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Analysis of Natural Regeneration and Vegetation Status of Tree Species of a Biodiversity Hotspot in Bangladesh

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ABSTRACT

Natural regeneration is crucial for ecosystem restoration and sustainable forest growth. This study provides first comprehensive assessment of naturally regenerating tree species in the Rema-Kalenga Wildlife Sanctuary (RKWS), Bangladesh. Data was collected via systematic random sampling, using 50 plots (20m × 20m), each containing five 1m × 1m subplots, and totaling 250 subplots. The study found 859 individuals representing 67 identified species across 34 families, alongside 5 unidentified species. Among them, 774 individuals (63 species) were native, 24 individuals (4 species) were exotic, and 61 individuals remained 5 unidentified species. Moraceae was the most prevalent family (Family Importance Value = 23.11%) with *Streblus asper* emerging as the most prevalent dominant species (Important Value Index =19.71). Biodiversity indices revealed structural differences between native and exotic regeneration. Native species demonstrated high diversity, richness and evenness (Shannon-Wiener = 3.4540, Richness = 9.3211, Evenness = 0.8337), indicating a mature, stable ecosystem with high functional resilience and even distribution. Conversely, exotic species exhibit low richness and evenness but a paradoxically higher species diversity index (exotic 0.1667 vs. native 0.0814). This disparity reflects the extreme dominance of a few aggressive individuals, signaling an early-stage invasion risk capable of gradually displacing native flora despite the current limited abundance of exotic species. These findings offer crucial baseline insights into the sanctuary's current vegetation status. Ultimately, this study provides a vital scientific foundation for selecting appropriate tree species for future afforestation initiatives and sustainable conservation management strategies within the RKWS.

1. Introduction

Forests are dynamic, renewable natural resources that adopt and evolve through natural regeneration [1]. The capacity of a tree species to successfully complete its life cycle is a vital process for its long-term persistence within a community [2]. Consequently, natural regeneration serves as a critical indicator of forest health, its disruption by changing site factors remains a major concern for ecologists [3]. Forest community structures are primarily driven by site-specific ecological characteristics, species diversity, and regeneration dynamics [4].

The early development phases of trees, including seedlings, saplings, and coppices, are heavily influenced by seasonal variations in micro-environmental factors, which ultimately shape and maintain population structures [5]. Quantitative vegetation assessments are therefore essential, as they identify rare, poorly documented, or ecologically vulnerable, thereby determining the conservation value of specific forest sites [6].

Studying the ecological dynamics of natural tree species regeneration and mitigating anthropogenic challenges may maximize conservation efforts to foster sustainable development and resilience in forest ecosystems [7].

Tropical forests have a massive impact by providing critical ecosystem services like water regulation, carbon sequestration, and climate stabilization and they shelter nearby

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50% of the world's terrestrial animal and plant species [8]. However, growing human population and rapid urbanization have placed a considerable strain on natural forest regeneration. This strain justifies the need for well-formulated policies that ensure the long-term, sustainable forest conservation [9]. Ultimately, the success of sustainably utilizing tropical forests depends heavily on the ability of local flora to regenerate naturally [10]. This ecosystem recovery following a disturbance is the result of a complex interplay among environmental components that driven the natural regeneration process [11].

Bangladesh, a South Asian country, renowned for its rich biodiversity, is facing severe reduction in forest cover. This decline is primarily driven by urban development, agricultural expansion, and the over-exploitation of natural resources [12]. However, natural regeneration promotes ecological restoration across the country [4]. It supports biodiversity by providing a platform for local species and diverse habitats to thrive [4]. This ecological renaissance boosts environmental resilience; ensuring that vital processes like pollination and nutrient cycling continue to function effectively [13].

The Rema-Kalenga Wildlife Sanctuary (RKWS) is the second largest natural forest in Bangladesh, surpassed only by the Sundarbans [14, 15]. Officially designated a protected area, it hosts a diverse range of plant and animal species, playing a crucial role in preserving the country's ecological legacy [15, 16]. The same study also highlights that the sanctuary significantly contributes to safeguarding Bangladesh's ecological balance by providing vital ecological services.

However, between 1994 and 2022, the conversion of forest land into the commercial agricultural land, alongside anthropogenic activities, like the illegal harvesting of vegetation, and tourism, significantly impacted the biodiversity of the RKWS [14]. It is a major threat to the existence of the sanctuary [17]. Moreover, some invasive species have negatively impacted on local ecosystems within the sanctuary [18]. Conversely, a study claimed that forest cover depletion reversed during the co-management period from 2003 to 2018 [19].

Given the ecological importance of the RKWS, evaluating its current natural regeneration and vegetation status is essential for establishing long-term forest sustainability and protection strategies. Because no prior studies have investigated these conditions in the RKWS, this research aims to provide valuable insights by assessing the qualitative and quantitative characteristics of its regeneration processes. Ultimately, this study offers a comprehensive evaluation of species regeneration diversity and status, allowing for a deeper understanding of the sanctuary's overall health. Furthermore, these findings will provide vital insights into the current state of RKWS tree species, shedding light on the ecological balance of the region.

2. Materials and methods

2.1. Study area

The RKWS is located in the Habiganj District of northeastern Bangladesh (Figure 1). The geographical coordinates are 24°06′–24°14′ N latitude and 91°34′–91°41′ E longitude [20]. The sanctuary comprises 1,796 hectares, divided into three parts known as Rema, Chonbari, and Kalenga [20, 21]. The landscape is characterized by a collection of hill ranges of different elevations and lower altitude valleys [22]. The highest peak stands at 67 meters above sea level [22].

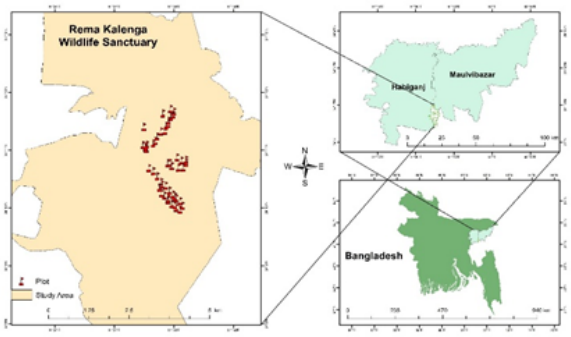


Figure 1. Map of the study area.

It has a tropical climate characterized by abundant rainfall from April to September and a dry season from November to March [21]. The average annual temperature ranges from 9.6°C to 34.8°C, accompanied by a significant rainfall of 4,162 mm [23].

The woodland within the sanctuary was designated as a wildlife sanctuary because of its requirements for conservation and its significant biodiversity [20]. The area is distinguished by its tropical evergreen to semi-evergreen forest, which serves as a natural habitat for many primate species. This includes globally endangered *Hoolock hoolock* and *Trachypithecus phayrei* and globally vulnerable *Ursus tibetanus*, *Nycticebus bengalensis*, and *T. pileatus*. *T. pileatus* has been identified as the flagship species of the sanctuary [24, 25].

2.2. Data acquisition

In September–October 2023, the study was carried out at RKWS to assess the species composition, density, and diversity of naturally regenerating indigenous and exotic tree species. To collect data for RKWS, a direct field survey was conducted using a systematic random sampling approach to select plots. A total of 50 rectangular sampling plots, each measuring 20m × 20m, were laid out with a spacing of 50 meters between them. Five 1m × 1m subplots were established in each plot, positioned at the four corners and the center for data collection. The survey included the identification and counting of plants beyond trees with a diameter at breast height (DBH) less than or equal to 5 cm which were seedlings, saplings, and coppice.

2.3. Data analysis

To evaluate the health, composition and future resilience of RKWS's ecosystems, the following phyto-sociological analyses were done in this study: density (d), relative density (Rd), abundance (A), relative abundance (RA), frequency (F), relative frequency (RF) and importance value index (IVI). Following ecological analyses were done to evaluate health, sustainability and future structural composition of the sanctuary: family relative density (FRd), fam-

Table 1. Equations used in data analysis

No.	Equation	Ref.
1	$d = \frac{\text{Total no. of species in all the quadrants}}{\text{Total no. of quadrants studied}}$	[26]
2	$Rd = \frac{\text{Total no. of individuals of the species} \times 100}{\text{Total no. of individuals of all species}}$	[26]
3	$A = \frac{\text{Total no. of individuals of a species in all the quadrants}}{\text{Total no. of quadrants where the species occurred}}$	[26]
4	$RA = \frac{\text{Abundance of one species} \times 100}{\text{Total Abundance}}$	[26]
5	$F = \frac{\text{Total no. of quadrants in which species occurred}}{\text{Total no. of quadrants studied}}$	[26]
6	$RF = \frac{\text{Frequency of one species} \times 100}{\text{Total Frequency}}$	[26]
7	$IVI = RF + Rd + RA$	[27]
8	$FRd\,\% = \frac{\text{No. of Individuals in a family} \times 100}{\text{Total no. of individuals}}$	[28]
9	$FRdI\,\% = \frac{\text{No. of Species in a family} \times 100}{\text{Total number of species}}$	[28]
10	$FIV = FRd + FRdI$	[28]
11	$SDI = \frac{\text{Total number of species}}{\text{Total number of individuals in the sample}}$	[29]
12	$R = \frac{\text{Total number of species} - 1}{\ln(\text{Total number of individuals in the sample})}$	[30]
13	$H = -\sum P_i \ln P_i$	[31]
14	$H_{max} = \ln(\text{Total number of species})$	[32]
15	$E = \frac{H}{\ln(\text{Total number of species in the sample})}$	[33]
16	$D = \sum P_i^2$	[34]
17	$D' = 1 - S$	[34]

ily relative density index (FRdI), family importance value (FIV), species diversity index (SDI), species richness index (R), Shannon–Wiener diversity index (H), Shannon's maximum diversity index (Hmax), species evenness index (E), Simpson index (D) and Dominance of Simpson index (D'). Table 1 show all equations used in data analysis.

3. Results and discussion

3.1. Results

3.1.1. Qualitative characteristics

This study sought to evaluate the tree species diversity and regeneration dynamics within the RKWS, Bangladesh. In total, 859 individual trees were recorded, comprising 67 identified species across 34 families, along with 5 unidentified species (Table 2). Among them, 774 individuals from 63 tree species were found to be indigenous, whereas 24 individuals from 4 tree species were exotic, and 61 individuals were from 5 unidentified tree species (Table 2). It was found that almost 99.19% of the species regenerated through seedlings or saplings, while the remaining 0.81% was observed to regenerate through coppicing (Figure 2).

The families found in the study were classified into several groups: families consisting of one species, families consisting of two to three species, and families consisting of more than three species. Among the 34 families observed, 47.06% consisted of only one species, 38.24% included two to three species, and 14.71% comprised more than three species. The Moraceae family exhibited the highest diversity, with seven species, while Phyllanthaceae, Myrtaceae, Meliaceae, and Fabaceae each had four species. In contrast, Anacardiaceae and Fagaceae had three species each, and Verbenaceae, Rutaceae, Lauraceae, Elaeocarpaceae, Lythraceae, Apocynaceae, Combretaceae, Rubiaceae, Lamiaceae, Malvaceae, and Dipterocarpaceae had two species each. Lastly, the rest of the families were each represented by a single species. Furthermore, five unknown species were discovered at various sites during the study.

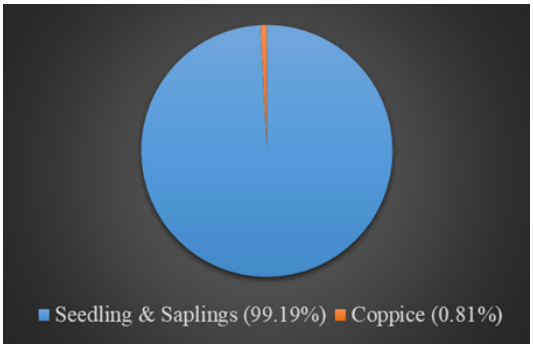


Figure 2. Regeneration mode of tree species in RKWS.

Table 2. Tree species composition in RKWS

Family	Scientific name	Local name	I/E	Seedling (nos)	Sapling (nos)	Coppice (nos)
Verbenaceae	*Vitex peduncularis*	Awal	I	14	3	0
	Vitex glabrata	Badruk	I	17	2	0
Phyllanthaceae	*Aporusa dioica* (Roxb.) Müll.Arg	Kakra	I	46	7	0
	Antidesma ghaesembilla	Bon anna	I	2	1	0
	Phyllanthus emblica L	Amloki	I	4	1	0
	Baccaurea motleyana	Lotkon	I	1	0	0
Rutaceae	*Glycosmis pentaphylla* (Retz.) DC	Kawthoti	I	35	3	0
	Zanthoxylum rhetsa (Roxb.) DC	Bajna	I	0	1	0
Myrtaceae	*Syzygium cumini* (L.) Skeel	Kalo Jam	I	40	7	0
	Syzygium grande	Dhaki Jam	I	32	2	0
	Syzygium fruticosum DC.	Khudi Jam	I	7	0	0
	Syzygium amplexicaule (DC.) N.P.Balakr	Guti Jam	I	14	3	0
Lauraceae	*Cinnamomum glaucescens*	Gonroi	I	1	0	1
	Actinodaphne angustifolia	Pichli	I	36	1	2
Elaeocarpaceae	*Elaeocarpus varunna*	Bon Jolpai	I	18	5	0
	Elaeocarpus floribundus	Belpoi	I	1	0	0
Lythraceae	*Lagerstroemia speciosa* (L.)	Jarul	I	6	4	0
	Lagerstroemia parviflora Roxb.	Sidha Jarul	I	6	6	0
Apocynaceae	*Alstonia scholaris*	Chatim	I	1	1	0
	Holarrhena antidysenterica (Heyne ex Roth) DC	Kurchi	I	2	0	0
Moraceae	*Streblus asper*	Sheora	I	41	4	0
	Artocarpus Chama	Chapalish	I	20	4	0
	Artocarpus lacucha Buch-Ham	Dewa	I	14	1	0
	Ficus virens	Sada Dumur	I	23	0	0
	Ficus hispida	Dumur	I	2	0	0
	Ficus ingens (Miq.)	Lal Dumur	I	2	0	0
	Ficus racemosa L	Jogo Dumur	I	4	0	0
Combretaceae	*Terminalia bellirica*	Bohera	I	14	3	0
	Terminalia chebula	Haritaki	I	2	0	0
Sterculiaceae	*Pterospermum acerifolium* (L.)	Moskanda	I	22	3	0
Flocourtiaceae	*Hydnocarpus kurzii* (King) Warb	Chalmugra	I	7	1	0
Meliaceae	*Toona ciliata* M.Roem	Rongi	I	18	1	0
	Aphanamixis polystachya (Wall.) Parker	Pitraj	I	12	1	0
	Chukrasia tabularis	Chikrasi	I	5	0	0
	Azadirachta indica A. Juss	Neem	I	2	1	0
Rubiaceae	*Gardenia coronaria* Buch.-Ham	Sit	I	6	0	0
	Hymenodictyon orixensis (Roxb.) Mabb	Bon Thona	I	8	1	0
Anacardiaceae	*Spondias pinnata* (L. f.) Kurz	Amra	I	6	1	0
	Mangifera laurina	Uriam	I	4	0	0
	Lannea coromandelica (Houtt.) Merr	Badi	I	5	0	0
Bignoniaceae	*Oroxylum indicum* Vent.	Thona	I	10	3	0
Dilleniaceae	*Dillenia pentagyna*	Hargoja	I	6	5	0
Lamiaceae	*Gmelina arborea*	Gamar	E	2	1	0
	Tectona grandis L. f.	Segun	E	1	1	2
Fabaceae	*Erythrina variegata* L	Mander	I	21	2	0
	Xylia xylocarpa (Roxb.)	Lohakath	I	7	2	0
	Pithecellobium angulatum	Kaimulla	I	4	1	0
	Acacia catechu Willd.	Khoyer	I	2	0	0
Malvaceae	*Abroma augustum* (L)	Ulot Kombol	I	6	0	0
	Sterculia villosa Roxb.	Chandul	I	6	1	0
Fagaceae	*Quercus fenestrata*	Soto Batna	I	1	0	0
	Castanopsis castanicarpa (Roxb.) Spach.	Hingra	I	9	3	0
	Cyclobalanopsis oxyodon	Batna	I	2	0	0

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Table 2 – *continued from previous page*

Family	Scientific name	Local name	I/E	Seedling (nos)	Sapling (nos)	Coppice (nos)
Smilacaceae	*Smilax ovalifolia*	Kumri	I	3	0	0
Burseraceae	*Protium serratum*	Neur	I	14	0	0
Clusiaceae	*Garcinia cowa* Roxb. ex DC	Kaw	I	15	0	0
Dipterocarpaceae	*Dipterocarpus turbinatus*	Garjan	I	12	4	0
	Anisoptera scaphula	Boilam	I	5	5	0
Euphorbiaceae	*Suregada multiflora*	Ban-naranga	E	13	1	0
Theaceae	*Schima wallichii*	Bonak	I	17	0	0
Juglandaceae	*Engelhardtia spicata* Losch ex Bl	Bollos	I	2	0	0
Bombacaceae	*Bombax ceiba* L	Shimul	I	4	2	0
Aquifoliaceae	*Ilex godajam*	Lud	I	10	1	0
Rhizophoraceae	*Bruguiera parviflora*	Lal Kakra	I	9	4	0
Celastraceae	*Lophopetalum wightianum* Arn	Raktan	I	3	0	0
Caesalpinoideae	*Cassia siamea* Lamk	Minjiri	E	3	0	0
Peraceae	*Chaetocarpus castanocarpus*	Sada Kakra	I	2	0	0
	Unidentified 1	Afin	–	18	3	2
	Unidentified 2	Mon	–	4	2	0
	Unidentified 3	Botawal	–	11	1	0
	Unidentified 4	Guruj	–	14	0	0
	Unidentified 5	Bellom	–	5	1	0

3.1.2. *Quantitative characteristics*

The present study sheds light on the importance of family importance value (FIV) and importance value index (IVI) of the recorded species in the RKWS.

The FIV indices of the detected species were displayed in Table 3. Results indicated that the Moraceae family exhibited the highest FIV percentage (23.11%), followed by the Myrtaceae family (17.78%), and the Phyllanthaceae family (12.78%). Conversely, the lowest FIV was observed in the Peraceae and Juglandaceae families, which exhibited values of 1.62%.

The current study examined the frequency, density, abundance, and importance value index (IVI) of plant species in the RKWS. The study found that *Aporusa dioica* (Roxb.) Müll.Arg, *Syzygium cumini* (L.) Skeel, and *Streblus asper* had the highest population densities, with density and relative density values of 0.212 and 6.17%, 0.188 and 5.47%, and 0.18 and 5.24%, respectively. Conversely, *Zanthoxylum rhetsa* (Roxb.) DC, *Baccaurea motleyana*, *Quercus fenestrata*, and *Elaeocarpus floribundus* exhibited the lowest densities and relative densities of 0.004 and 0.12% respectively (Table 3).

Regarding frequency and relative frequency, *Alstonia scholaris* had the highest occurrence rate, with a frequency of 12.4 and a relative frequency of 4.91%. It was followed by *Aporusa dioica* (Roxb.) Müll.Arg and *Actinodaphne angustifolia*, which had frequencies of 11.6 and relative frequencies of 4.60%. On the other hand, *Baccaurea motleyana*, *Zanthoxylum rhetsa* (Roxb.) DC, *Elaeocarpus floribundus*, *Ficus hispida*, *Terminalia chebula*, *Acacia catechu* Willd., and *Quercus fenestrata* had the lowest frequencies and relative frequencies of 0.4% and 0.16% respectively (Table 3).

Furthermore, *Streblus asper* had the highest population density, with an abundance and relative abundance of 22.50 and 14.16%, respectively. *Vitex glabrata*, *Protium serratum*, and *Suregada multiflora* had abundances and relative abundances of 9.50 and 5.98%, 7 and 4.40%, and 7 and 4.40%, respectively, making them the next most abundant species. Conversely, *Alstonia scholaris* exhibited the least abundance and relative abundance of 0.06 and 0.04%, respectively (Table 3).

Ultimately, the importance value index (IVI) scores were computed for each species, incorporating the density, frequency, and abundance of each species. The species with the highest IVI ratings were *Streblus asper* (19.71), *Aporusa dioica* (Roxb.) Müll.Arg (11.92), and *Syzygium cumini* (L.) Skeel (10.21). On the other hand, *Baccaurea motleyana*, *Zanthoxylum rhetsa* (Roxb.) DC, *Elaeocarpus floribundus*, and *Quercus fenestrata* exhibited the lowest Importance Value Index (IVI) scores of 0.90 (Table 3).

To obtain a more comprehensive comprehension of the regeneration state of both native and non-native species in the RKWS, various biological diversity indexes were examined. These included the Species richness index (R), Species diversity index (SDI), Shannon-Winner diversity index (H), Species evenness index (E), and Simpson index (D). The Shannon-Winner diversity index (H) and Shannon's maximum diversity index (Hmax) were highest for indigenous species (3.4540 and 4.1431, respectively) compared to exotic species (0.1316 and 1.3863, respectively). Similarly, Species richness index (R), and Species evenness index (E) were highest for indigenous species (9.3211 and 0.8337, respectively), also Simpson index (D) was highest for indigenous species (0.0253) while exotic species R is 0.9440, E is 0.0949, and D is 0.0003. Species diversity index (SDI) was higher for exotic species (0.1667) than indigenous species (0.0814). Dominance of Simpson index (D') was highest for exotic species (0.9997) compared to indigenous species (0.9747) (Figure 3).

3.2. Discussion

Assessing the process of natural regeneration is a vital aspect of efficient forest management, as it is necessary for the growth of flourishing forest ecosystems [35]. This study examines natural regeneration and tree species diver-

sity in RKWS, offering valuable insight into the ecological patterns of this key biodiversity hotspot in Bangladesh. The findings of this study elucidate the natural regeneration patterns and biodiversity status, which indicate a robust regeneration capacity and a high level of species diversity, with significant implications for forest management and biodiversity conservation.

Table 3. Phyto-sociological analyses of regenerating species in RKWS

Scientific name	Density	RD (%)	Frequency (%)	RF (%)	Abundance	RA (%)	IVI
Vitex peduncularis	0.068	1.98	4.8	1.90	1.42	0.89	4.77
Vitex glabrata	0.076	2.21	0.8	0.32	9.50	5.98	8.51
Aporusa dioica (Roxb.) Müll.Arg	0.212	6.17	11.6	4.60	1.83	1.15	11.92
Antidesma ghaesembilla	0.012	0.35	6.8	2.69	0.18	0.11	3.15
Phyllanthus emblica L	0.02	0.58	1.2	0.48	1.67	1.05	2.11
Baccaurea motleyana	0.004	0.12	0.4	0.16	1.00	0.63	0.90
Glycosmis pentaphylla (Retz.) DC	0.152	4.42	11.2	4.44	1.36	0.85	9.72
Zanthoxylum rhetsa (Roxb.) DC	0.004	0.12	0.4	0.16	1.00	0.63	0.90
Syzygium cumini (L.) Skeel	0.188	5.47	8.4	3.33	2.24	1.41	10.21
Syzygium grande	0.136	3.96	4.4	1.74	3.09	1.94	7.65
Syzygium fruticosum DC.	0.028	0.81	1.2	0.48	2.33	1.47	2.76
Syzygium amplexicaule (DC.) N.P.Balakr	0.068	1.98	4	1.58	1.70	1.07	4.63
Cinnamomum glaucescens	0.008	0.23	5.2	2.06	0.15	0.10	2.39
Actinodaphne angustifolia	0.156	4.54	11.6	4.60	1.34	0.85	9.98
Elaeocarpus varunna	0.092	2.68	5.2	2.06	1.77	1.11	5.85
Elaeocarpus floribundus	0.004	0.12	0.4	0.16	1.00	0.63	0.90
Lagerstroemia speciosa (L.)	0.04	1.16	4	1.58	1.00	0.63	3.38
Lagerstroemia parviflora Roxb.	0.048	1.40	0.8	0.32	6.00	3.78	5.49
Alstonia scholaris	0.008	0.23	12.4	4.91	0.06	0.04	5.19
Holarrhena antidysenterica (Heyne ex Roth) DC	0.008	0.23	0.8	0.32	1.00	0.63	1.18
Streblus asper	0.18	5.24	0.8	0.32	22.50	14.16	19.71
Artocarpus Chama	0.096	2.79	2	0.79	4.80	3.02	6.61
Artocarpus lacucha Buch-Ham	0.06	1.75	3.6	1.43	1.67	1.05	4.22
Ficus virens	0.092	2.68	1.6	0.63	5.75	3.62	6.93
Ficus hispida	0.008	0.23	0.4	0.16	2.00	1.26	1.65
Ficus ingens (Miq.)	0.008	0.23	0.8	0.32	1.00	0.63	1.18
Ficus racemosa L	0.016	0.47	0.8	0.32	2.00	1.26	2.04
Terminalia bellirica	0.068	1.98	7.2	2.85	0.94	0.59	5.43
Terminalia chebula	0.008	0.23	0.4	0.16	2.00	1.26	1.65
Pterospermum acerifolium (L.)	0.1	2.91	2.8	1.11	3.57	2.25	6.27
Hydnocarpus kurzii (King) Warb	0.032	0.93	6.4	2.54	0.50	0.31	3.78
Toona ciliata M.Roem	0.076	2.21	6.4	2.54	1.19	0.75	5.49
Aphanamixis polystachya (Wall.) Parker	0.052	1.51	0.8	0.32	6.50	4.09	5.92
Chukrasia tabularis	0.02	0.58	1.2	0.48	1.67	1.05	2.11
Azadirachta indica A. Juss	0.012	0.35	0.8	0.32	1.50	0.94	1.61
Gardenia coronaria Buch.-Ham	0.024	0.70	2	0.79	1.20	0.76	2.25
Hymenodictyon orixensis (Roxb.) Mabb	0.036	1.05	1.2	0.48	3.00	1.89	3.41
Spondias pinnata (L. f.) Kurz	0.028	0.81	3.2	1.27	0.88	0.55	2.63
Mangifera laurina	0.016	0.47	0.8	0.32	2.00	1.26	2.04
Lannea coromandelica (Houtt.) Merr	0.02	0.58	2	0.79	1.00	0.63	2.00
Oroxylum indicum Vent.	0.052	1.51	0.8	0.32	6.50	4.09	5.92
Dillenia pentagyna	0.044	1.28	4.4	1.74	1.00	0.63	3.65
Gmelina arborea	0.012	0.35	4.4	1.74	0.27	0.17	2.26
Tectona grandis L. f.	0.016	0.47	1.2	0.48	1.33	0.84	1.78
Erythrina variegata L	0.092	2.68	2	0.79	4.60	2.89	6.36
Xylia xylocarpa (Roxb.)	0.036	1.05	3.2	1.27	1.13	0.71	3.02
Pithecellobium angulatum	0.02	0.58	8	3.17	0.25	0.16	3.91
Acacia catechu Willd.	0.008	0.23	0.4	0.16	2.00	1.26	1.65
Abroma augustum (L)	0.024	0.70	2	0.79	1.20	0.76	2.25
Sterculia villosa Roxb.	0.028	0.81	2.8	1.11	1.00	0.63	2.55
Quercus fenestrata	0.004	0.12	0.4	0.16	1.00	0.63	0.90

continued on next page

Table 3 – *continued from previous page*

Scientific name	Density	RD (%)	Frequency (%)	RF (%)	Abundance	RA (%)	IVI
Castanopsis castanicarpa (Roxb.) Spach.	0.048	1.40	6.4	2.54	0.75	0.47	4.40
Cyclobalanopsis oxyodon	0.008	0.23	6.4	2.54	0.13	0.08	2.85
Smilax ovalifolia	0.012	0.35	5.2	2.06	0.23	0.15	2.55
Protium serratum	0.056	1.63	0.8	0.32	7.00	4.40	6.35
Garcinia cowa Roxb. ex DC	0.06	1.75	6.4	2.54	0.94	0.59	4.87
Dipterocarpus turbinatus	0.064	1.86	5.2	2.06	1.23	0.77	4.70
Anisoptera scaphula	0.04	1.16	3.2	1.27	1.25	0.79	3.22
Suregada multiflora	0.056	1.63	0.8	0.32	7.00	4.40	6.35
Schima wallichii	0.068	1.98	4.8	1.90	1.42	0.89	4.77
Engelhardtia spicata Losch ex Bl	0.008	0.23	0.8	0.32	1.00	0.63	1.18
Bombax ceiba L	0.024	0.70	4.8	1.90	0.50	0.31	2.91
Ilex godajam	0.044	1.28	4.8	1.90	0.92	0.58	3.76
Bruguiera parviflora	0.052	1.51	4.8	1.90	1.08	0.68	4.10
Lophopetalum wightianum Arn	0.012	0.35	0.8	0.32	1.50	0.94	1.61
Cassia siamea Lamk	0.012	0.35	0.8	0.32	1.50	0.94	1.61
Chaetocarpus castanocarpus	0.008	0.23	0.8	0.32	1.00	0.63	1.18
Unidentified	0.092	2.68	4.8	1.90	1.92	1.21	5.79
Unidentified	0.024	0.70	1.2	0.48	2.00	1.26	2.43
Unidentified	0.048	1.40	5.6	2.22	0.86	0.54	4.15
Unidentified	0.056	1.63	7.6	3.01	0.74	0.46	5.10
Unidentified	0.024	0.70	6	2.38	0.40	0.25	3.33

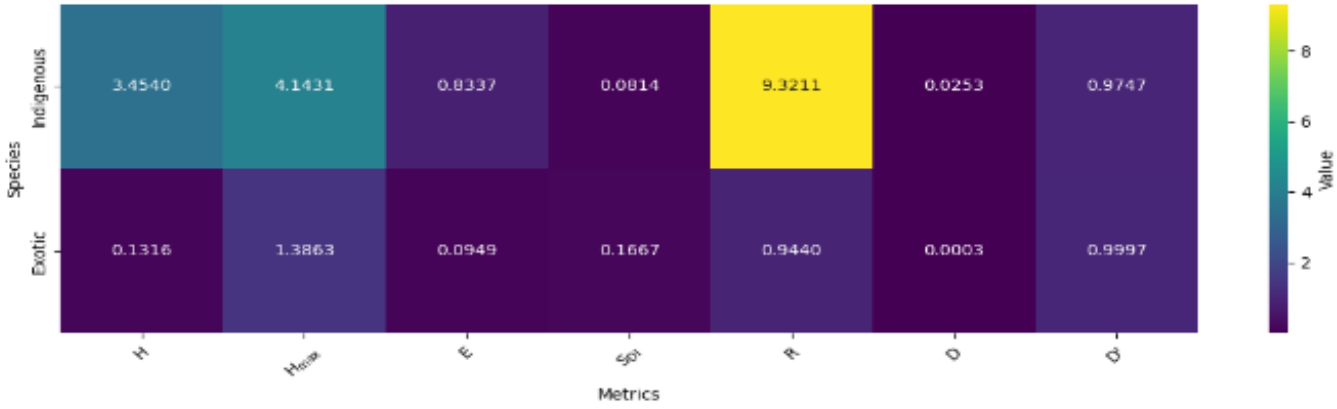


Figure 3. Different ecological indices for indigenous and exotic species.

The survey documented 72 tree species across 34 families in RKWS, a figure notably higher than that reported in other forest ecosystems in Bangladesh. For comparison, 52 species recorded in the Sitapahar natural forest [36], 64 species identified in natural forests and 40 in enrichment plantations in the Chittagong (south) forest division, [37] and 47 regenerating species found in the village common forest in Bandarban [35, 36, 37]. This elevated species richness in RKWS highlights its ecological vitality and underscores the effectiveness of its protected status in supporting diverse tree regeneration.

However, direct quantitative comparisons of metrics such as Relative Density (Rd), Relative Abundance (RA), and Importance Value Index (IVI) across different studies must be made with caution. Sampling designs vary considerably (plot size, number of plots, minimum stem diameter included), as do forest types (e.g., tropical evergreen vs. dry deciduous), successional stages, and disturbance histories. All of these factors can profoundly influence regeneration estimates. Therefore, the following comparisons are intended to highlight broad ecological patterns rather than to assert strict numerical superiority or inferiority of RKWS relative to other sites.

The predominance of regeneration through seedlings and saplings over coppicing further suggests a healthy seed-based regeneration process, likely supported by a viable seed bank and efficient dispersal mechanisms facilitated by the sanctuary's fauna. This contrasts with higher coppicing in Bangabandhu Sheikh Mujib Safari Park (BSMSP) (28%) [38], Chunati Wildlife Sanctuary (CWS) (13%) [39].

The dominance of *Aporusa dioica* (Roxb.) Müll.Arg, *Syzygium cumini* (L.) Skeels, and *Streblus asper* in population density and relative density suggests these species are well-adapted to local environmental conditions, enabling them to establish dense populations. This exceeds values reported in other Bangladeshi forests, such as Khadim-

nagar National Park and Tilagor Eco-Park (KNP/TGEP), where *Tectona grandis* had a relative density of 11.7% [40], and Madhupur National Park (MNP), where *Shorea robusta* reached 42.24% [39]. Moreover, similar trends are observed in other tropical regions, such as Ethiopia's Munessa Natural Forest (MNF), where *Croton macrostachyus* constitutes 25.38% of the relative density [41], and Indonesia's Gunung Jagat Nature Reserve Area (GJNRA), where *Machilus rimosa* (Blume) represents 16.60% at the seedling level [42].

However, *Alstonia scholaris* exhibited the highest frequency and relative frequency (4.91%), indicating its widespread distribution across habitats, even if its localized density is comparatively lower. This contrast underscores that high frequency does not necessarily correlate with high density, reflecting differences in species' dispersal strategies or niche preferences. Notably, these figures exceed the relative frequencies recorded for other dominant species in comparable studies, namely – 6.25% for *Dipterocarpus turbinatus* in BSMSP [38] and *Ficus racemosa* at 14.55% in Satchari National Park (SNP) [43]. In Ethiopia's MNF, *Croton macrostachyus* recorded a relative frequency of 14.71% [41], while at the seedling level in Indonesia's GJNRA, *Machilus rimosa* (Blume) accounted for 10.49% [42].

Streblus asper exhibits remarkable ecological dominance with a high abundance and a relative abundance of 14.16%, signifying its dense occurrence and numerical superiority within its occupied plots. Secondary species, including *Vitex glabrata*, *Protium serratum*, and *Suregada multiflora*, display moderate abundances and relative abundances (5.98%, 4.40%, and 4.40%), contributing to community diversity without surpassing the dominant species. Notably, this surpasses the highest recorded relative abundances of *Shorea robusta* in MNP (11.42%) [40] and *Syzygium cumini* in BSMSP (6.29%) [38], suggesting that *Streblus asper* establish dense stands in its habitat, likely driven by successful recruitment and growth. Even in broader comparisons, *Streblus asper* maintains competitive dominance, though it remains below the exceptionally high relative abundance of *Podocarpus falcatus* (44.15%) reported in MNF, Ethiopia [41].

The synthesis of these metrics into the IVI revealed *Streblus asper* (19.71) as the most ecologically significant species, surpassing others due to its high scores across all parameters. The IVI values serve as indicators of a species' overall dominance within the study area [44]. While this IVI is lower than dominant values recorded in other sites, such as *Shorea robusta* (66.25) in MNP [40], *Artocarpus chaplasha* (41.73) in SNP [43], and *Syzygium fruticosum* (24.10) in BSMSP [39], but higher than *Tectona grandis* (29.66) in KNP/TGEP [23]. This difference likely reflects contrasting forest ecology: Madhupur is a dry deciduous Sal forest where a single climax species naturally dominates, whereas RKWS is a mixed tropical evergreen forest characterized by higher species evenness and lower single-species dominance. Thus, a lower IVI in RKWS does not indicate poorer regeneration but rather a fundamentally different community structure. In a broader regional context, the IVI of *Streblus asper* is considerably lower than *Podocarpus falcatus* (70.29) in MNF, Ethiopia [41], and *Machilus rimosa* (Blume) at the seedling level (27.09) in GJNRA, Indonesia [42], and highlighting variations in species dominance across forest ecosystems. *Aporusa dioica* (11.92) and *Syzygium cumini* (10.21), while dominant in density, ranked lower in IVI due to comparatively lower frequency and abundance, emphasizing that ecological importance hinges on a balance of multiple factors.

The Moraceae family exhibits a high Family Importance Value (FIV) of 23.11% in RKWS, primarily driven by its member *Streblus asper*, which boasts a high Importance Value Index (IVI). Additionally, other Moraceae species, such as *Artocarpus chama* and *Ficus racemosa*, further contribute to the family's ecological success through effective seed dispersal mechanisms that enhance forest regeneration and structure. The strong correlation between high FIV and IVI values and adaptive reproductive traits underscores the integral role of these families, especially Moraceae, in maintaining forest structure, enhancing regeneration, and supporting faunal diversity within RKWS. The high FIV of Moraceae and Myrtaceae reflects their fleshy fruits adapted for animal dispersal, and RKWS's intact frugivore community (primates and birds) likely enhances their regeneration success over wind- or gravity-dispersed families. This is lower than SNP's Moraceae FIV of 52.48% [43] but aligns with CWS (FIV 16.21%) [39] and exceeds KNP/TGEP (FIV 24.24%) [45], suggesting Moraceae's consistent importance across Bangladeshi forests, likely due to effective dispersal by fauna and adaptability. Besides Moraceae, families such as Myrtaceae (FIV 17.78%) and Phyllanthaceae (FIV 12.78%) were identified as important groups, likely benefiting from similar dispersal advantages and favorable microhabitat conditions, contrasting with BSMSP's Myrtaceae (FIV 37.66%) and Euphorbiaceae (FIV 30.33%) dominance [38]. Notably, in GJNRA at the seedling level, the Lauraceae family recorded a high FIV of 28.47%, reflecting its ecological prominence at the seedling level and reinforcing the family's foundational role in tropical Asian forest regeneration dynamics [42].

The results of different biological diversity indices indicate that the Shannon-Wiener diversity index (H), Shannon's maximum diversity index (Hmax), the species richness index (R), the species evenness index (E), and the Simpson index (D) were highest for indigenous species. The native species show high biodiversity with a Species Richness Index (R =9.32), Shannon-Wiener Index (H = 3.45), and Evenness (E = 0.83), while exotic species have lower richness (R = 0.94), diversity (H = 0.13), and evenness (E = 0.09), but high dominance (D' = 0.99). The Simpson's Diversity Index (D) is 0.02 for natives (high diversity) and 0.0003 for exotics (low diversity). The Species Diversity Index (SDI) is 0.08 for natives and 0.17 for exotics. RKWS's native species diversity is similar to that of CWS [39] and KNP/TGEP [45], with Shannon-Wiener indices around 3.6. Notably, this level of diversity is comparable to that observed in other ecologically rich forest areas, including the Parque Estadual das Araucárias (PEAR) in Brazil [46] and Zegie in Ethiopia [47], where Shannon diversity indices also approximate 3.7, highlighting the globally significant biodiversity of RKWS's native flora [48] suggest that species richness is an essential criterion for identifying areas that require conservation efforts to protect biodiversity [48]. In contrast,

the species diversity index (SDI) and the dominance of the Simpson index (D') were highest for exotic species. A study argued that greater diversity can lead to increased community stability [49]. The results indicate indigenous species contribute to a more diverse, species-rich, and ecologically balanced ecosystem. In contrast, exotic species, though exhibiting lower overall diversity, often lead to dominance by one or a few aggressive species. This suggests that native ecosystems maintain healthier equilibrium, whereas exotic species tend to be less diverse but more dominated by a few.

4. Conclusion

In conclusion, this study provides a comprehensive assessment of the natural regeneration and diversity status of tree species in the RKWS, aligning closely with the original research aim. Regenerating individuals belonging to 72 tree species from 34 different families, dominated by Moraceae, Myrtaceae, and Phyllanthaceae. These families play a pivotal role in sustaining regeneration, supported by seed-driven processes and high indigenous diversity. It highlights the sanctuary's ecological health, driven by a diverse array of native trees, and points to the influential role of certain species in shaping the forest's composition. It also reveals a contrast between the rich diversity of indigenous species and the limited but notable presence of exotic ones, offering critical insights for conservation. However, due to the scarcity of comprehensive data, this study could not establish definitive relationships between regeneration patterns and critical biotic factors (e.g., seed dispersal mechanisms) or abiotic factors (e.g., gap size and microhabitat conditions). Despite these limitations, the study establishes a critical baseline for understanding RKWS's regeneration dynamics. Overall, our findings not only fulfill the study's aim by elucidating the composition, diversity, and structural parameters of regenerating species but also offer actionable insights for biodiversity conservation and forest management in protected areas of Bangladesh.

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