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Diversity of Tree Species in Gap Regeneration under Tropical Moist Semi-Deciduous Forest: An Example from Bia Tano Forest Reserve

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Abstract: In a quest to improve the diversity and conservation of native tree species in tropical African forests, gap regeneration remains all-important nature-promoting silviculture practice and ecosystem-based strategy for attaining these ecological goals. Nine gaps of varying sizes (286–2005 m²) were randomly selected: three each from undisturbed, slightly disturbed and disturbed areas within Bia Tano Forest Reserve of Ghana. Within individual gaps, four transects (North–South–East–West directions) followed by 10 subsampling regions of 1 m² at 2 m apart were established along each transect. Data showed 63 tree species from 21 families in the study. Although, all estimated diversity indices showed significant biodiversity improvements in all gaps at $p < 0.05$ level. Yet, there were no significant variations amongst gaps. Additionally, tree species differed between gaps at the undisturbed and the two disturbance-graded areas while no differences were presented between disturbance-graded areas. Balanced conservation between Green Star and Reddish Star species and imbalanced conservation between Least Concern, Near Threatened and Vulnerable species in the International Union for Conservation of Nature (IUCN) Red List were found, showing the reserve’s long-term prospects for economic and ecological benefits of forest management. Thus, there is a need for higher priority for intensive management to regulate various anthropogenic disturbances so as to protect the biological legacies of the reserve.

Keywords: Bia Tano Forest Reserve; conservation; gap; regeneration; species composition; species diversity

1. Introduction

Tropical forests are so endowed with beautiful vegetation that often display a great diversity of tree species including other life forms. Tropical forests mostly present a broad spectrum of optimal growing habitats that have ecologically tolerable niches for the regeneration of diversified tree species [1,2]. Globally, tropical forests are recognized as the most extensive terrestrial biodiversity [2–4], with the tropical moist forests forming an integral component of the global natural forests [5]. So, understanding stand composition and structure is a useful silviculture knowledge in evaluating species conservation, forest management and forest sustainability [6,7]. Unfortunately, most tropical forests are subjects of various environmental and anthropogenic pressures [2,8–10], and thus, if not managed properly, they may pose adverse effects on floral biodiversity in the future. Therefore, silviculture and forest management interventions which are beneficial to the maintenance of the overall biodiversity, productivity and sustainability of tropical forests are needful [11]. For sustainable tropical forest management, natural regeneration is crucial for the preservation and maintenance of biodiversity because it contributes substantially to tree species dynamics and composition within several tropical

forest ecosystems [6,12,13]. Nevertheless, natural regeneration is best enhanced within the gap environment [14–16].

Gap regeneration could be defined as the natural regeneration prevailing under forest canopy gaps. Gaps are openings within forest canopies formed through death(s) or injury(s) of one or more trees in a stand [14,17]. Gap formation is the single most critical event which defines the composition and spatial structure of tropical forests [8] because of its frequent occurrences in the tropics [10,14,18]. The process of gap formation promotes mechanisms for species richness by offering regeneration microsites that have niche diversification along the gap-created light gradient [14,16] for the empowerment of tree species coexistence, and thus, species diversity [18,19]. Furthermore, gaps remain a decisive phase in natural regeneration because they generally determine what would regenerate and also drive the floristic composition of the whole forest cycle following forest disturbances [14,16]. Primarily, species composition within gaps is significantly determined by the chance of gap formation rather than regeneration niches [19,20]. Moreover, the floristic nature of forest communities can predict the regeneration success of tree species depending on the ecological characteristics at growing sites, species diversity and regeneration status of species [6,12]. Notwithstanding, the diagnostic combinations of vegetation characteristics (forest types and vegetation architecture), gap characteristics, plant functional traits and site conditions [21] factors comprehensively influence tree regeneration in gaps. However, the responses of natural regeneration of different tree species in gaps are different because of individual species ecological requirements for growth, particularly concerning their differential light regimes [19,21]. Subsequently, this leads to the organization of tree species with different physiological light-specific demands for establishment and growth in gaps [15,16].

Due to the long-standing exploitation and trade of economic timber products with their bulk quantities being harvested from natural tropical moist forests [9]. Logging operations continue to be more intensified pronouncedly in the semi-deciduous zones than in any other forest type in Ghana due to the hosts of higher densities of economically desirable timber tree species [9,22]. Considering the economic benefits tropical moist semi-deciduous forest offers at both local and global fonts coupled with its immeasurable significant ecological contribution specifically towards global plant biodiversity conservation. It is, therefore, a necessity to strategically channel attention to this positive effect of logging: gap formation on the maintenance of biodiversity extant, which particularly champions restoration and conservation of natural regeneration of different tree species. In Ghana, many floral biodiversity studies have been conducted at other moist semi-deciduous forests namely; Tinte Bepo Forest Reserve [9,23], Pra-Anum Forest Reserve [24] and Asenanyo River Forest [25] as well as other forest types like the moist evergreen forest type [23], including other forest reserves such as Atewa Range Forest Reserve [26], Anhwiaso North Forest Reserve [27] and Kakum Conservation Area [28]. Unfortunately, Bia Tano Forest Reserve (Bia Tano FR) has received very little floral biodiversity research assessment, despite being one of the most cherished forest reserves in Ghana because of its immense economic contribution to the forestry industry in the country. Against this background, the study sought to address the following objectives: (1) to examine regeneration dynamics between natural regeneration tree species with contradictory shade tolerance mechanism at undisturbed, slightly disturbed and disturbed areas within Bia Tano FR (2) to evaluate composition and diversity of natural regeneration tree species in different gaps and (3) to assess variabilities from the impact of varying intensities of anthropogenic disturbances on the conservation status of tree species in gap regeneration.

2. Materials and Methods

2.1. Study Site Description

Bia Tano FR is an African tropical moist semi-deciduous forest (latitude 6°53'–7°05' N and longitude 2°32'–2°42'; 213 m–274 m a.s.l) (Figure 1) in the Ahafo Region of Ghana, West Africa. Bia Tano FR was established in 1937. It covers a total area of 18,197 ha and is being managed by Goaso Forest District under the auspices of Forest Services Division of Forestry Commission of Ghana.

Bia Tano FR shares boundaries with Goa Shelterbelt in North East, Bia Shelterbelt in North West and Bokoni Forest Reserve in the South. Geologically, Bia Tano FR is lying on metamorphosed sediments of lower Birimian age, predominantly schist and phyllites that are spread almost throughout the reserve's bedrock giving rise to weathered soils with low-activity clays. Ochrosol is the prevailing soil type. Annual precipitation ranges between 1250 and 1750 mm while the average monthly minimum and maximum temperatures are 26 °C and 29 °C correspondingly [29]. Great floristic diversity is the biodiversity hallmark of this reserve known for more than 190 plant species representing a manifest diversity of trees, shrubs, herbs and climbers or lianas. Bia Tano FR harbors abundant share of numerous common Ghanaian native tree species that normally find their optimum regeneration conditions in the moist semi-deciduous forest zone reaching a height between 50 to 60 m at the upper canopy creating two or more main cohorts at the forest canopy structure. Three International Union for Conservation of Nature Red List of Threatened Species™ (International Union for Conservation of Nature (IUCN) Red List) including *Baphia nitida*, *Celtis mildbraedii* and *Nesogordonia papaverifera* tree species are prevalent in this reserve.

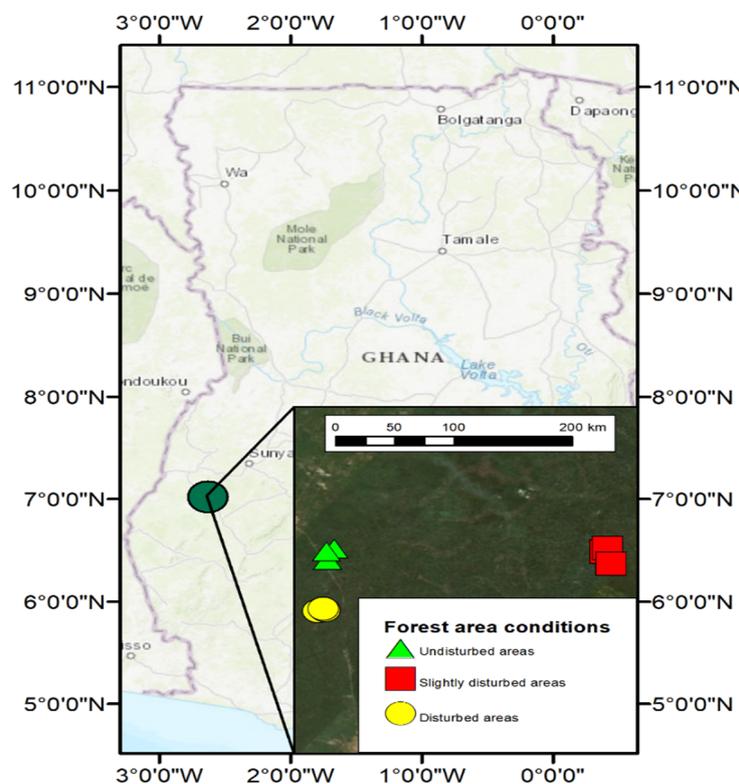


Figure 1. Locations of study areas within Bia Tano Forest Reserve of Ghana.

2.2. Sampling Design

Due to the rich floristic composition and diversity of tree species in Bia Tano FR, anthropogenic disturbances such as logging of timber trees (legal and/or illegal logging) and harvesting of Non-Timber Forest Products (NTFPs) are quite common. Nonetheless, logging stands tall and remains the most significant disturbance variable that explains variations in the various studied forest areas. Based on this, the study site was purposively stratified into three different forest areas to denote varying degrees of anthropogenic disturbances taking place in the forest reserve and assigning Forest Condition Score for tropical forests by Hawthorne and Abu-Juam [30] to illustrate the concise state of the various categorized forest site conditions. Therefore, the undisturbed area belongs to Forest Condition Score 1: this area shows rare signs ($\leq 2\%$) of anthropogenic disturbance (logging) with a good canopy cover; slightly disturbed belongs to Forest Condition Score 2: this area shows few signs ($>2 < 10\%$) of

anthropogenic disturbance with ecologically tolerant mosaic through good regeneration of timber trees and other forest plants, and finally, the disturbed area belongs to either Forest Condition Score 3 or 4: this area shows serious signs ($\geq 11 \leq 75\%$) of visible evidence of anthropogenic disturbance indicating slight to heavy disturbed canopy cover from unregulated logging operations.

To capture the proper appraisal of composition and diversity of natural regeneration tree species in gaps, which are the main focus of this study, i.e., gap regeneration at undisturbed, slightly disturbed and disturbed areas were considered. In the three forest areas, nine (9) gaps were randomly selected comprising three (3) each from undisturbed (Gap 1 = 1895 m²; Gap 2 = 1244 m², Gap 3 = 1249 m²), slightly disturbed (Gap 4 = 1425 m²; Gap 5 = 1465 m², Gap 6 = 2005 m²) and disturbed (Gap 7 = 286 m²; Gap 8 = 607 m², Gap 9 = 884 m²) areas, respectively. In each of the nine (9) selected gaps, a 20 m long four (4) distinct transects to the North (N), South (S), East (E) and West (W) directions were laid from gap centers. Then, all gap centers serving as reference points were georeferenced with the Geographical Positioning System gadget (Garmin GPSMAP, model 66st). After that, 10 circular subsampling regions of 1 m² area (56 cm radius) were marked at 2 m intervals along each transect (N-S-E-W). However, before this gap layout, one subsampling region was earlier created at all gap centers. A total of three hundred and sixty-nine (369) subsampling regions, comprising one hundred and twenty-three (123) (i.e., forty-one (41) per each gap) each for the undisturbed, slightly disturbed and disturbed areas, were used in evaluating natural regeneration tree species in gaps at Bia Tano FR.

2.3. Data Collection and Organization

Within every 1 m² subsampling region, natural regeneration tree species were first identified to species level, assessed morphologically and enumerated with the assistance of a botanist from the Department of Forest Science, the University of Energy and Natural Resources of Ghana and Photo Guide for Forest Trees in Ghana [31]. Species with the diameter at breast height (DBH) <10 cm and height ≤ 300 cm were considered as viable gap regeneration data. The DBH and height features of various natural regeneration tree species were measured using digital calipers (KENDO brand; 35,301 Model; ± 0.01 mm accuracy) and diameter tape (Stanley PowerLock brand), respectively. The data from the three studied forest areas were recorded on separate data sheets to prevent the mixing up of data.

Furthermore, gap regeneration was grouped into three functional tree species according to their natural shade tolerance mechanism (STM) in gap ecology namely; (1) Pioneers, i.e., sun-loving and ecologically light tolerable tree species; (2) nonpioneer light-demanding species (NPLD), i.e., intermediate ecologically light-shade tolerable tree species and, (3) shade bearers, i.e., ecologically shade-tolerant tree species [32,33]. To gain a better understanding of the effect of STM on the dynamics and distribution of tree species under gap regeneration is paramount in ecological studies. Therefore, we hypothesized that different growth behavior and pattern of tree species in gaps would occur as the reason for species' unique individual life-long ecological growth attributes. Based on the findings of previous studies that, in most tropical forests, there is a sequential ecological replacement of tree species essentially through regeneration shifts in species composition [12,22]. Most significant for pioneers, whose abundance begin to decline some years after logging (e.g., after 4 years [14], 7 years [24], 12 years [34], 20 years [35]) due to shorter life span from a more rapid growth character and higher mortality rates and consequently, at the later stages of succession, they are progressively replaced by a more slowly growing nonpioneer species [13].

2.4. Data Analysis

Paleontological Statistics (PAST) 3.24 educational software package [36] was utilized in calculating various assessed biodiversity indices. ANOVA and post hoc Tukey HSD analyses were carried out to show the significance of plant diversity variables means at $p < 0.05$ level, and all these analytical data procedures were executed with STATISTICA software package (13.4.0.14 version; TIBCO Corporation

Inc; Palo Alto, CA, USA). Microsoft Excel software package (2016 version; Redmond, WA, USA) was also used for the graphical presentations of results.

Additionally, relative density (%) was also calculated for each presented species.

$$\text{Relative density} = \frac{\text{Sum of particular species}}{\text{Sum of all presented species}} \times 100 \quad (1)$$

Formulas for different analyzed biodiversity indices based on adopted Equations (Eqn.) from (2) to (7) according to Harper [37] are as follows.

Taxa (S) describes the number of presented species.

Total number (n) of presented individual species.

Simpson's index (1-D) measures the evenness of the natural regeneration community with its indicative values ranging from 0 to 1.

$$D = \sum_i \left(\frac{n_i}{n} \right)^2 \quad (2)$$

Shannon diversity index (H) considered the number of individuals as well as the number of taxa varying from 0 for communities with only a single taxon to high values for communities with many taxa, each with few individuals.

$$H = - \sum_i \frac{n_i}{n} \ln \frac{n_i}{n} \quad (3)$$

Evenness ($e^{\hat{H}/S}$) is another index that measures the evenness of individuals within the taxa community and is widely used to characterize species diversity in a community.

Menhinick's index (Mk).

$$\frac{S}{\sqrt{n}} \quad (4)$$

Margalef's index (Mf)

$$(S - 1)/\ln(n) \quad (5)$$

Equitability (J) measures the evenness whereby individuals are divided among the taxa present and is also known as Pielou's evenness.

$$J = \frac{H}{\ln(S)} \quad (6)$$

Fisher's alpha (α)

$$S = a * \ln(1 + n/a) \quad (7)$$

Meanwhile, two coefficient similarity indices were explicitly defined and calculated according to the equation formulated by Raup et al. [38] based on the binary function of absence-presence data.

Sorensen's coefficient similarity index (SCSI) emphasizes joint appearances of species present in both compared paired groups rather than their mismatches of species occurrences. This index is also termed as the Dice similarity coefficient [37]. SCSI was used for the pairwise comparison of species composition of the three different conditions of forest areas [27].

$$\text{SCSI} = 2M/(2M + N) \quad (8)$$

Jaccard coefficient similarity index (JCSI) is another form of similarity index for binary data which has equal relevance as SCSI [38]; however, it was used to give a clear state of the presence or absence of species between different paired forest areas [39].

$$\text{JCSI} = M/(M + N) \quad (9)$$

where; S is the number of taxa, n is the number of individuals, D is Dominance, n_i is the number of individuals of taxon i th, \ln is the logarithm, a is Fisher's alpha, M is the number of species matches

within the comparison pair and N is the sum number of species frequencies at forest areas in a column with a presence in just one row of species frequency.

3. Results

3.1. Description of Tree Species Composition in Gaps

A total of 752 individuals belonging to 63 species from 21 families and 52 genera were enumerated in the study (Table 1). Malvaceae and Meliaceae, with ten (10) species each, were the most diverse families, followed by Fabaceae with eight (8) species, and Moraceae with six (6) species while Melastomataceae, Ochnaceae, Olacaceae, Pandaceae, Putranjivaceae, Rutaceae, Sapindaceae and Urticaceae families were presented by only one species each. NPLD topped species composition with 27 species, followed by pioneers with 21 species while SB accrued the lowest count of 15 species. With conservation status of tree species, 32, 12, 12 and 7 species were acknowledged as Green Star, Pink Star, Scarlet Star and Red Star, respectively, under Conservation Star Ratings (CSR) system while under International Union for Conservation of Nature Red List of Threatened Species™ (IUCN Red List) system, higher count of Least Concern (LC) (34) species compared to Vulnerable (VU) (14) and Near Threatened (NT) (3) species were recognized alongside 12 other Not Evaluated (NE) not enlisted Red List species (NE*). *Nesogordonia papaverifera*, *Baphia nitida* and *Blighia sapida* species were commonly present in all gaps with their abundant proliferation records in Gap 9 (38%), Gap 4 (37%) and Gap 6 (13%), respectively.

Table 1. Cont.

Species	Families	Conservation System			Relative Density (%)								
		STM	CSR	IUCN	Gap 1	Gap 2	Gap 3	Gap 4	Gap 5	Gap 6	Gap 7	Gap 8	Gap 9
<i>Trichilia tessmannii</i> Harms.	Meliaceae	NPLD	Green	LC	—	—	—	—	2.13	3.85	—	—	—
<i>Trilepisium madagascariense</i> DC.	Moraceae	NPLD	Green	NE*	—	—	—	—	—	—	1.18	0.94	—
<i>Khaya anthotheca</i> (Welw.) C. DC.	Meliaceae	SB	Scarlet	VU	—	—	—	—	—	—	—	—	1.12
<i>Guarea cedrata</i> (A.Chev.) Pellegr.	Meliaceae	SB	Red	VU	0.81	—	—	—	—	—	—	—	—
<i>Celtis mildbraedii</i> Engl.	Cannabaceae	SB	Pink	LC	8.13	4.26	2.13	11.27	—	1.92	24.12	13.21	25.84
<i>Nesogordonia papaverifera</i> (A. Chev.) Capuron ex N. Hallé.	Malvaceae	SB	Pink	VU	30.89	19.15	10.64	21.13	19.15	9.62	4.71	11.32	38.20
<i>Strombosia glaucescens</i> Engl.	Olacaceae	SB	Pink	LC	—	—	—	—	4.26	13.46	2.94	3.77	—
<i>Baphia nitida</i> Lodd.	Fabaceae	SB	Green	LC	7.32	27.66	31.91	36.62	21.28	9.62	1.76	1.89	2.25
<i>Carapa procera</i> DC.	Meliaceae	SB	Green	LC	—	—	—	—	2.13	—	—	—	—
<i>Chrysophyllum albidum</i> G. Don.	Sapotaceae	SB	Green	NT	1.63	—	—	—	—	—	5.29	5.66	3.37
<i>Cleidion gabonicum</i> Baill.	Euphorbiaceae	SB	Green	NE*	8.94	—	—	—	—	—	—	—	—
<i>Glyphaea brevis</i> (Spreng.) Monach.	Malvaceae	SB	Green	NE*	0.81	2.13	—	—	—	—	—	—	—
<i>Hymenostegia afzelii</i> (Oliv.) Harms.	Fabaceae	SB	Green	NE*	—	—	—	—	17.02	3.85	—	—	—
<i>Mallotus oppositifolius</i> (Geiseler) Müll.Arg.	Euphorbiaceae	SB	Green	VU	—	2.13	10.64	—	—	—	—	—	—
<i>Memecylon lateriflorum</i> (G. Don) Bremek.	Melastomataceae	SB	Green	LC	—	—	—	—	6.38	17.31	—	1.89	6.74
<i>Microdesmis keayana</i> J. Léonard.	Pandaceae	SB	Green	NE*	13.82	2.13	2.13	7.04	—	5.77	2.35	1.89	—
<i>Monodora myristica</i> (Gaertn.) Dunal.	Annonaceae	SB	Green	LC	—	—	—	—	4.26	3.85	—	—	—
Total					100	100	100	100	100	100	100	100	100

Source: authors construct [2020].

3.2. Regeneration Dynamics between Pioneers and Shade Bearers in Gaps at Different Site Conditions

Our analysis investigating the ecological regeneration shift of pioneers to shade bearers in gap regeneration at three different forest areas in Figure 2 by logarithmic equations indicated that the rate of sequential replacement of pioneers by shade bearers in gaps at the slightly disturbed area (+1.2) was highly rapid compared to the undisturbed area (+7.8) whereas a worse ecological replacement was found at the disturbed area (+24.8). Besides, a stronger replacement relationship between concerned species within gaps at slightly disturbed (76%) and undisturbed (70%) areas were observed, while a much weaker ecological association was detected in disturbed areas (28%).

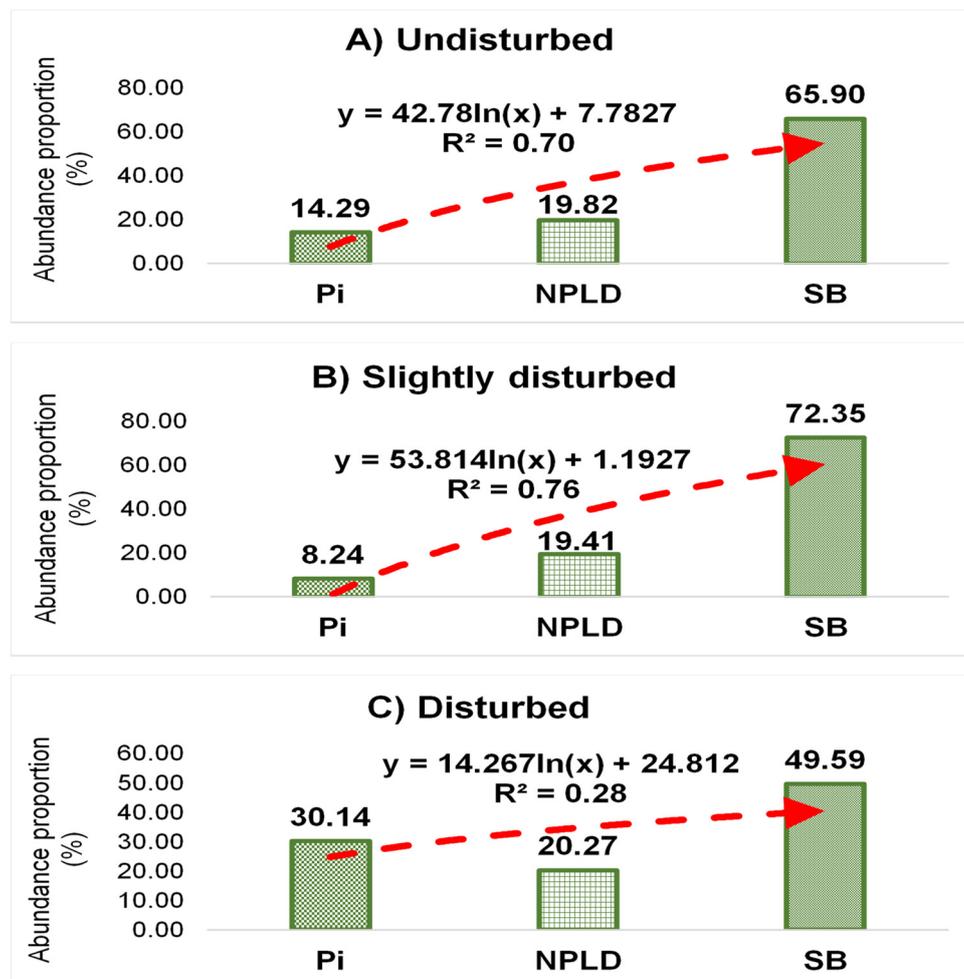


Figure 2. Ecological regeneration shift of tree species in gap regeneration under different forest areas (A–C). Pi—Pioneers, NPLD—Nonpioneer light-demanding species and SB—Shade bearers. Source: authors construct [2020].

3.3. Description of Tree Species Diversity in Gaps

Estimations of various engaged diversity indices (Taxa (mean range 11–28 S), Simpson's index (0.8–0.9 1-D), Shannon diversity (1.9–2.8 H), Evenness (0.4–0.7 e^H/S), Equitability (0.7–0.9 J), Menhinick (1.4–2.7 Mk), Margalef (2.5–5.7 Mf) and Fisher alpha (4.3–12.2 α)) revealed higher species diversity in gap regeneration (Table 2). Further, all estimated diversity indices showed significant biodiversity improvements in all studied gaps at $p < 0.05$ significance level. Yet still, there were no significant variations from gap to gap, except for Gap 8 (12 α) that significantly measured the highest species diversity for the Fisher alpha index (Table 2).

Table 2. Various biodiversity indices comprising Taxa (S), Individuals (N), Simpson's index (1-D), Shannon diversity index (H), Evenness index (e^{-H/S}), Menhinick's richness (Mk), Margalef (Mf), Equitability (J) and Fisher alpha (α) presenting species diversity of gap regeneration at Bia Tano Forest Reserve of Ghana. Mean values with corresponding standard errors in parentheses are presented.

Gaps	S	N	Diversity Indices						
			1-D	H	e ^{-H/S}	Mk	Mf	J	α
Gap 1	26	123	0.86(0.02) ab	2.52(0.11) cd	0.49(0.05) ab	2.25(0.09) b	5.00(0.21) d	0.78(0.03) ab	9.49(0.58) b
Gap 2	15	47	0.85(0.03) ab	2.27(0.11) abcd	0.65(0.07) a	2.19(0.00) b	3.64(0.00) ac	0.84(0.04) ab	7.61(0.00) b
Gap 3	11	47	0.80(0.03) ab	1.92(0.12) a	0.64(0.07) ab	1.56(0.05) a	2.51(0.09) b	0.81(0.44) ab	4.31(0.21) a
Gap 4	14	71	0.79(0.04) ab	1.99(0.13) ab	0.54(0.06) ab	1.58 (0.08) a	2.89(0.16) ab	0.76(0.04) ab	4.86(0.36) a
Gap 5	18	47	0.87(0.02) ab	2.42(0.12) abcd	0.67(0.07) ab	2.48(0.15) bc	4.16(0.26) c	0.85(0.03) ab	9.65(1.02) b
Gap 6	18	52	0.89(0.02) ab	2.54(0.10) cd	0.73(0.06) b	2.40(0.09) bc	4.13(0.17) c	0.89(0.03) b	9.13(0.62) b
Gap 7	19	170	0.78(0.02) ab	2.02(0.10) abc	0.42(0.04) a	1.38(0.00) a	3.31(0.00) a	0.70(0.03) a	5.09(0.00) a
Gap 8	28	106	0.91(0.01) b	2.77(0.09) d	0.58(0.05) ab	2.69(0.03) c	5.72(0.07) d	0.83(0.03) ab	12.18(0.24) c
Gap 9	15	89	0.77(0.03) a	1.88(0.12) a	0.47(0.05) ab	1.48(0.11) a	2.89(0.22) ab	0.71(0.04) ab	4.69(0.48) a
df			8	8	8	8	8	8	8
F			3.97	8.49	3.13	37.97	44.35	3.21	32.51
p			**	***	*	***	***	*	***

Means bearing same letters describe homogenous groups while those with different letters show significant differences at considered $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***) significance levels, respectively. Source: authors construct [2020].

In addition, composite tree species in gaps for paired undisturbed \times slightly disturbed areas as well as paired undisturbed \times disturbed areas showed lower SCSi values of less than 0.5 representing 33% and 32% of mutual similar species, respectively, following JCSI measure. Nonetheless, paired slightly disturbed \times disturbed areas showed a greater SCSi value of more than 0.5 representing a higher shared similar species of 37% by JCSI measure (Table 3).

Table 3. Using Sorensen's Coefficient Similarity Index (SCSi) and (JCSI) Jaccard Coefficient Similarity Index to compare species composition among three contrasting forest areas.

Paired Areas	Species Presence		Similarity Indices	
	Unique Species	Shared Species	SCSi	JCSI
Undisturbed \times slightly disturbed	36	16	0.49	0.33
Undisturbed \times disturbed	34	16	0.48	0.32
Slightly disturbed \times disturbed	32	18	0.54	0.37

Source: authors construct [2020].

3.4. Description of Conservation Status of Tree Species in Gaps

Among species variations within site-condition level (vertical comparison) (Table 4), significant differences between species at undisturbed ($df = 3$, $F = 6.136$, $p = 0.018$) and slightly disturbed ($df = 3$, $F = 16.542$, $p = 0.001$) areas for CSR system and only slightly disturbed area ($df = 3$, $F = 14.353$, $p = 0.001$) for the IUCN Red List system were measured, respectively. Nevertheless, no significant difference ($p > 0.05$) was estimated among species at the disturbed area for the CSR system and repeatedly, at undisturbed and disturbed areas, respectively, for the IUCN Red List system. More so, among site-condition variations within species level (horizontal comparison), only VU species showed significant difference among studied site conditions ($df = 2$, $F = 20.448$, $p = 0.002$), revealing species higher significant mean regeneration density at disturbed areas compared to the other two forest areas (Table 4).

Table 4. Multiple comparison tests of the conservation status of tree species in gap regeneration under three different forest areas from a regional Conservation Star Ratings (CSR) and global International Union for Conservation of Nature (IUCN) Red List of Threatened Species™ perspectives. Mean values with corresponding standard errors in parentheses are presented.

Conservation System	Conservation Status	Mean Regeneration Density Per Hectare (n/ha)		
		Undisturbed	Slightly Disturbed	Disturbed
CSR	Green Star	244 (36.38) a	216 (28.11) a	449 (161.49)
	Pink Star	142 (68.64) ab	116 (37.15) ab	1134 (482.26)
	Red Star	65 (11.86) b	16 (9.75) b	1230 (874.59)
	Scarlet Star	21 (5.36) b	12 (2.45) b	85 (30.77)
IUCN Red List	LC	215 (8.00)	235 (47.68) a	1332 (636.5)
	NT	49 (15.92)	2 (2.34) b	248 (127.38)
	VU	138 (42.22) A	69 (19.24) b A	351 (31.99) B
	NE*	71 (59.23)	54 (13.10) b	967 (781.13)

Means bearing the same letters describe homogenous groups while those with different letters show significant differences at $p < 0.05$ significance level in columns (between species variation—lower-case letters) and rows (between forest areas variation—upper-case letters), respectively. However, means without any alphabet showed no significant differences at $p < 0.05$ significance level. LC—Least Concern, NT—Near Threatened, VU—Vulnerable and NE*—Not Evaluated (NE) not enlisted Red List species. Source: authors construct [2020].

4. Discussion

4.1. Assessment of Regeneration Dynamics between Pioneers and Shade Bearers in Gap Regeneration

The lower abundance proportion of pioneers in gap regeneration in this study substantiates that the proliferation of pioneers is temporary, and with time, regeneration composition gradually begins to shift to shade bearers [13,24]. The imbalance between high establishment and low survival rates of pioneers in gaps explains the observed regeneration dynamics of pioneers in Figure 2. This ecological behavior of pioneers creates an opportunity for nonpioneers to always take over regeneration under gap ecology by increasing their abundance proportions [13]. Another reason was the height of the bordering trees of gaps which transformed the incoming high direct light factor into a low direct light and high diffuse light conditions at gap microsites leading to the creations of unexpected comparable shading conditions, pronouncedly found after the fifth positions of subsampling regions (within 12–20 m² area). This limiting light conditions within gaps became an inconvenient growing condition for the development of pioneers but favorable for the unmatched proliferation of shade bearers. Previous studies by Čater et al. [15] proved our observation. Thus, it confirms that shade bearers have physiological and morphological plasticity, which grants them the adaptation ability to grow well and survive better under light environments like that of gaps [42]. Additionally, physiological processes such as photosynthesis could probably be linked to the observable fast replacement rate of pioneers to shade bearers within gaps at undisturbed and slightly disturbed areas. For instance, pioneers have high dark respiration, compensation point, saturation limit and quantum yield efficiency that only make them significantly flexible for growth under different light conditions, but not sufficient enough for their survival under total forest shade condition while nonpioneer species could illustrate relatively little increase in growth when light factor intensifies because of their low dark respiration, compensation and saturation points characteristics [23]. This explains why weighted abundance percentages of shade bearers (66–72%) in gaps at undisturbed and slightly disturbed areas were comparatively higher than those weighed for pioneers (8–14%), respectively. Similarly, this regeneration dynamics trend of ecological relationship between tree species with divergent STM in gap regeneration has been reported in the Brazilian rainforest [43]. Furthermore, a contradictory observation was made at the disturbed areas where regeneration shifts from pioneers to shade bearers composition in gaps was extremely slow and unpredictable. This gives an indication that disturbed areas probably created resilient grounds for the survivability of pioneers' regeneration as compared to other forest areas. The occurrence of

the rate of pioneer regeneration reaching equilibrium with pioneer mortality rate as the result of regular adequate light supply and minimum soil surface disturbances from frequent anthropogenic disturbances in gaps at the disturbed area significantly defend this regeneration succession. Similar findings have been reported in tropical South American forests [13,44]. Hence, our result attests that pioneers are the worst variants, while shade bearers are the late opportunistic tree species in gap regeneration.

Generally, our results were contrary to studies of Abiem et al. [33] who found no apparent association between tree species with contrasting shade tolerance mechanisms.

4.2. Assessment of Composition and Diversity of Tree Species in Gap Regeneration

4.2.1. Species Composition

The higher species count (63) in this study (Table 1) justifies that tropical African forests are plant species enriched [4,33]. Our result is consistent with studies from China [21] and Brazil [13,44] but opposes to other works conducted in Europe, e.g., [15,19,45] and elsewhere in Asia, e.g., [20,46], where usually less than ten (10) tree species were enumerated in gap regeneration experiments in broadleaved mixed forests.

Additionally, the predominant composition of NPLD species in the total species composition was discovered in results. This finding has been reported also in mixed-oak forests at the southern Appalachians in America, where shade-intermediate *Quercus rubra* and *Acer rubrum* species abundantly occurred in the different studied gap plots [47]. It is self-evident that NPLD species sidelined cohabiting gap-dependent pioneers in gap regeneration. This finding corroborates an assertion that pioneers always experience increasing competition from nonpioneers [48]. The inherent light-shade character of NPLD species assisted them to adapt immediately and easily to the ever-changing light conditions within gaps and possibly gave them a leading advantage over other species groups in gaps. Moreover, higher enumeration of pioneers compared to shade bearers was noted in this study. The biological light-loving characteristic of pioneers propelled their flourishing regeneration performances in gaps. This observation supports the statement that pioneers prefer gaps/light environments/open areas for germination and growth [13,20,33]. Amongst, the STM groups of species, shade bearers (15 species) obtained the least representation in the overall species composition. The biological shade-tolerant character and ecological shade demanding behavior limited their regeneration capability in gaps. The combination of Pink Star, Red Star and Scarlet Star is termed as Reddish Stars [30]. It was detected that studied gaps presented balanced proportion (1:1) between Green Star and Reddish Stars in assessed species composition under CSR system while under IUCN Red List system, the proportion of LC species was comparatively higher than NT, VU species as well as the NE* species (11:1:4:4), respectively. The imbalance between not threatened LC and threatened NT, VU species in the IUCN Red List is comparable to the account of Pelletier et al. [49]. In forest practice, species proportion is the most frequently used applicable species composition indicator which describes how species occupy a particular growing space at stand level and also serves as a reliable growth and yield predictor at the forest level [50]. The comparable presence of Green Star (32 species) and Reddish Stars (31 species), as well as a higher proportion of LC species, suggests that Bia Tano FR has a good forest standing in terms of ecological resilience for promoting concurrent economic and ecological agenda of sustainable forest management in the long-term.

Notwithstanding, the assemblage of different tree species with varying biological, ecological and conservation characteristics in studied gaps was possibly due to the generation of a wide range of regeneration niches within gaps. These niches became ecologically stable microsites that provided optimal diverse light condition requirements for different species with distinctive ecological growth demands as well as different developmental life history attributes. Our findings that gaps are excellent assemblage places for different species agree with a couple of studies (e.g., [16,20]) but protest strongly to an assertion from Jaloviar et al. [19] that gaps do not necessarily provide primary environments for

regeneration and species coexistence because they found the organization of relatively homogenous tree species composition in gaps during their studies.

4.2.2. Species Diversity and Similarity Check

Many studies have recounted the significance of species diversity on forest functioning, productivity, stability and provision of ecosystem services [45,50,51]. However, this study would be contributing to the important effect of gap regeneration on tree species diversity from the tropical African viewpoint. From the study results, a wealthy worth of tree species was expressly observed (Table 1), which indicated rich biodiversity across all evaluated gaps in Bia Tano FR. Presented high species diversity and richness in gaps (Table 2) could primarily be linked to two explanatory factors. The first explanatory factor being that gaps as the growing sites for the investigation of tree species diversity. Therefore, gaps as growing spaces usually offer adequate amounts of needful growth resources for seed germination and seedling development due to their ability to sequester resources [42]. The influence of gaps on microenvironmental heterogeneity factors such as variability in light, soil moisture, soil temperature and nutrient availability leads to the promotion and maintenance of species diversity within gap sites [52]. The second explanatory factor being that Bia Tano FR as a growing habitat for the investigation of tree species diversity. Therefore, the ecological settings within this particular tropical moist semi-deciduous forest type provided a broad spectrum of optimal growing niches for different suites of tree species [53]. This, in effect, significantly influenced and improved the organization of high species diversity and richness within gaps across the three studied forest areas. This validates the statement that Bia Tano FR has a magnificent species diversity comprising more than 190 plant species serving as one of the outstanding floral biodiversity repositories in Ghana [53]. Further, it was observed that gaps (i.e., Gaps 7–9) at disturbed areas enumerated the highest species individuals in the study. The massive contribution of native pioneers' regeneration significantly explained this observation. Constant high light availability in gaps [23], regular forest disturbances including other recurrent anthropogenic activities and fast-spreading nature of pioneers in tropical forests [31] seemingly influenced the prolific natural regeneration behavior of pioneers at disturbed areas. However, copious seed supply from parent stands, seed dispersal from the canopy cover, seeds repository and available healthy mother trees at undisturbed areas influenced the high number of species individuals in Gap 1. A similar observation was made in the tropical rainforest of the Congolese Basin in the Republic of Congo, where Ifo et al. [39] detected that studied plots at degraded and primary forests achieved the highest taxa and species individuals' records and they affirmatively associated soil type, rainfall trends, anthropogenic action, and land-use change as the underlying reasons for their observation. Contrary to our results, the range of values for Simpson's (0.96–0.97 1-D), Shannon diversity (3.77–3.90 H), Menhinick (2.51–2.82 Mk), Margalef (11.62–13.06 Mf), and Fisher alpha (20.72–24.16 α) indices obtained in another study at Kakum Conservation Area (highly protected area in Ghana) by Wiafe [28] were comparatively higher than the respective range of values estimated in this study. Nonetheless, the maximum attained value of the Equitability index (0.89 J) was relatively higher than the range of values for the same diversity index in Wiafe's [28] study.

According to the literature [27], if the SCSi value is lower than 0.5, then the paired communities share different species composition, but if the index is greater than 0.5, then the paired communities share similar species composition. Therefore, the species similarity tests (Table 3) revealed a clear distinction of species composition in gaps between undisturbed \times slightly disturbed areas and again, between undisturbed \times disturbed areas, respectively. Nonetheless, it could be deduced that slightly disturbed \times disturbed areas shared similar species composition. Apart from paired undisturbed \times disturbed areas (0.48) that shared parallel outcome with results of undisturbed and heavily disturbed areas (0.33) in Wiafe [25], both undisturbed \times slightly disturbed (0.49) and slightly disturbed \times disturbed (0.54) areas shared contradictory results with their counterparts; undisturbed and slightly disturbed (0.55) and slightly disturbed and heavily disturbed (0.47) areas, respectively, in the same mentioned study. Additionally, it was observed that gaps at undisturbed \times slightly disturbed areas shared a higher number

of different tree species, followed by undisturbed \times disturbed areas while slightly disturbed \times disturbed areas presented poor species dissimilarity records (Table 3). The dissimilarities of unique species composition could probably be associated to the contrasting ecological settings from different intensities of forest disturbance events at the studied forest areas, differences in microenvironmental conditions at the stand level together with differential conditions within gap microsites that substantively determine species germination, establishment and development at the forest understory. Conversely, similar forest site conditions due to the slight variations of forest disturbance regimes (intensity, scale, and frequency) between slightly disturbed and disturbed areas created regeneration avenues that favored tree species with similar life history attributes ending up in the assemblage of a high count of common species (18 species).

4.3. Assessment of Conservation Status of Tree Species in Gap Regeneration

Species conservation schemes have become an integral component of biodiversity and conservation studies of forests because they give a clear picture of the conservation status of various tree species and at the same time, bring out the conservation potential of a forest by drawing attention to the exact state of tree species vulnerability to life-long exploitation attributes and intensity alongside revealing the current state of forest degradation in general. For this paper, the considered CSR and IUCN Red List systems are particularly significant in evaluating the comprehensive conservation status of all identified tree species in gap regeneration. Therefore, the CSR system is a robust scientific-based accepted species conservation scheme for assessing forest trees in Ghana describing the rarest to common tree species by *Star Ratings* [30] while the IUCN Red List system is a key tool for conservation [49] and authoritative guide to the status of biodiversity relevant to all species (i.e., plants and animals) and all regions of the world [41] revealing the global level conservation status of tree species in this study.

From the presented CSR results (Table 4), four Stars out of the seven (7) (i.e., Green Star, Pink Star, Red Star, Scarlet Star, Blue Star, Gold Star and Black Star) recognized Stars under CSR were found in the study. The prevalent composition of Pink Star and Green Star species in gaps at undisturbed and slightly disturbed areas could be attributed to the dominance of these tree species in the forest ecosystem. Our results are consistent with the findings of Akoto et al. [27] who enumerated the abundance proportion of natural regeneration of Green Star species at three different vegetation types, respectively. Besides, these groups of species are not under any form of exploitation threats because they have moderate to low commercial interests [28]. Hence, these two Star Ratings have no particular conservation concerns for now in Ghana. Further, low seeds production coupled with poor quality and inviable seeds by few unproductive and overly matured Scarlet and Red Stars trees due to the restricted passive forest management guideline at undisturbed areas while overexploitation of mother Scarlet and Red Star trees at slightly disturbed areas could be explained for the unimpressive regeneration performances of both Star species within gaps at those forest areas. Generally, the low regeneration composition of Scarlet Star and Red Star species in gap regeneration was possible to challenge their status as commodities of high financial value and utilitarian merit by undermining their population structure and degrading their bioquality in the study site. However, no species belonging to Blue Star, Gold Star and Black Star (high conservation concern) were encountered across all studied forest areas. Similar studies in other forest reserves of the moist semi-deciduous forest zone of Ghana documented the same findings [54,55]. The rarity of these species in gap regeneration projects substantive evidence on forest degradation in terms of biological legacy and genetic quality at the study site. The values of the various Star Ratings could be helpful guides for the identification of genetic hotspots within forests [22]. In view of this, disturbed areas seem to be genetically viable for biodiversity hotspots of Green Star, Pink Star, Red Star, and Scarlet Star species of the study area.

For IUCN Red List system, the significant widely spread of LC species within gaps at slightly disturbed areas indicated the predominant spreading of their mother producing trees which required no protection priority because of minimal hunting concern by loggers while nature-degrading overexploitation regimes of various tree species for economic benefits were associated with the

significant low regeneration of NT and VU species [56]. This finding supports the statement that reducing the intensity of logging is important for the conservation of species [1]. In addition, among the three forest areas variations, the disturbed area deemed fit for the protection and conservation of VU species as it significantly maintained abundant regeneration of these species. This finding is different from the assertion that rising deforestation might increase the likelihood that vulnerable species would go extinct [3]. However, our results indicated a good number (12 species, 19%) of NE* species. This has been mentioned in another study that only 5% of plant species housed in the Global Biodiversity Information Facility were presently listed on the IUCN Red List and as at now, the conservation status of most plant species is unknown [49]. Meanwhile, Walker et al. [57] addressed that plant species assessed for the IUCN Red List were not randomly chosen but reflected geographic and taxonomic preferences, including their relevance to list threatened species. Finally, there was no regeneration indication of higher extinction risk species (Endangered (EN), Critically Endangered (CR), Extinct in the wild (EW) and Extinct (E)). Our results agree with the claim that most tropical plant species lack extinction risk assessments, limiting scientists' ability to identify conservation priorities particularly in tropical African flora where potential threats of a high level of species extinction risk (33%) are quite imminent [2]. Generally, our results underlined the winning position of Bia Tano FR to championing the global call for sustainable management, protection and conservation of tree species [56,58,59] through excellent ecological forest restoration and recovery mechanisms within gaps after various degrees of forest disturbances. Therefore, the urgent need for forest managers to prioritize the protection of this forest reserve towards the enhancement of species biodiversity and conservation.

5. Conclusions

In a quest to improve the diversity and conservation of native tree species in tropical African forests, gap regeneration remains all-important nature-promoting silviculture practice and ecosystem-based strategy for attaining these ecological goals. Bia Tano FR is a very important forest reserve in Ghana due to its rich floral diversity and resourcefulness for future conservation efforts by providing suitable habitats for several threatened tree species. However, the sustainability of Bia Tano FR largely depends on species structure, composition, and diversity. In this study, gaps were proved as a crucial silviculture intervention and indispensable growing spaces in the forest that offered remarkable conditions for high natural regeneration yield and diversity. It was observed that gap creations positively affected the structural complexity of Bia Tano FR. Regimes of anthropogenic disturbances could not significantly explain species diversity but became the single measured variable that significantly explained species composition, regeneration shift and conservation variations. Shade bearers were abundant and stable at undisturbed and slightly disturbed areas, while pioneers were abundant and stable at the disturbed area. Additionally, shade bearers were the most rapidly replacing tree species while pioneers were the fast diminishing tree species in succession under gap regeneration. Besides, Green Star and Pink Star were the frequent occurring species while Red Star and Scarlet Star were scarcely occurring species at undisturbed and slightly disturbed areas, respectively, at the regional scale while at the global scale, LC species attained predominant records at the expense of NT and VU species significantly at the slightly disturbed area while among forest areas comparison test revealed disturbed area as potent regeneration grounds for the competitive advantage of VU species.

Overall, the results add to the body of evidence for the impact of different intensities of disturbances on the population structure of tropical plant diversity. Our novel conservation status appraisal approach, crucial to the in-depth understanding of African tropical tree diversity represents a significant step to data-driven comprehensive conservation assessments applicable beyond the continental scales. Presented detailed analyses of results plus robust findings would enable conservation researchers and managers to identify taxonomically verified and high-quality species distribution datasets including unassessed species that are not currently recognized as species of global concern. Therefore, our study is important for the identification of conservation hotspots in need of further evaluation for sustainable forest management prioritization. Additionally, our results provide conservation-relevant

knowledge that promotes the management of floral biodiversity based on conservation guidelines, gap regeneration: a pressing strategy for tree species richness and preservation worldwide.

Lastly, we strongly discourage anthropogenic activities (i.e., overexploitation of species, unsustainable economic and habitat destruction activities) that erode biological legacies but encourage forest protection programs that safeguard the world's threatened tree species from extinction. Additionally, we recommend further studies comparing the results of this study with other tropical African forests within the moist semi-deciduous zone so as to validate the actual biodiversity and conservation stance of this forest type.

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