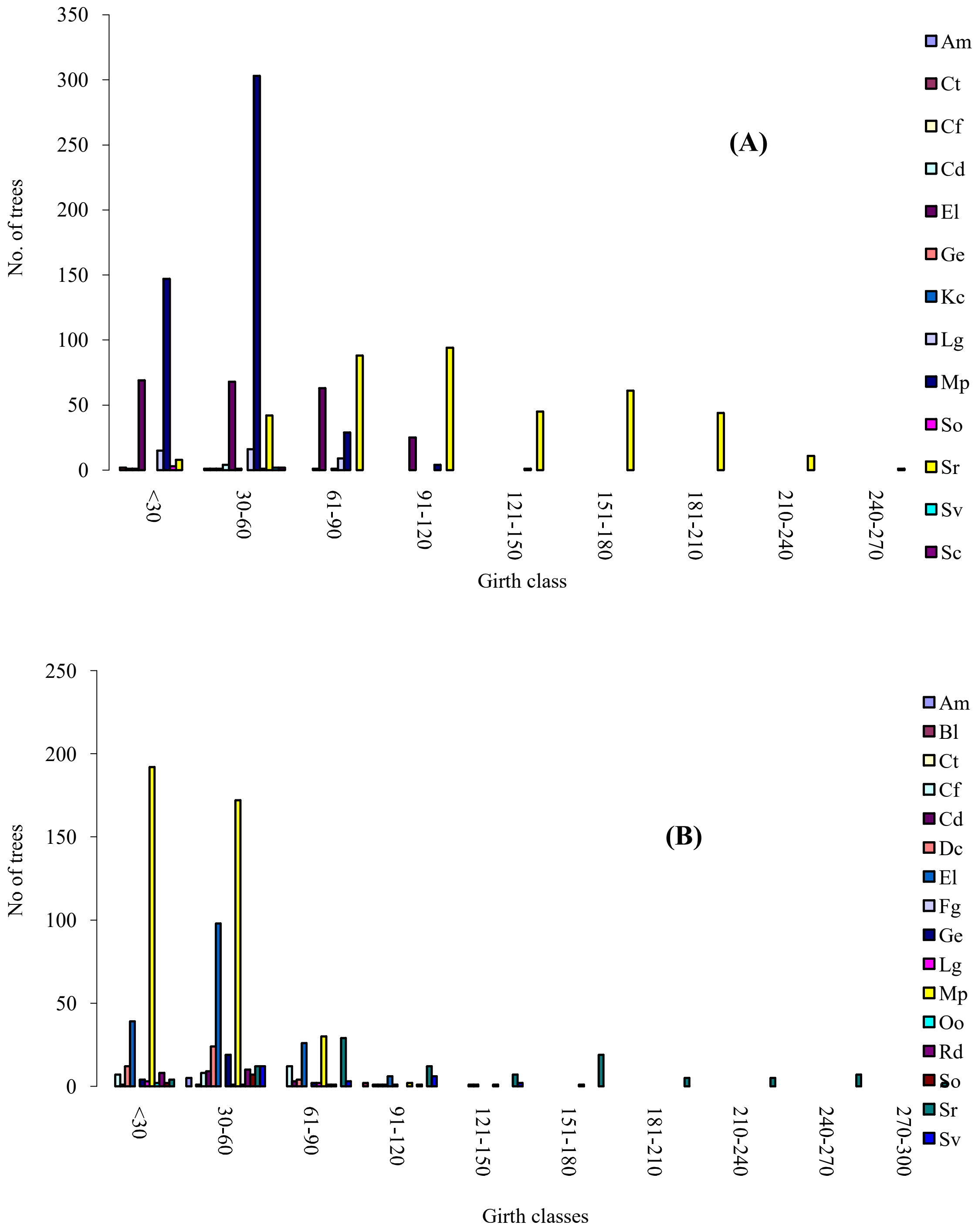

Figure 5. Population structure of tree species in (A) Northern tropical dry deciduous plain *Shorea robusta* forests; (B) Northern tropical dry deciduous Shivalik *Shorea robusta* forests. Abbreviations: Am- *Aegle marmelos*; Ct- *Casearia tomentosa*; Cf- *Cassia fistula*; Cd- *Cordia dichotoma*; El- *Ehretia laevis*; Kc- *Kydia calycina*; Lg- *Litsea glutinosa*; Mp- *Mallotus phillipensis*; So- *Schleichera oleosa*; Sr- *Shorea robusta*; Sv- *Sterculia villosa*; Sc- *Syzygium cumini*; Dc- *Diospyros cordifolia*; Bl- *Buchonarica lanzens*; Oo- *Ougenia oojeinensis*; Rd- *Randia dumetorum; Ficus glomerata* (The figure shows the distribution of tree individuals across girth classes in two *Shorea robusta* forest types, indicating differences in regeneration and population structure)

showed an even greater skew, with 90.12% of individuals in lower girth classes, indicating vigorous recruitment but limited representation of older trees (Figure 8B).

Mixed deciduous forests in YFD also showed dominance of lower girth classes (80.11%), (Figure 9A) whereas in PFD, a relatively balanced distribution was observed

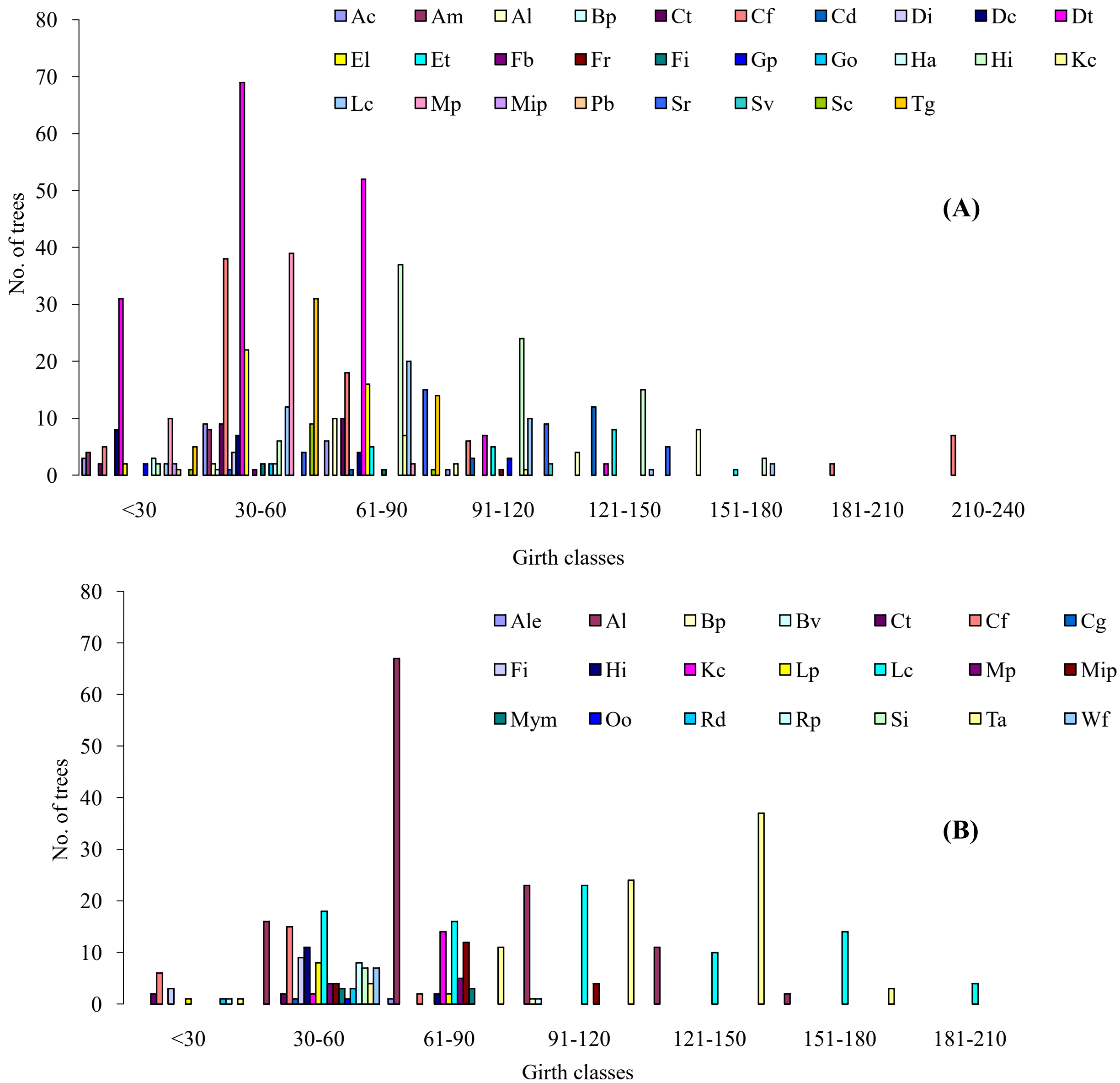

Figure 6. Population structure of tree species in (A) Mixed deciduous forests at Yamunanagar forest division; (B) Northern tropical dry deciduous forests at Panchkula forest division. Abbreviations: Am-*Aegle marmelos*; Ct- *Casearia tomentosa*; Cf- *Cassia fistula*; Cd- *Cordia dichotoma*; El- *Ehretia laevis*; Kc- *Kydia calycina*; Lg- *Litsea glutinosa*; Mp- *Mallotus phillipensis*; So- *Schleichera oleosa*; Sr- *Shorea robusta*; Sv- *Sterculia villosa*; Sc- *Syzygium cumini*; Dc- *Diospyros cordifolia*; Bl- *Buchonarica lanzens*; Oo- *Ougenia oojeinensis*; Rd- *Randia dumetorum; Ficus glomerata;* Ac- *Acacia catechu;* Ale- *Acacia Leuchophloea;* Al- *Anogeissus latifolia;* Bp- *Bauhinia purpurea;* Bv- *Bauhinia varigata;* Fr- *Ficus religiosa;* Fb-*Ficus bengalensis;* Gp- *Garuga pinnata;* Go- *Grewia optiva;* Lc- *Lannea coromendelica;* Mip- *Mitragyna parviflora;* Ha- *Holoptelea integrifolia;* Ta- *Terminalia alata.*

(The figure shows the distribution of tree individuals across girth classes in two forest types, reflecting differences in regeneration patterns and population structure).

(63.48% lower and 35.58% intermediate girth classes), indicating comparatively stable population structure and better representation of different age classes (Figure 10A). In contrast, dry deciduous forests of PFD exhibited an extreme concentration (99.78%) of individuals in lower girth classes, suggesting recent regeneration following disturbance or selective removal of mature trees (Figure 9B).

Subtropical pine forests displayed a more balanced distribution across girth classes, with 45.37% in lower, 43.69% in intermediate, and 10.92% in higher girth classes,

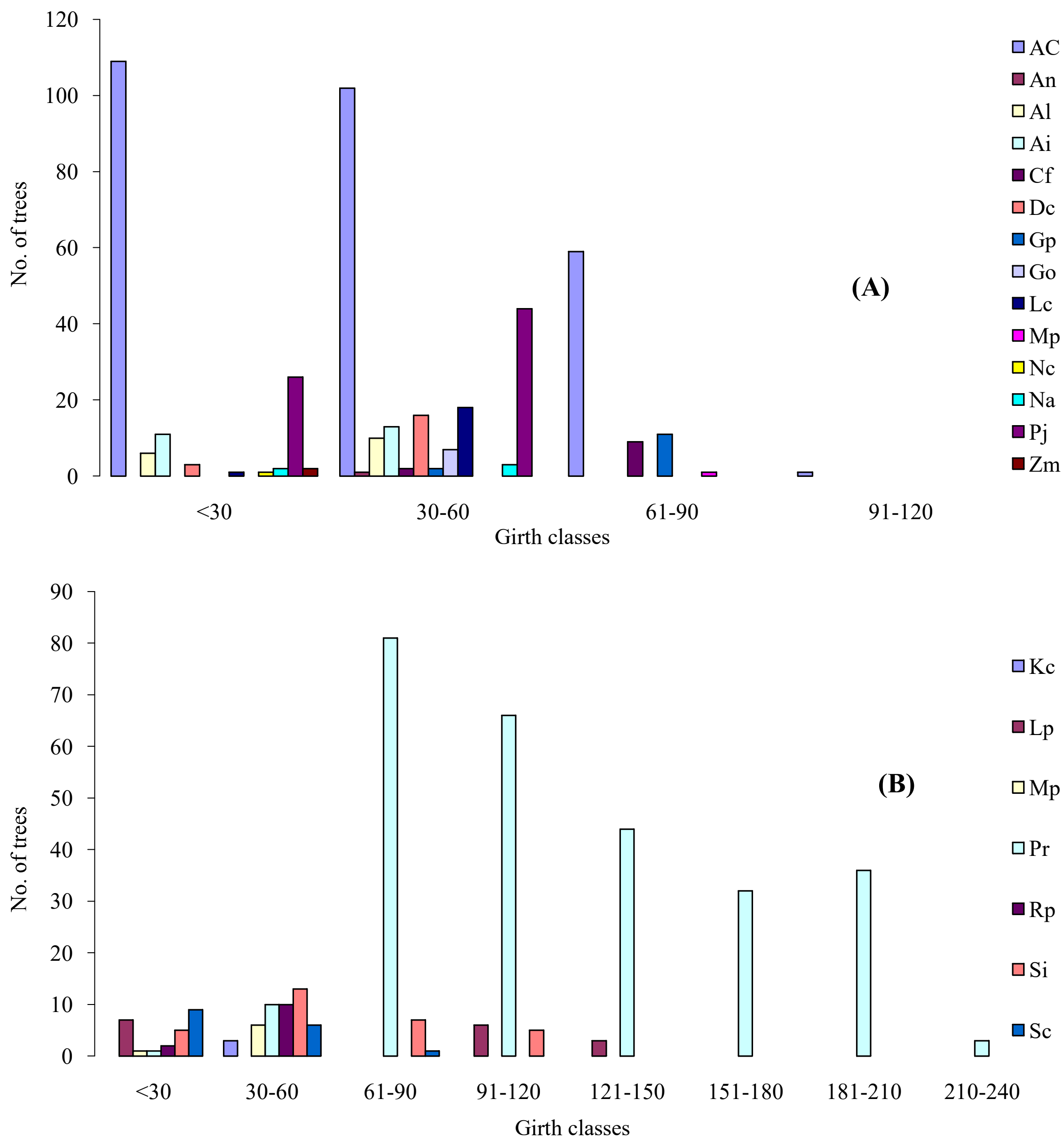

Figure 7. Population structure of tree species in (A) Dry deciduous forests; (B) Sub-tropical pine forests in Panchkula Forest Division. Abbreviations: Ac- *Acacia catechu*; Al- *Anogeissus latifolia*; Ai- *Azadirachta indica*; Cf- *Cassia fistula*; Dc- *Diospyros cordifolia*; Gp- *Garuga pinnata*; Go- *Grewia optiva*; Lc- *Lannea coromendelica*; Mp- *Mallotus phillippensis*; Nc- *Naringi crenulata*; Na- *Nyctanthes arbor-tristis*; Zm-*Ziziphus mauritiana*; Kc- *Kydia calycina*; Lp- *Lagerstromia parviflora*; Pr- *Pinus roxburghii*; Si- *Sapium insinge*; Sc- *Syzugium cumini* (The figure shows the distribution of tree individuals across girth classes in dry deciduous and subtropical pine forests, indicating differences in regeneration and population structure).

indicating relatively stable population dynamics (Figure 10B). The dominance of *Pinus roxburghii* Sarg.in intermediate and higher girth classes reflect its persistence and competitive advantage in these ecosystems.

The predominance of individuals in lower girth classes across most forest types suggests an inverse J-shaped distribution pattern, widely recognised as an indicator of continuous regeneration and sustainable forest dynamics.

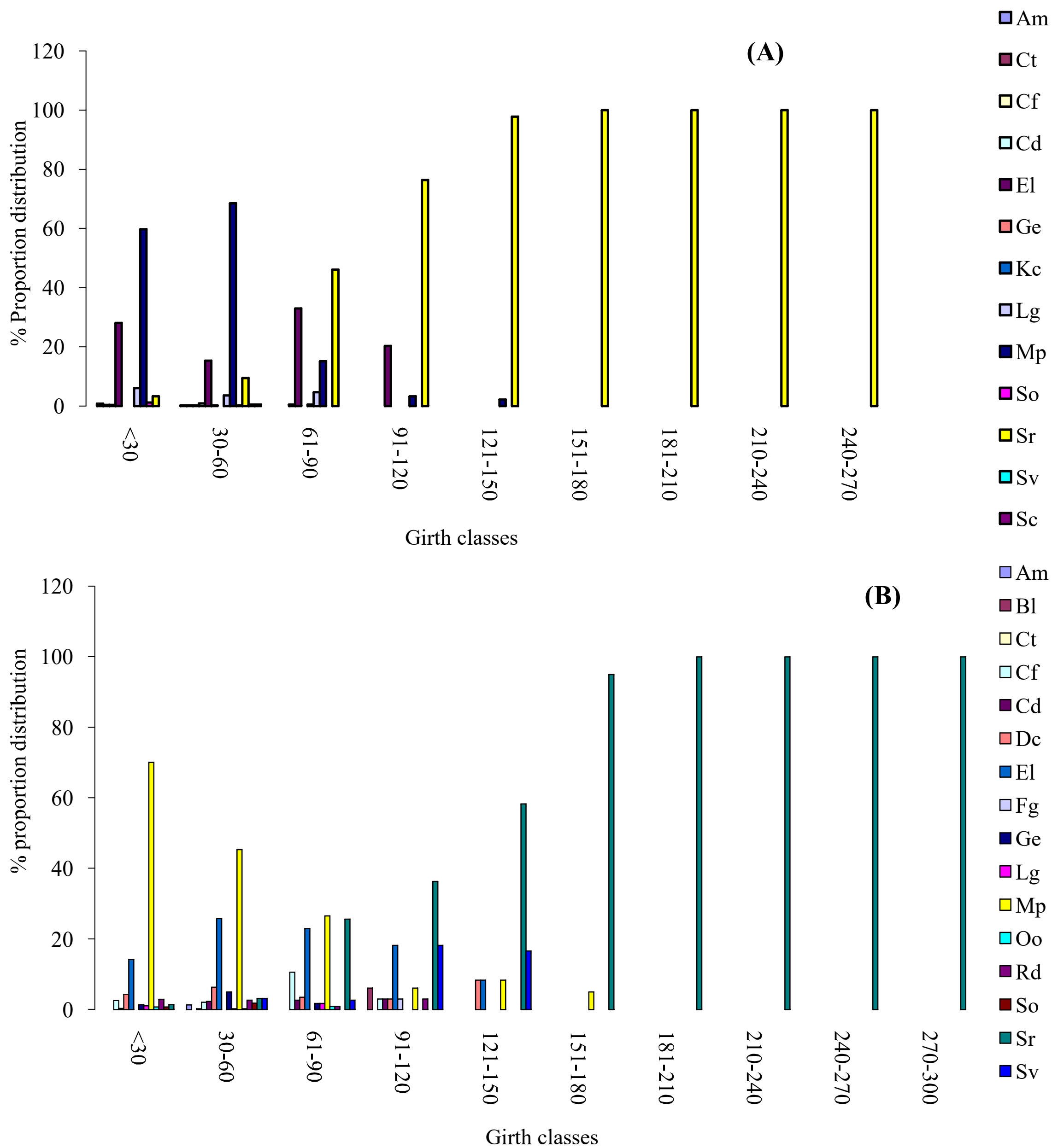

Figure 8. Relative percentage proportion distribution of different tree species in (A) Northern tropical dry deciduous plain *Shorea robusta* forests; (B) Northern tropical dry deciduous Shivalik *Shorea robusta* forests. Abbreviations: Am- *Aegle marmelos*; Ct- *Casearia tomentosa*; Cf- *Cassia fistula*; Cd- *Cordia dichotoma*; El- *Ehretia laevis*; Kc- *Kydia calycina*; Lg- *Litsea glutinosa*; Mp- *Mallotus phillipensis*; So- *Schleichera oleosa*; Sr- *Shorea robusta*; Sv- *Sterculia villosa*; Sc- *Syzygium cumini*; Dc- *Diospyros cordifolia*; Bl- *Buchonarica lanzens*; Oo- *Ougenia oojeinensis*; Rd- *Randia dumetorum; Ficus glomerata* (The figure shows species-wise relative percentage composition of trees in two *Shorea robusta* forest types, indicating differences in species dominance and community composition)

However, the low proportion of larger trees in certain forest types may reflect past disturbances, anthropogenic pressures, or selective harvesting.

3.3. Dominance–Diversity Patterns and Community Organization

Dominance–diversity curves for the trees (Figure 11),

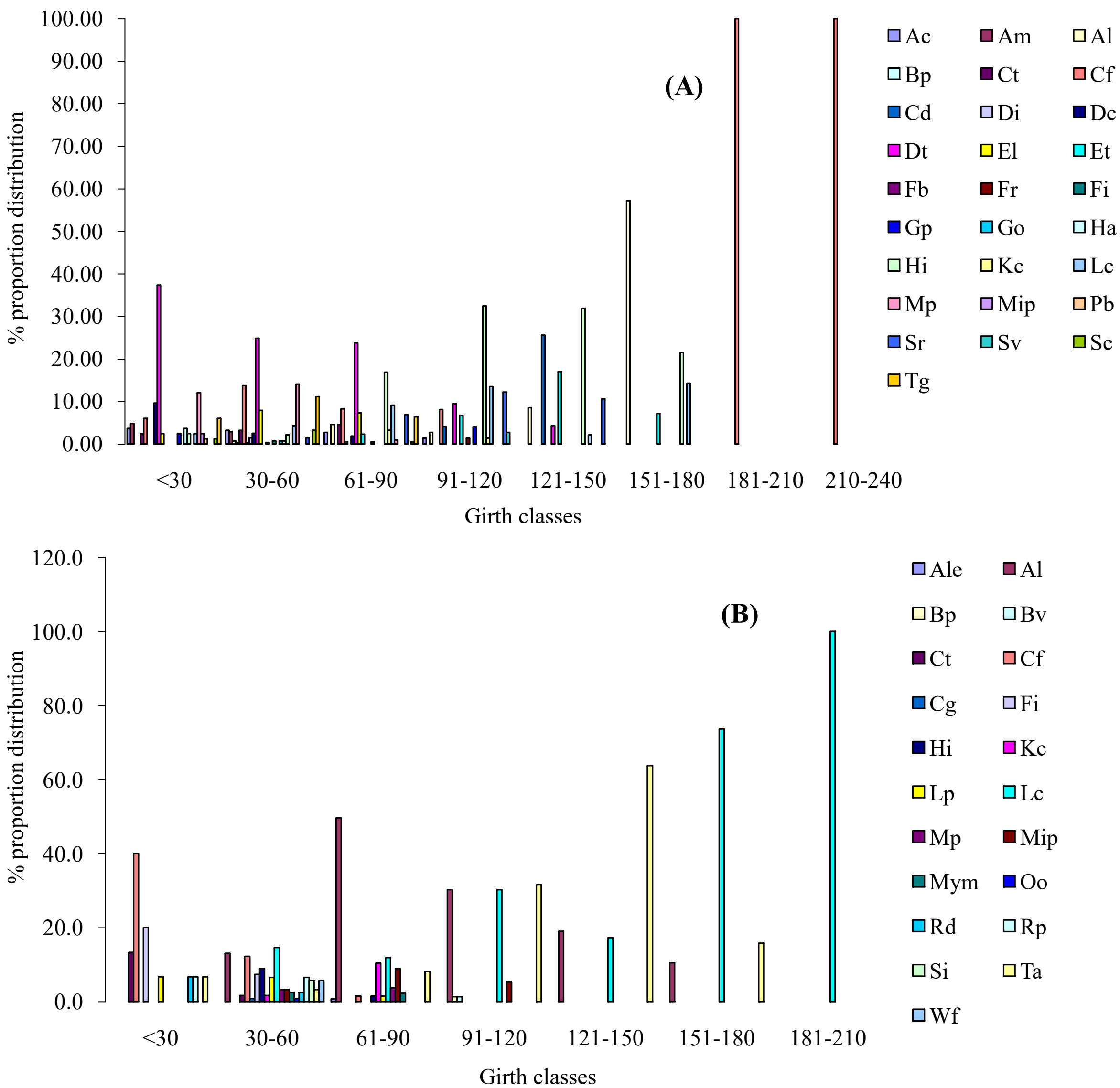

Figure 9. Relative percentage proportion distribution of tree species in (A) Mixed deciduous forests in Yamunanagar Forest Division; (B) Northern tropical dry deciduous forests in Panchkula Forest Division. Abbreviations: Am- *Aegle marmelos*; Ct- *Casearia tomentosa*; Cf- *Cassia fistula*; Cd- *Cordia dichotoma*; El- *Ehretia laevis*; Kc- *Kydia calycina*; Lg- *Litsea glutinosa*; Mp- *Mallotus phillipensis*; So- *Schleichera oleosa*; Sr- *Shorea robusta*; Sv- *Sterculia villosa*; Sc- *Syzygium cumini*; Dc- *Diospyros cordifolia*; Bl- *Buchonarica lanzens*; Oo- *Ougenia oojeinensis*; Rd-*Randia dumetorum;* Fg- *Ficus glomerata;* Ac- *Acacia catechu;* Ale- *Acacia leuchophloea;* Al- *Anogeissus latifolia;* Bp- *Bauhinia purpurea;* Bv- *Bauhinia varigata;* Fr- *Ficus religiosa;* Fb- *Ficus bengalensis;* Gp- *Garuga pinnata;* Go- *Grewia optiva;* Lc- *Lannea coromendelica;* Mip- *Mitragyna parviflora;* Ha- *Holoptelea integrifolia;* Ta- *Terminalia alata* (The figure shows species-wise relative percentage composition of trees in two forest types, indicating variation in species dominance and community structure)

shrubs (Figure 12), and herbaceous layers (Figure 13) across the studied forest ecosystems largely followed a log-normal distribution pattern. This indicates that species abundances are distributed among several species with moderate dominance, reflecting equitable resource partitioning and niche differentiation. Such log-normal distributions are characteristic of structurally complex and relatively stable communities, particularly in mixed deciduous forests where species diversity was highest. The pattern suggests that no single species overwhelmingly dominates the community, allowing the coexistence of multiple species. Similar trends observed in shrub and herbaceous layers further support the heterogeneous and well-structured nature of these ecosystems.

3.4. Species Diversity and Community Indices

Species diversity indices varied significantly among forest types and vegetation layers, reflecting differences in species composition, dominance, and ecological conditions. For the tree layer, Shannon's diversity index ranged from

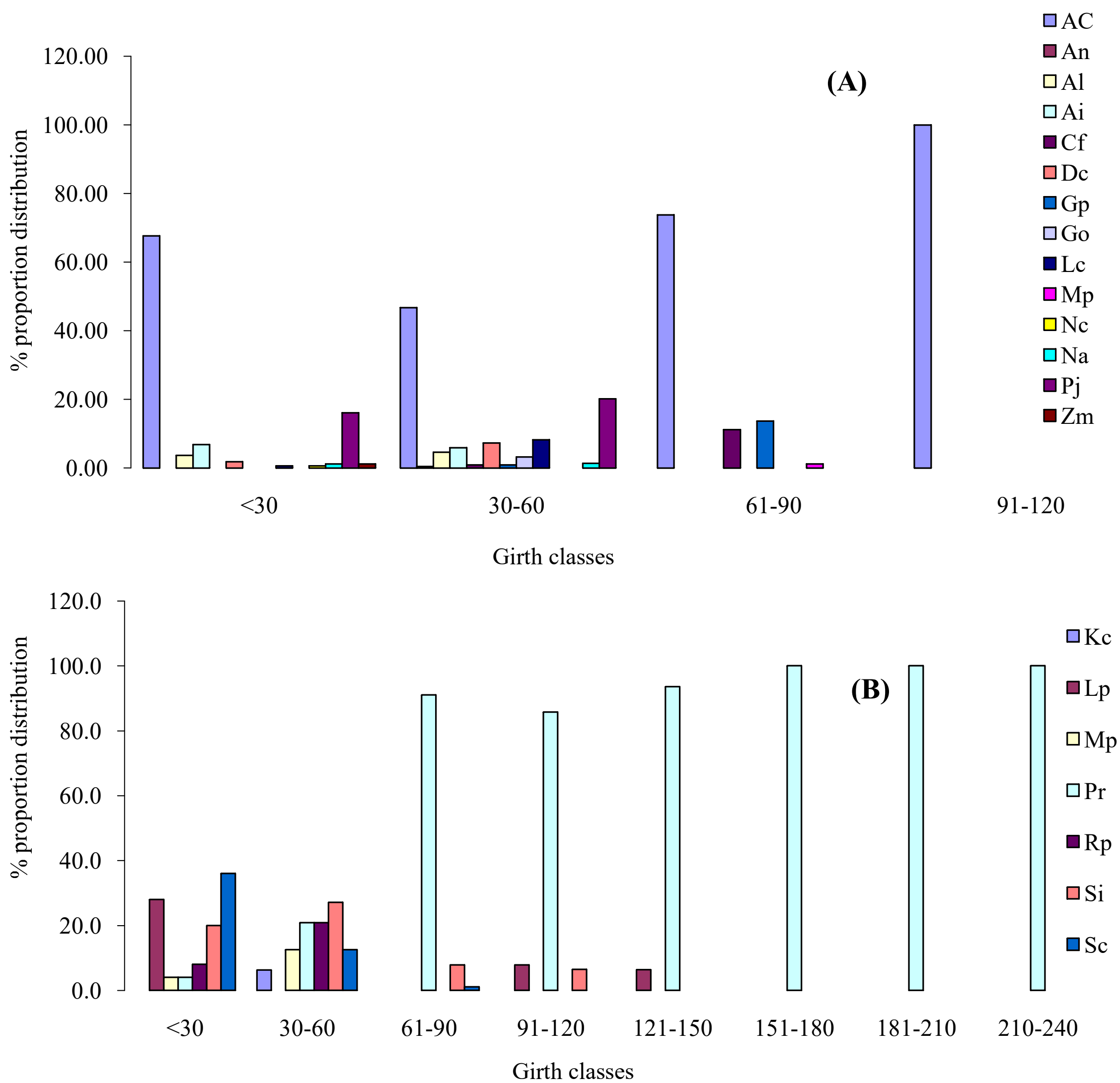

Figure 10. Relative percentage proportion distribution of tree species in (A) Mixed deciduous forests; (B) Sub-tropical pine forests in Panchkula Forest Division. Abbreviations: Ac- *Acacia catechu*; Al- *Anogeissus latifolia*; Ai- *Azadirachta indica*; Cf- *Cassia fistula*; Dc- *Diospyros cordifolia*; Gp- *Garuga pinnata*; Go- *Grewia optiva*; Lc- *Lannea coromendelica*; Mp- *Mallotus phillippensis*; Nc- *Naringi crenulata*; Na- *Nyctanthes arbor-tristis*; Zm- *Ziziphus mauritiana*; Kc- *Kydia calycina*; Lp- *Lagerstromia parviflora*; Pr- *Pinus roxburghii*; Si- *Sapium insinge*; Sc- *Syzugium cumini* (The figure shows species-wise relative percentage composition of trees in mixed deciduous and subtropical pine forests, indicating variation in species dominance and community structure)

1.237 in subtropical pine forests to 2.510 in mixed deciduous forests of PFD, indicating higher diversity in mixed forests and lower diversity in conifer-dominated systems (Table 4). Simpson's concentration of dominance was highest in subtropical pine forests (0.455), reflecting strong dominance by *Pinus roxburghii* Sarg., whereas lower values in mixed forests indicate more equitable species distribution (Table 4).

Species richness (Margalef's index) was highest in mixed deciduous forests in PFD (7.440), further emphasizing their role as biodiversity-rich ecosystems (Table 4). Equitability (Pielou's index) was generally higher in deciduous forests, suggesting balanced species distribution.

In the shrub layer, diversity was highest in subtropical pine forests, while dominance was greatest in mixed deciduous forests of PFD, indicating uneven species distribution. Herbaceous diversity was notably high in subtropical pine forests (H = 3.450), likely due to favorable light conditions and reduced canopy cover (Table 4). Climbers exhibited comparatively lower diversity but contributed to vertical complexity and ecological interactions. Overall, diversity indices suggest that mixed deciduous forests support higher biodiversity and ecological stability, whereas subtropical pine forests exhibit higher dominance and lower diversity due to monospecific tendencies.

3.5. Ecological Implications and Forest Dynamics

The observed patterns of species composition, population structure, and diversity indices collectively reflect the influence of environmental gradients, resource availability, and disturbance regimes on forest ecosystems. The Shannon diversity values (1.237–2.510) fall within the reported range for Indian forests, indicating moderate to high diversity (Table 4).

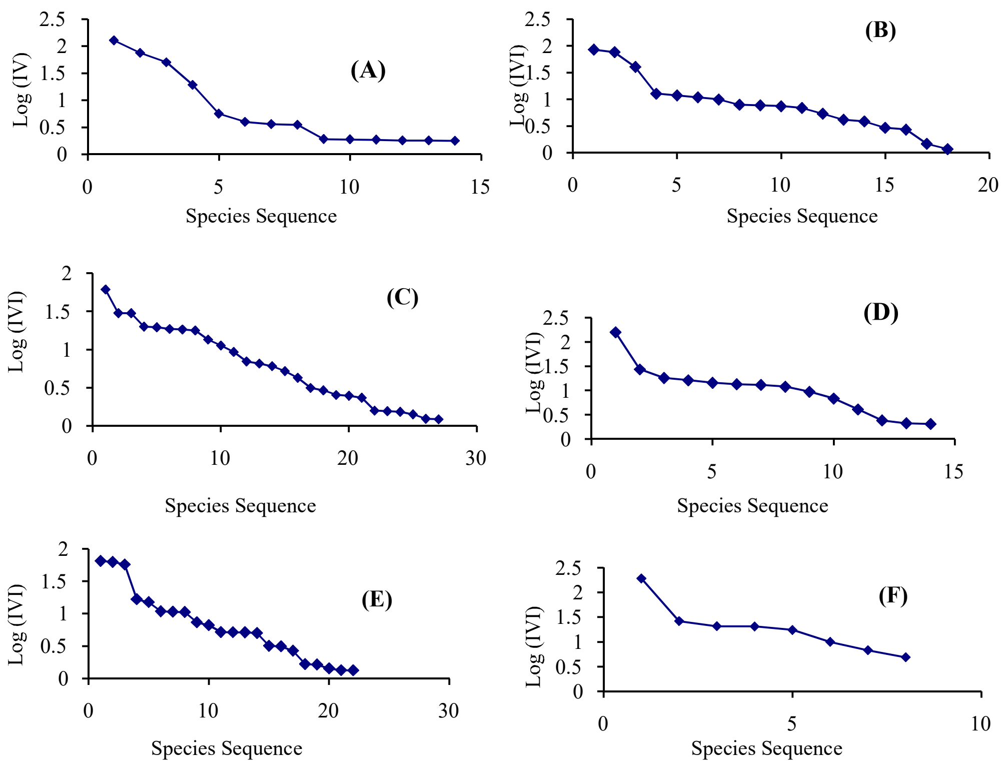

Figure 11. Dominance – diversity curves of Tree species in (A) Northern tropical dry deciduous plain *Shorea robusta* forests (YFD); (B) Northern tropical dry deciduous Shivalik *Shorea robusta* forests (YFD); (C) Northern tropical mixed dry deciduous forests (YFD); (D) Northern tropical dry deciduous forests (PFD); (E) Mixed dry deciduous forest (PFD); (F) Subtropical pine forests (PFD). (The figure shows dominance–diversity relationships of tree species across forest types, highlighting variations in species richness, evenness, and dominance patterns).

Variation in dominance values highlights differences in species interactions and competitive hierarchies across forest types. Higher dominance in subtropical pine forests suggests ecological simplification, whereas lower dominance in mixed forests indicates greater structural complexity and stability.

The widespread presence of invasive species such as *Lantana camara* L. poses a significant ecological challenge, as it can suppress native regeneration and alter community composition. Therefore, effective management strategies should focus on controlling invasive species and promoting native biodiversity to maintain ecosystem resilience.

3.6. Phenology and Regeneration Dynamics of *Shorea robusta* C.F. Gaertn

Phenological observations in *Shorea robusta* C.F. Gaertn. forests revealed distinct seasonal patterns in leaf fall, flowering, fruiting, and regeneration. The species regenerates through both seeds and vegetative means, such as coppicing and root suckers. Seed germination is highly dependent on timely monsoon rainfall, with viability declining rapidly under delayed precipitation. Seedlings typically establish in moist leaf litter under shaded conditions, but their survival is strongly influenced by moisture availability and microhabitat conditions. Leaf fall occurs between February and May, coinciding with the dry season, while leaf flushing and flowering are triggered by

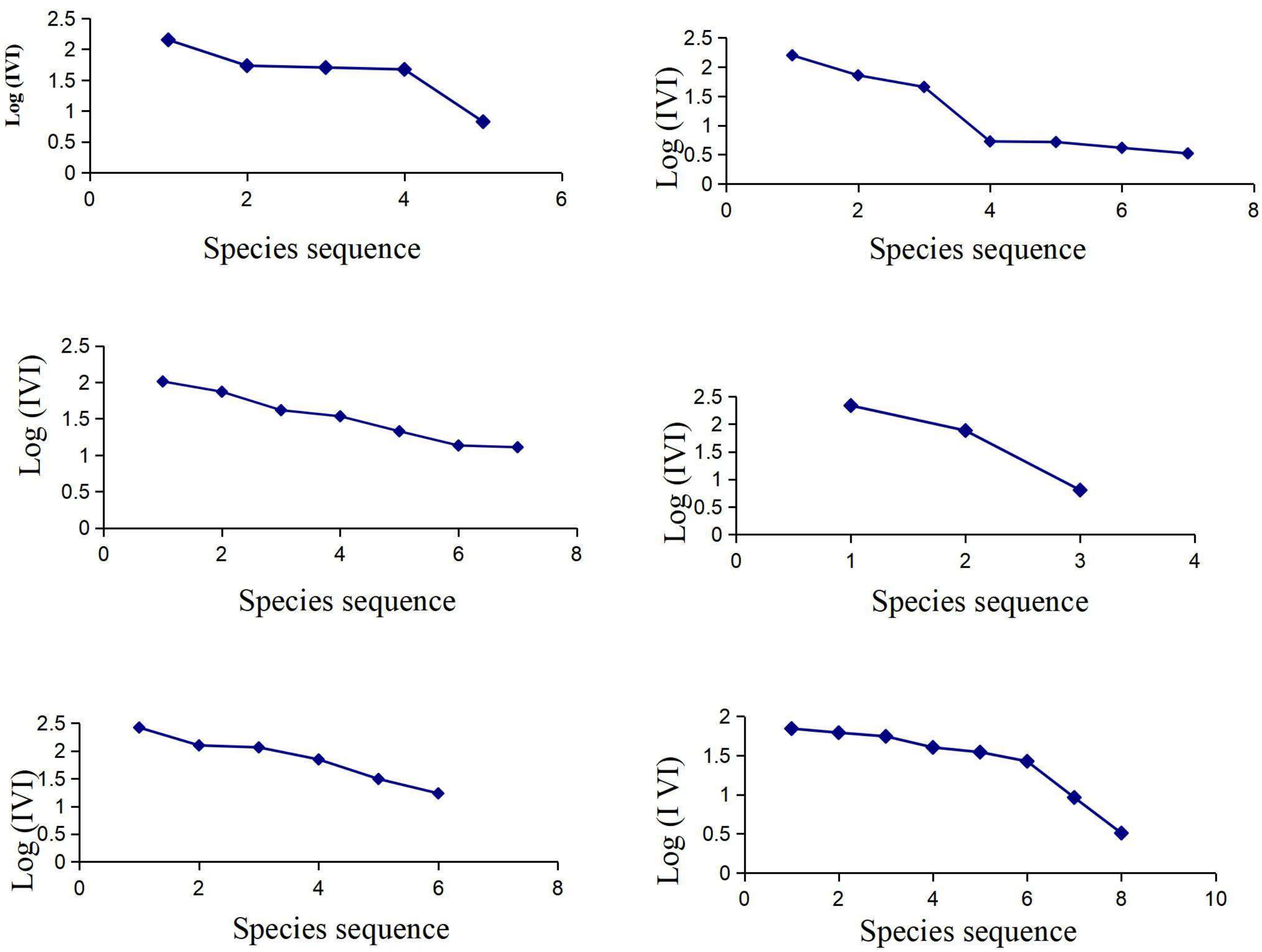

Figure 12. Dominance– diversity curves of Shrub species in (A) Northern tropical dry deciduous plain *Shorea robusta* forests (YFD); (B) Northern tropical dry deciduous Shivalik *Shorea robusta* forests (YFD); (C) Northern tropical mixed dry deciduous forests (YFD); (D) Northern tropical dry deciduous forests (PFD); (E) Mixed dry deciduous forest (PFD); (F) Subtropical pine forests (PFD). (The figure shows rank–abundance (dominance–diversity) patterns of shrub species across forest types, highlighting differences in species richness, evenness, and dominance)

increasing temperature and photoperiod. These phenological patterns reflect adaptive strategies to seasonal climatic variability. Overall, regeneration dynamics in *Shorea robusta* C.F. Gaertn. forests are closely linked to environmental conditions, particularly rainfall and moisture availability, which ultimately influences forest structure and long-term sustainability. The observed variation in community characteristics across forest types highlights the strong influence of edaphic factors and biotic interactions in shaping vegetation structure and diversity. Soil heterogeneity, nutrient availability, and moisture gradients likely contributed to differential species establishment and survival, resulting in distinct diversity patterns across sites. Similar findings have been reported in recent studies, where environmental gradients and site conditions significantly influenced species diversity and forest composition (Kumar et al., 2022; Sharma et al., 2025; Dar et al., 2025).

The studies indicate that the biodiversity of dry deciduous forests is most important because of their vulnerability to habitat loss. The log-normal distribution pattern observed in dominance–diversity curves suggest a relatively stable and mature community structure, where resources are partitioned among a large number of species without extreme dominance by a few taxa. This pattern is generally an indicator of ecological equilibrium and niche diversification. However, it is important to note that such

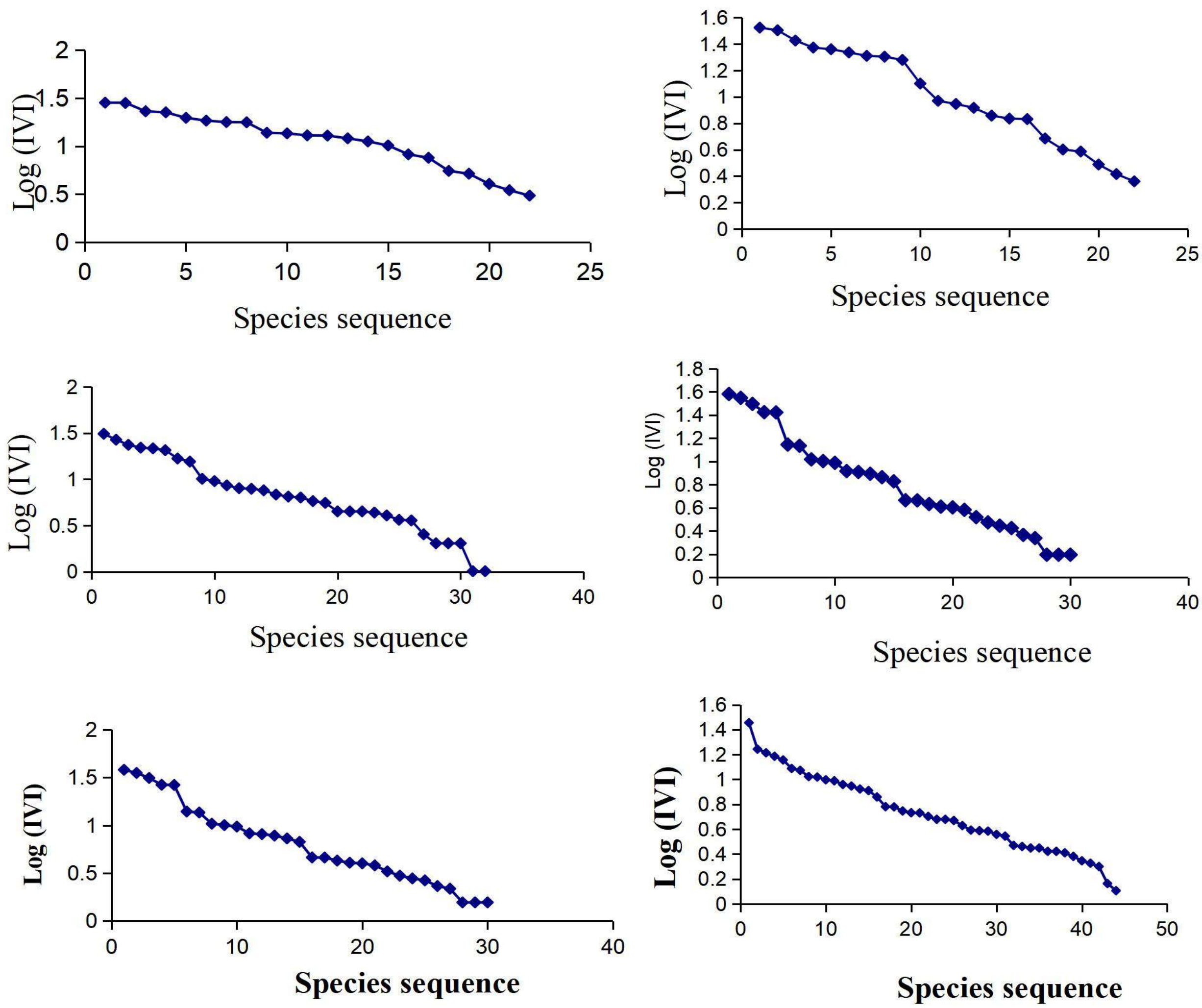

Figure 13. Dominance– diversity curves of Herb species in (A) Northern tropical dry deciduous plain *Shorea robusta* forests (YFD); (B) Northern tropical dry deciduous Shivalik *Shorea robusta* forests (YFD); (C) Northern tropical mixed dry deciduous forests (YFD); (D) Northern tropical dry deciduous forests (PFD); (E) Mixed dry deciduous forest (PFD); (F) Subtropical pine forests (PFD). (The figure shows rank–abundance (dominance–diversity) patterns of herb species across forest types, highlighting variations in species richness, evenness, and dominance).

Table 3. Phyto-sociological analyses of various functional groups in forests of the Northwestern Himalayan Foothills in Haryana

Forest types	Average tree dfensity (trees ha^{-1})	Average basal area ($m^2 ha^{-1}$)	Plant species (n)	Dominant species (IVI)	IVI variation of rest of species
Yn-SRP	823	55.20	14*	*Shorea robusta* C.F. Gaertn. IVI =127.89)	74.98 to 1.72*
			06**	*Lantana camara* L. (IVI =141.65)	54.01 to 06.71**
			20***	*Heteropogon contortus* (L.) P. Beauv. (IVI =28.41)	23.11 to 03.48***
			06****	*Ichnocarpus frutescens* (L.) W.T.Aiton (IVI =110.54)	109.22 to 15.36****
Yn-SSR	971	23.93	17*	*Mallotus philippensis* (Lam.) Müll.Arg. (IVI = 85.27)	76.69 to 01.18*
			07**	*Lantana camara* L. (IVI = 158.83)	72.16 to 04.13**
			23***	*Heteropogon contortus* (L.) P. Beauv. (IVI =30.99)	28.41 to 04.12***
			06****	*Millettia extensa* (Benth.) Benth. ex Baker (IVI =125.5)	62.92 to 07.11****
Yn-MDDF	518	21.78	20*	*Diospyros exculpta* Buch.-Ham. IVI = 61.11)	52.59 to 01.42*
			07**	*Lantana camara* L. (IVI = 102.66)	74.15 to 12.83**
			31***	*Heteropogon contortus* (L.) P. Beauv. (IVI =30.99)	26.77 to 02.02***
			02****	*Ichnocarpus frutescens* (L.) W.T.Aiton IVI =250.6)	0 to 49.31****
Pk-DDF	502	7.52	15*	*Senegalia catechu* (L.f.) P.J.H.Hurter& Mabb. (IVI = 158.32)	20.10 to 02.05*
			06**	*Lantana camara* L. (IVI = 217.17)	60.05 to 03.20**
			27***	*Achyranthes aspera* L. (IVI = 38.11)	35.31 to 01.56***
			05****	*Pueraria tuberosa* (Roxb. ex Willd.) DC.(IVI =94.85)	70.35 to 21.76****
Pk-MDDF	378	23.82	25*	*Ceropegia bhatii* S.R.Yadav & Shendage Wall. (IVI= 65.16)	62.83 to 00.18*
			06**	*Lantana camara* L. (IVI = 158.0)	78.00 to 02.11**
			39***	*Achyranthes aspera* L. (IVI = 28.52)	17.55 to 01.45***
			05****	*Pueraria tuberosa* (Roxb. ex Willd.) DC.(IVI =94.85)	70.35 to 21.37****
Pk-STP	315	34.42	09*	*Pinus roxburghii* Sarg. (IVI = 193.41)	26.29 to 06.02*
			08**	*Colebrookea oppositifolia* Sm. (IVI = 69.46)	61.59 to 09.16**
			41***	*Adiantum capillus-veneris* L.(IVI = 29.01)	25.00 to 00.93***
			05****	*Ichnocarpus frutescens* (L.) W.T.Aiton (IVI = 162.15)	46.69 to 16.62****

Details & Abbrevations: Functional groups: * Trees, ** Shrubs, *** Herbs, **** Climbers
Northern tropical dry deciduous *Shorea robusta* forest- (Yn-SRP); Northern tropical dry deciduous Shivalik *Shorea robusta* forest- (Yn-SSR); Mixed dry deciduous forests at Yamunanagar Forest Division- (Yn-MDDF); Dry deciduous Forest at Panchkula Forest Division- (Pk-DDF); Mixed dry deciduous forests at Panchkula Forest Division- (Pk-MDDF); Subtropical Pine- (Pk-STP)

Table 4. Floristic diversity of forests of the Northwestern Himalayan Foothills in Haryana

Forest type	Shannon's index (H)				Margalef's index (D)				Simpson's index (Cd)				Pielou index (e)			
	T	S	H	C	T	S	H	C	T	S	H	C	T	S	H	C
YN-SRP	1.40	1.33	2.93	1.37	4.99	0.69	7.39	3.45	0.21	0.30	0.05	0.29	0.83	0.40	1.71	0.41
YN-SSR	1.61	1.28	2.83	1.42	1.97	1.12	7.28	4.30	0.26	0.36	0.06	0.27	0.70	0.44	1.65	0.43
YN-MDDF	2.44	1.69	3.13	0.44	4.93	0.99	9.55	0.72	0.10	0.21	0.05	0.72	1.24	0.62	2.04	0.05
Pk-DDF	2.15	1.31	2.96	1.51	3.29	0.85	7.91	16.03	0.15	0.35	0.06	0.23	1.07	0.13	1.90	0.46
Pk-MDDF	2.51	1.58	3.28	1.51	7.44	0.81	11.44	16.03	0.12	1.17	0.03	0.23	1.57	0.53	2.34	0.46
Pk-STP	1.23	1.86	3.45	1.30	1.74	1.19	12.93	8.32	0.45	0.16	0.04	0.35	0.45	0.73	2.46	0.39

Details & Abbreviations: Northern tropical dry deciduous *Shorea robusta* forest- (Yn-SRP); Northern tropical dry deciduous Shivalik *Shorea robusta* forest- (Yn-SSR); Mixed dry deciduous forests at Yamunanagar forest Division- (Yn-MDDF); Dry deciduous Forest at Panchkula Forest Division- (Pk-DDF); Mixed dry deciduous forests at Panchkula Forest division- (Pk-MDDF); Subtropical Pine- (Pk-STP); Tree- (T); Shrub- (S); Herb- (H); climber- (C) distributions may also arise in moderately disturbed systems where competitive exclusion is reduced, allowing coexistence of multiple species (Ette et al., 2023; Dar et al., 2025). Therefore, while the log-normal model reflects high diversity, it does not necessarily imply the absence of disturbance. The Shannon diversity index values (1.237–2.510) indicate moderate species diversity compared to global tropical forest standards. Although these values are higher than those of some *Shorea robusta* C.F. Gaertn., forests of the Eastern Himalaya (Uma Shankar, 2001), they remain lower than those reported for highly diverse tropical evergreen forests (Knight, 1975). This suggests that the studied forests, while diverse, may be experiencing ecological limitations such as seasonal drought, soil constraints, or anthropogenic pressures including grazing, fuel wood extraction, and fragmentation. Recent studies have similarly emphasized that human-induced disturbances and land-use changes can significantly reduce species diversity and alter community composition (Thounaojam et al., 2021; Chandra et al., 2025; Dar et al., 2025).

Furthermore, the relatively moderate diversity values may also reflect the dominance of *Shorea robusta* C.F. Gaertn., a species known for forming mono-dominant or semi-dominant stands, which can limit under storey diversity through shading and competitive resource uptake. This aligns with the concept that dominance by a single species can reduce evenness, thereby influencing overall diversity indices. Another critical aspect is the scale of observation and methodology used for diversity estimation. Recent advancements using remote sensing and machine learning approaches have shown that diversity estimates can vary significantly depending on spatial resolution and sampling design (Kumar et al., 2022; Ette et al., 2023). Therefore, methodological constraints should also be considered when comparing diversity values across studies. The forest ecosystems of YFD and PFD exhibit heterogeneous vegetation structure, moderate to high species diversity, and active regeneration patterns. Mixed deciduous forests emerge as biodiversity-rich systems with relatively stable community structure, whereas subtropical pine forests exhibit greater dominance and lower diversity. The predominance of lower girth classes indicates ongoing regeneration; however, the limited presence of mature individuals in some forests suggests past disturbances. The invasion of *Lantana camara* L. represents a critical threat to ecosystem stability. These findings emphasize the need for site-specific forest management strategies focusing on invasive species control, conservation of native biodiversity, and maintenance of ecological resilience to ensure long-term sustainability of forest ecosystems.

4. CONCLUSION

The present study demonstrates that the forest ecosystems of the north-western Himalayan Shivalik foothills in Haryana exhibit considerable variation in floristic composition, vegetation structure, and functional group dynamics across different forest types. A total of 137 plant species belonging to 61 families were recorded, highlighting the rich floristic diversity of the region. Mixed deciduous forests supported the highest species diversity and richness with relatively balanced community structure, whereas subtropical pine forests exhibited greater species dominance and lower diversity. The dominance–diversity curves followed a log-normal distribution, indicating structurally organized plant communities with balanced species distribution across most forest types.

The population structure revealed a predominance of individuals in lower girth classes, indicating active regeneration in the majority of forest ecosystems. However, the comparatively low representation of mature trees in certain forest types suggests differences in stand structure and regeneration status. Functional group analysis showed distinct patterns in the dominance and distribution of trees, shrubs, herbs, and climbers among forest types, reflecting the influence of local environmental conditions on community composition. The widespread occurrence and dominance of *Lantana camara* L. in the shrub layer further emphasizes its prominence across the studied forests.

Overall, the study provides a comprehensive assessment of the floristic composition, vegetation structure, diversity patterns, and regeneration status of the major forest ecosystems of the north-western Himalayan Shivalik foothills. These findings establish a scientific baseline for understanding vegetation dynamics and biodiversity patterns in the region and contribute valuable information for future ecological assessment and monitoring of these forest ecosystems.

Acknowledgements

The support and encouragement from Kurukshetra University, Kurukshetra, and CSIR, New Delhi, are duly acknowledged. The authors would like to acknowledge the help and support received from the Haryana Forest Department during the field survey.

CRediT authorship contribution statement

Ravi Kumar: Conceptulization, Data collection, Methedology, software, writing original draft, Formal analysis, Tabulation, Data curation. **Kushal:** Data collection, Tabulation, formal analysis, Data curation. **Subrata Nandy:** Software for Map preparation, Reviewing and editing. **Balkar Singh:** Reviewing and editing.

Conflict of interest

The authors declare that they have no competing financial interests or personal relationships that may have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

No AI tools were used in data collection, analysis, or interpretation.

Data availability statement

Data generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

REFERENCES

Ayyappan, N., & Parthasarathy, N. (1999). Biodiversity inventory of trees in a large-scale permanent plot of tropical evergreen forest at Varagalaiar, Anamalais, Western Ghats, India. *Biodiversity Conservation, 8*, 1533-1554.

Bhuyan, J.M., Nandy, S., Padalia, H., Pebam, R., Nath, A.J., Kushwaha, S.P.S., & Das, A.K. (2025). Harnessing time-series satellite data and deep learning to monitor historical patterns of deforestation in the eastern Himalayan foothills of India. *Journal of the Indian Society of Remote Sensing*, *53*(4), 993-1008.

Bonan, G.B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science, 320*, 1444-1449.

Champion, H.G., & Seth, S.K. (1968). *A revised survey of forest types of India.* Indian Forest Record., (pp. 286) New Series, Govt. of India Press- New Delhi.

Chandra, A., Naithani, H.B., & Verma, P.K. (2025). Forest phyto-diversity assessment of West Champaran District of Bihar, Eastern India. *American Journal of Agriculture and Forestry*, *13*(2), 103-117.

Chaturvedi, R.K., Ranjith, G., & Jayaraman, M. (2011). Impact of climate change on Indian forests: A dynamic vegetation modeling approach. *Mitigation and Adaptation Strategies for Global Change, 16*, 119-142.

Chovatiya, V.N., Chaitanya, K., Reddy, Y., Rout, Y., Jauhari, R., & Patel, B. (2025). Plant Species Composition and Diversity in Tropical Dry Mixed-Deciduous Forest of Telangana, India. *Indian Journal of Ecology*, *52*(5), 1119-1132.

Condit, R. (1996). Defining and mapping vegetation types in mega-diverse tropical forests. *Trends of Ecology and Evolution, 11*, 4-5.

Curtis, J.T., & McIntosh, R.P. (1951). An upland forest continuum in the prairie-forest border region of Wisconsin. *Ecology, 32*, 476-498.

Curtis, J.T. (1959). *The vegetation of Wisconsin: an ordination of plant communities*. University of Wisconsin Pres.

Dar, J.A., Rathaude, S.K., Irtiqa, S., Abdul Rahim, P.P., Wani, Z.A., Kothandaraman, S. (2025). Disturbance intensity drives structural, compositional and diversity attributes in tropical dry forests of Central India. *Trees, Forests and People*, *20*, 100864.

Dixit, A.M. (1997). Ecological evaluation of dry tropical forest vegetation: An approach to environmental impact assessment. *Tropical Ecology, 38*, 87-100.

Ette, J.S., Ritter, T., & Vospernik, S. (2023). Insights into forest structural diversity indicators with machine learning. *Biodiversity and Conservation, 32*, 1019-1046.

Fisher, M., Martin, L., McGowan, E.S., van Hase, A.J.H.M., Petrokofsky, G., & Spierenburg, M. (2014). Linking conservation and poverty reduction: Landscapes, people and power. *Biodiversity & Conservation, 23*, 2937-2953.

Food and Agriculture Organization (2020). *Global Forest Resources Assessment 2020: Main report*. Rome: FAO. https://doi.org/10.4060/ca9825en.

Forest Survey of India (FSI). (2021). *India State of Forest Report 2021*. Ministry of Environment, Forest and Climate Change, Government of India, Dehradun.

Forest Survey of India (FSI). (2023). *India State of Forest Report 2023*. Ministry of Environment, Forest and Climate Change, Government of India, Dehradun.

HARSAC/CRID, Govt. of Haryana (2021a) *Main report: JSA-CTR Scientific action plan for Panchkula,* Report no 16, page no. 4; 74 pages. https://hsac.org.in/jal/Notification/Panchkula.pdf

HARSAC/CRID, Govt. of Haryana (2021b) *JSA-CTR Scientific action plan for Yamunanagar,* report no. 22, page no. 5; 60 pages. https://hsac.org.in/jal/Notification/Yamunanagar.pdf

IPCC (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Cambridge University Press.

Johnston, M., & Gillman, M. (1995). Tree population studies in low-diversity forests, Guyana I. Floristic composition and stand structure. *Biodiversity Conservation, 4*, 339-362.

Knight, D.H. (1975). A phytosociological analysis of species-rich tropical forest on Barro Colorado Island, panama. *Ecological Monograph*, *45*, 259-289.

Kumar, A., Marcot, B.G., & Saxena, A. (1999). Tree species diversity and distribution patterns in tropical forests of India. *Journal of Tropical Ecology*, *15*(3), 333-354.

Kumar, A., Ram, J., & Tewari, A. (2001). Plant diversity and community structure of forest ecosystems in India. *Forest Ecology and Management*, *148*(1-3): 73-83.

Kumar, A., Marcot, B.G., Saxena, A., Singh, S. P., & Marak, T.T.C. (2002). Floristic composition and species richness in relation to disturbance gradients in Indian forests. *Environmental Conservation*, *29*(3): 356-368.

Kumar, A., Gupta, A.K., Marcot, B.G., Saxena, A., Singh, S.P., & Marak, T.T.C. (2006). Management of forests in India for biological diversity and forest productivity: A new perspective. Garo Hills Conservation Area (GCA). Wildlife Institute of India - USDA Forest Service collaborative project report, vol. IV, Wildlife Institute of India, Dehradun. https://digitalrepository.wii.gov.in/handle/123456789/1316

Kumar, R., Gupta, S.R., Singh, S., Patil, P., & Dhadhwal, V.K. (2011). Spatial distribution of forest biomass using remote sensing and regression models in northern Haryana, India. *International Journal of Ecology and Environmental Sciences*, *37*(1), 21-30.

Gupta, S.R., & Kumar, R. (2014). Biodiversity conservation and ecosystem services of forests in Siwaliks of Northern India. *International Journal of Ecology and Environmental Sciences, 40*(1), 15-28.

Kumar, R., & Gupta, S.R. (2014). Vegetation composition and plant biodiversity in forest ecosystems of Siwaliks in Northern Haryana. *Indian Journal of Fundamental and Applied Life Sciences, 4*(2), 76-88.

Singh, V., Kumar, R., & Bhalla, E. (2016). Plant diversity patterns and tree population structure in tropical dry deciduous forests in semiarid region of north western India. *International Research Journal of Biological Sciences, 5*(4), 19-31.

Kumar, P., Singh, R., Kumar, A., & Pandey, P.C. (2022). Calculating forest species diversity using Sentinel-2A data. *Ecological Informatics, 69*, 101652.

Kushwaha, S.P.S., & Nandy, S. (2012). Species diversity and community structure in sal (*Shorea robusta* C.F. Gaertn.) forests of two different rainfall regimes in West Bengal, India. *Biodiversity and Conservation*, *21*(5),1215-1228.

Kushwaha, S.P.S., Nandy, S., Shah, M.A., Agarwal, R., & Mukhopadhyay, S. (2018). Forest cover monitoring and prediction in a Lesser Himalayan elephant landscape. *Current Science*, *115*(3), 510-516.

Magurran, A.E., (1988). *Ecological Diversity and Its Measurement.* Sydney Croom Helm, London. pp. 179.

Mansingh, A., Pradhan, A., Sahoo, S.R., Cherwa, S.S., Mishra, B.P., Rath, L.P., Ekka, N.J., Panda, B.P. (2025). Tree diversity, population structure, biomass accumulation, and carbon stock dynamics in tropical dry deciduous forests of Eastern India. *BMC Ecology and Evolution, 25*, 48.

Mesa-Sierra, N.M., de la Peña-Domene, M., Campo, J., Giardina, C.P. (2025). Restoration of tropical dry forest: an analysis of constraints and successes across a highly threatened biome. *Frontiers in Environmental Science, 12*. https://doi.org/10.3389/fenvs.2024.1458613

Murphy, P.G., & Lugo, A.E. (1986). Ecology of tropical dry forests. *Annual Review of Ecology and Systematics, 17*, 67-88.

Odum, E.P., (1971). *Fundamentals of Ecology*. Saunders College Publishing, Philadelphia.

Pan Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S., & Hayes, D. (2011). A large and persistent carbon sinks in the world's forests. *Science*, *333*(6045), 988-993.

Parthasarathy, N. (1999). Tree diversity and distribution in undisturbed and human-impacted sites of tropical wet evergreen forest in southern Western Ghats, India. *Biodiversity Conservation, 8*,1365-1381.

Parthasarathy, N. (2001). Changes in forest composition and structure in three sites of tropical evergreen forest around Sengaltheri, Western Ghats. *Current Science, 80*, 389-393.

Pascal, J.P., & Pelissier, R. (1996). Structure and floristic composition of a tropical evergreen forest in south-west India. *Journal of Tropical Ecology*, *12*,191-214.

Phillips, E.A. (1959). *Methods of vegetation study*. Henry Holt and Co., Inc. (pp. 107).

Phillips, O.L., Vargas, P.N., Monteagudo, A.L., Cruz, A.P., Zans, M.E.C., Sanchez, W.G., Yli-halla, M., & Rose, S. (2003). Habitat association among Amazonian tree species: A landscape-scale approach. *Journal of Ecology, 91*, 757-775.

Raghubanshi, A.S., & Tripathi, A. (2009). Effect of disturbance, habitat fragmentation, and invasive plants on floral diversity in dry tropical forest of Vindhyan highlands: A review. *Tropical Ecology ,50*, 57-69.

Shannon, C.E., & Wiener, W. (1949). *The mathematical theory of communication.* Vol. 27, University of Illinois Press, Urbana. (pp. 379-423).

Sharma, R. P., Vacek, Z., Vacek, S., Kučera, M., & Gallo, J. (2025). Species diversity estimation in a typical tropical forest: suitable phenological stage and spatial resolution. *Ecological Indicators*, *168*, 112345.

Singh, V., Kumar, R., & Bhalla, E. (2016). Plant diversity patterns and tree population structure in tropical dry deciduous forests in semiarid region of north western India. *International Research Journal of Biological Sciences, 5*(4), 19-31.

Thounaojam, E., Sahoo, U.K., Mishra, B.P., Lalramnghinglova, H., & Tynsong, H. (2021). Tree diversity and carbon storage in agroforestry systems. *Journal of Environmental Management, 298*,113470.

Uma Shankar (2001). A case of high Tree diversity in a Sal (*Shorea robusta* Gaertn. f.) dominated lowland forest of Eastern Himalaya: Floristic Composition, regeneration, and Conservation. *Current Science, 81*, 776-786.

Wadia, D.N. (1961). *Geology of India*. London: MacMillan & Co.

Whitford, P.B. (1949). Distribution of woodland plants in relation to succession and clonal growth. *Ecology, 30*, 199-208.

Yadav, A.S., & Yadav, R.K. (2005). Plant community structure of Balafort forest in Alwar, Rajasthan. *International Journal of Ecology and Environmental Sciences, 31*,109-117.