

Tree Species Coexistence and Diversity on Elevation Gradient of Elephant Camp Natural Forest, Nigeria

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Abstract Spatial species diversity and size inequality contribute to maintenance of tree species diversity in tropical forests. Coexistence of tree species requires interactions within and between spatial species and size diversity. However, elevation gradient has significant impact on growth and species interactions. Failure of most conservation efforts is due to inability to identify and maintain coexistence mechanisms existing in the forest. Understanding the contribution of elevation gradient to coexistence of tree species will improve conservation efforts and terrestrial carbon budgeting. Therefore, association between tree diversity and size inequality on elevation gradient of Elephant Camp Natural Forest was investigated. Eight (30m x 30m) plots were systematically demarcated on 1km line transects in each identified elevation (Hilltop and Valley-Bottom stands). Trees diameter-at-breast height (dbh) were enumerated and identified to species level. Tree dbh was measured and density estimated. Tree species diversity (Shannon-Weiner, Simpson and Margalef indices) and size inequality (Gini coefficient, skewness and Coefficient of variation) were computed. Stem volume and biomass were computed and converted to biomass carbon. Data collected were analysed using descriptive, correlation analysis and principal component analysis. Tree density varied from 435/ha to 767/ha. There was positive correlation between Skewness and Gini coefficient in Hilltop stand and negative correlation between Skewness and Simpson index in Valley-Bottom stand. The measures of tree size inequality and species diversity were strongly associated with each other in Valley-Bottom stand and not in Hilltop stand. Structural diversity and species diversity determined the competitive interaction among tree communities in Hilltop and Valley-Bottom stands, respectively.

Keywords Tree size inequality, Tree species diversity, Elevation gradient, Diameter distribution

1. Introduction

Species of plant grow and survive in a limited range of environment (Sharma *et al.*, 2020). This indicates that presence of most tree communities is site-specific and largely depends on various characteristics of the sites. However, elevation controls many site characteristics. Therefore, change in elevation can lead to significant change in numerous environmental factors (Mao *et al.*, 2015). Tree growth rate differs at different elevations due to change in characteristics of soil properties and climate (Mensah *et al.*, 2018; Sharma *et al.*, 2020). For example, water availability and soil nutrient may be limiting for tree growth in the upland compare to low elevation positions (Lopez *et al.*, 2021). Also, plants response to environmental variables may vary during their life time since they are dynamic systems (Uria-Diez *et al.*, 2014). Tree of different sizes may respond differently to environmental stresses (Rathgeber *et al.*, 2011). For example, Wichmann (2001) noted that increased water

availability benefits large trees more than small trees. De Luis *et al.* (2009) reported that tree sizes were more sensitive to environmental variables than tree species and Pommerening *et al.* (2021) reported that size diversity is caused by species mingling. Pattern of interaction of trees of different species and sizes indicates species mingling. Therefore, correlations between spatial species and size inequality are used to identify coexistence mechanisms of tree species diversity existing in a forest (Wang *et al.*, 2021a; Pommerening *et al.*, 2021). The existence of these correlations is crucial to conservation practices because they provide information on spatial structure of forest stand. However, the extent of the contribution of elevation gradient to mingling and consequently, coexistence of tree species alpha diversity is difficult to clarify. Moreover, failure of many conservation efforts on biodiversity is due to inability of foresters to identify and maintain functional coexistence mechanisms existing among tree species in the forest. Traditional diversity indices are no longer sufficient for measurement of conservation success (Graz, 2004). The value of conservation efforts is directly linked to maintenance of high diversity of species and spatial structure within the forest (Graz, 2004). Change in spatial structure may be observed on elevation gradient due to ecological and

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Received: Jul. 10, 2022; Accepted: Jul. 25, 2022; Published: Oct. 27, 2022

Published online at <http://journal.sapub.org/ijaf>

environmental differences. Hence, understanding the effect of elevation gradient on forest spatial structure can be used to improve tree species conservation efforts and climate change mitigation. Moreover, trees store large amount of carbon in the stem biomass. Tree species and size differ in the carbon storage capacity. Tree species and size control major ecosystem functions and services, respectively. Therefore, species diversity and size inequality can improve carbon storage capacity of a forest. Structural diversity of forest is required for better understanding of natural mechanisms that can be used to maintain coexistence tree species diversity so as to prevent loss of biodiversity and this is significant for climate change mitigation (Wang *et al.*, 2020). Also, identification of natural processes that cause association of spatial species and size diversity is crucial for conservation efforts decisions. Therefore, species diversity and/or size

inequality could be a focus of conservation efforts (Pommerening *et al.*, 2021). (Keren *et al.*, 2020) reiterated that it is important to understand the mechanisms regulating the interaction of tree of different species and sizes. Moreover, conservation of Elephant Camp Natural Forest (ECNF) has become a priority for the survival of the remaining herds of Forest Elephant in Nigeria and West African because ECNF is a unique corridor to other forest reserves and also, habitat that harbour some of the rare African Forest Elephants. ECNF is managed by African Forest Elephant Project initiative in Africa based in Nigeria. Therefore, conservation of forest structure of ECNF is important and critical. Therefore, this study quantified the association of tree species and size diversity in high and low elevation positions in Elephant Camp Natural Forest, Nigeria.

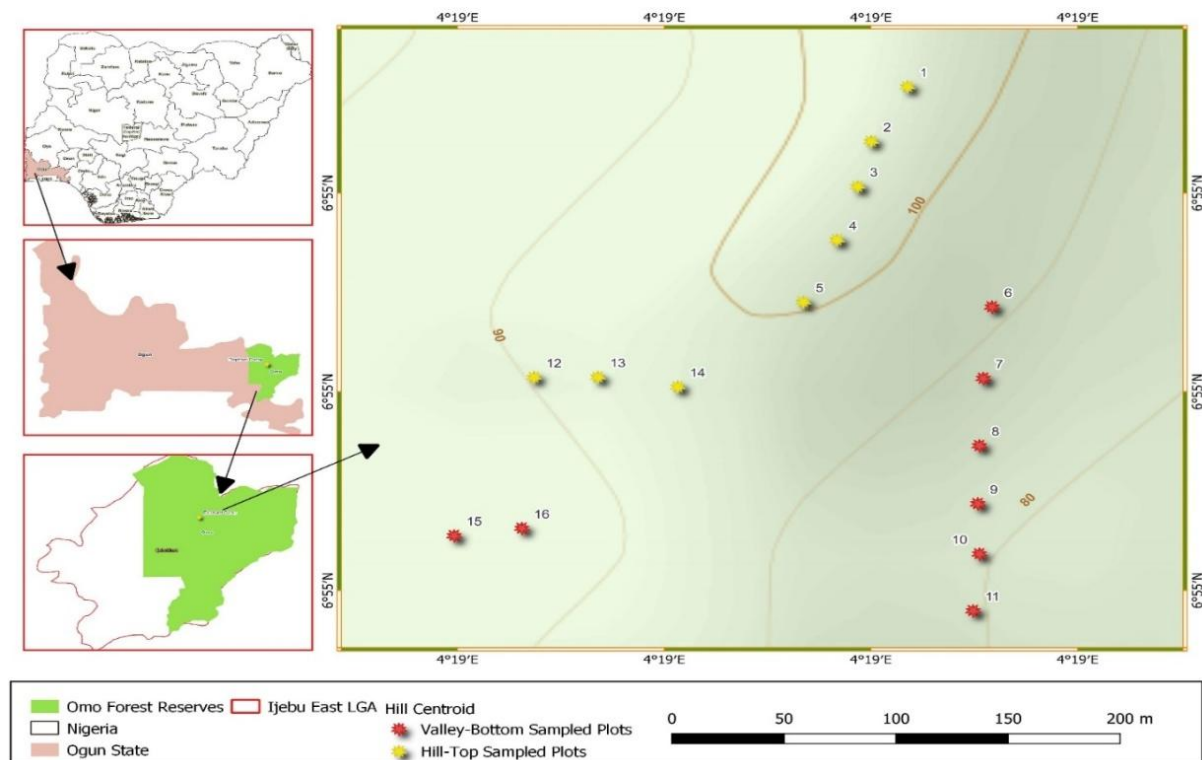


Figure 1. The spatial map of Elephant Camp Natural Forest in Omo Forest Reserve, Nigeria

2. Materials and Methods

The study was carried out in Elephant Camp Natural Forest in Omo Forest Reserve. The Omo Forest Reserve is located on Latitude 06.51.00 to 06.91.00 N and Longitude 04.22.48 to 04.32.48E at an altitude of 150m above sea level (asl) in Ijebu area of Ogun State in Southwestern, Nigeria (Ojo, 2004). Elephant Camp Natural Forest covers approximately 55,000ha. The soil is on basement complex with gneisses quartzitic rock and disintegrated to ferruginous brown soil with gravel content of approximately 40%.

The study area was purposively located on Hillslope (elevation range; 500-4800 m asl) of Elephant Camp Natural Forest. Therefore, Hillslope was divided into two elevation

belts (Hilltop forest and Valley-Bottom forest). The average above sea level is about m while the soil is typical with a gravel content of approximately 40%. The vegetation is natural secondary forest. There is large elevation gradient and slopy topography. Elevations of the plots of Hilltop stand are between 1250 and 3315m asl and Valley-Bottom stand are between 700 and 1050 asl.

The hillslope occurs at eastern part of Elephant Camp Natural Forest, with elevation range of 500-4800 m asl, was divided into two elevation belts (Hilltop stand and Valley-Bottom stand). A total of sixteen 900m² square plots were used for the study. Eight (900m²) plots were demarcated systematically on line transects of 350 m long at the middle of each elevation. It was impossible for eight

plots to be on one transect due to irregular land formation. Therefore, each elevation position has two line transects. Trees with ≥ 5 cm diameter-at-breast height (dbh) and ≥ 1.3 m height were enumerated and identified to species level on the field and when in doubt, specimen of tree species were collected and pressed for further authentication by comparing them with herbarium voucher specimens deposited in the Forestry Research Institute of Nigeria (FRIN) herbarium. The dbh and total height of all trees within each plot were measured. Stem volume and biomass were computed and converted to biomass carbon. The stem volume of individual stem was computed per plot in both upland and low elevation positions. The volume of individual stem obtained was multiplied with individual species wood density and converted to stem biomass per hectare. According to Bhatta et al. (2018), stem carbon is approximately 47% of the tree stem biomass.

3. Data Analysis

Size-density distribution of 10.0 cm dbh classes was generated for Hilltop and Valley-Bottom stands and compared. Skewness coefficient, Coefficient of variation and Gini coefficient were used to quantify tree size inequality based on dbh (Weiner and Thomas, 1986; Weiner and Solbrig, 1984; Bendel *et al.*, 1989) while Shannon-Weiner, Simpson, Margalef and species richness were used to quantify tree species diversity (Heip and Engel, 1974).

Species richness is refers to the number of different tree species encounter in each plot (Magurran, 1988; Heip and Engel, 1974). The relationship between tree size inequality measures and tree species diversity indices was determined using Spearman correlation analysis. Principal Component Analysis was used to explain the variation in the ecosystem services and the species diversity and size inequality of upland and low elevation position. The input data for the analysis were a total total of 8 parameters include; stem biomass carbon, Richness, Simpson, Shannon, Margalef, Evenness, Mean dbh and Gini-dbh.

Shannon-Weiner, Simpson and Margalef indices and species richness were used for assessment of species diversity in Hilltop and Valley-Bottom stands (Magurran, 1988).

Shannon-Weiner index of species diversity is expressed as:

$$H' = -\sum p_i \ln(p_i) \quad (1)$$

Where:

H' = Shannon-Weiner tree species diversity index

P_i = Proportion (n/N) of individuals of one particular species found (n) divided by the total number of individuals found (N), \ln = natural logarithm

Simpson index of tree species diversity (I-D)

$$D = 1 - \left(\frac{\sum n(n-1)}{N(N-1)} \right) \quad (2)$$

Where:

n = total number of individuals of a particular species

N = total number of individual of all species

Margalef's index of species richness (M)

$$M = \frac{(S-1)}{\ln N} \quad (3)$$

Where

S = total number of species in the community

N = total number of all individual trees

\ln = natural logarithm

Species Evenness (E)

$$E = \frac{H1}{\ln S} \quad (4)$$

$$Gini\ Coefficient = \frac{\sum (2j-n-1)ba_j}{\sum ba_j(n-1)} \quad (5)$$

1) Also, three measures of size inequality were applied

The formula for coefficient of variation is expressed as:

$$Coefficient\ of\ Variation = \frac{Standard\ deviation}{Sample\ mean} \times 100 \quad (6)$$

The formula for skewness coefficient is expressed as:

$$Skewness = \frac{\sum_i^N (xi-x)^3}{(N-1)*\sigma^3} \quad (7)$$

X_i = i^{th} Random Variable

X = Mean of the Distribution

N = Number of Variables in the Distribution

σ = Standard Distribution

4. Results

The mean dbh of Hilltop stand (21.39 cm dbh) was significantly different from mean dbh of Valley_Bottom stand (24.35cm dbh) at 0.05 level ($p \geq 0.038$). The dbh distribution of Hilltop and Valley-Bottom stands ranged from 4.50 to 97.00 cm dbh and 6.00 to 319.00 cm dbh, respectively. Inequality measures (Gini-coefficient, Skewness and Coefficient of Variation) of tree diameter of Valley-Bottom stand were higher than Hilltop stand (Table 1).

The highest stem density occurred at 1.0-20.1cm dbh in Hilltop (487/ha) and Valley-Bottom (431/ha) stands. Subsequently, size-density decreased rapidly to 11/ha and 13/ha at 60.1-80.0cm dbh in Hilltop and Valley-Bottom stands, respectively. Stem density of Valley-Bottom stand remained the same from 120.1-140.0 to 300.1-320.0cm dbh, and truncated at end of diameter distribution (300.1-320.0cm dbh) (Figure 2).

Small-sized trees (1.0-20.0cm dbh) accounted for the largest proportion of the total stems at Hilltop (66.0%) and Valley-Bottom (61.0%) stands. Large-sized trees (>60 cm dbh) contributed 8.3 and 25.5% in Hilltop and Valley-Bottom stands, respectively (Figure 2).

The distribution of Shannon-Weiner index and Margalef index of richness were right skewed for both Hilltop and Valley-Bottom stands. The distribution of Margalef index of richness was more skewed than other diversity indices in

Hilltop stand, followed by distribution of Shannon-Weiner index. Simpson index of tree diversity and Evenness index for Valley-Bottom stand and Hilltop stand were right skewed and left skewed. Simpson tree species diversity had the least Coefficient of Variation in both Hilltop (CV=0.11) and Valley-Bottom stands (CV= 0.10). Mean value of Evenness for Hilltop (0.61) was significantly different from Valley-Bottom stands (0.67) (t-test =0.006; df=; $p \leq 0.05$) (Table 2). Shannon-Weiner was significant positively correlated with Simpson indices of tree species diversity ($r=0.956$, $p=0.000$) but less positively correlated with Margalef index of richness ($r=0.840$, $p \leq 0.009$) at 0.05 level (Table 3a). Correlation was significantly positive between Gini and Skewness coefficients of diameter ($r=0.959$, $p=0.000$) at 0.05 level (Table 3a). Therefore, correlation showed close linear relationship between values of Gini-coefficient and Skewness coefficient in Hilltop stand. Also, the values of Shannon-Weiner was closely related to values of Simpson, and Margalef index of richness in Hilltop stand. Therefore, the measures of tree species diversity was strongly associated with changes in number or proportion of each tree species. Values of Gini-coefficient were closely related to skewness values in Hilltop stand.

Correlation was significantly negative between Simpson index of diversity and Skewness coefficient of diameter ($r = -0.848$, $p \leq 0.008$) at 0.05 level (Table 3b). Significant negative correlation was found between Margalef index of richness and skewness coefficient of diameter ($r = -0.85$, $p \leq 0.007$). However, Shannon-Weiner index of tree species

diversity correlated significantly with Evenness index of tree species in Valley-Bottom stand ($r = 0.916$, $p \leq 0.001$). Skewness coefficient of diameter had large negative relationship with Simpson Index of species diversity and Margalef index of richness in Valley-Bottom stand (Table 3b).

The first axis of PCA performed on the eight variables explained 95.56% of the total variability. Therefore, all the variables were well correlated with the first axis except Shannon which was mostly correlated with the second axis (2.43% of the total variability) in Hilltop stand. Conversely, the first and second axes explained 67.92% of the total variability in Valley-Bottom stand.

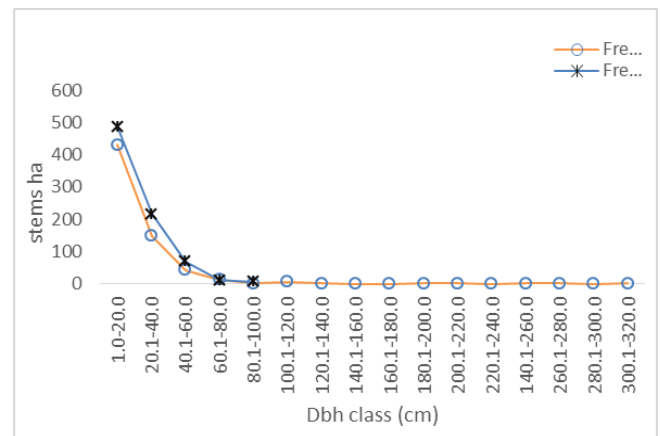


Figure 2. Diameter distribution of Hilltop and Valley-Bottom of Elephant-Camp Natural Forest

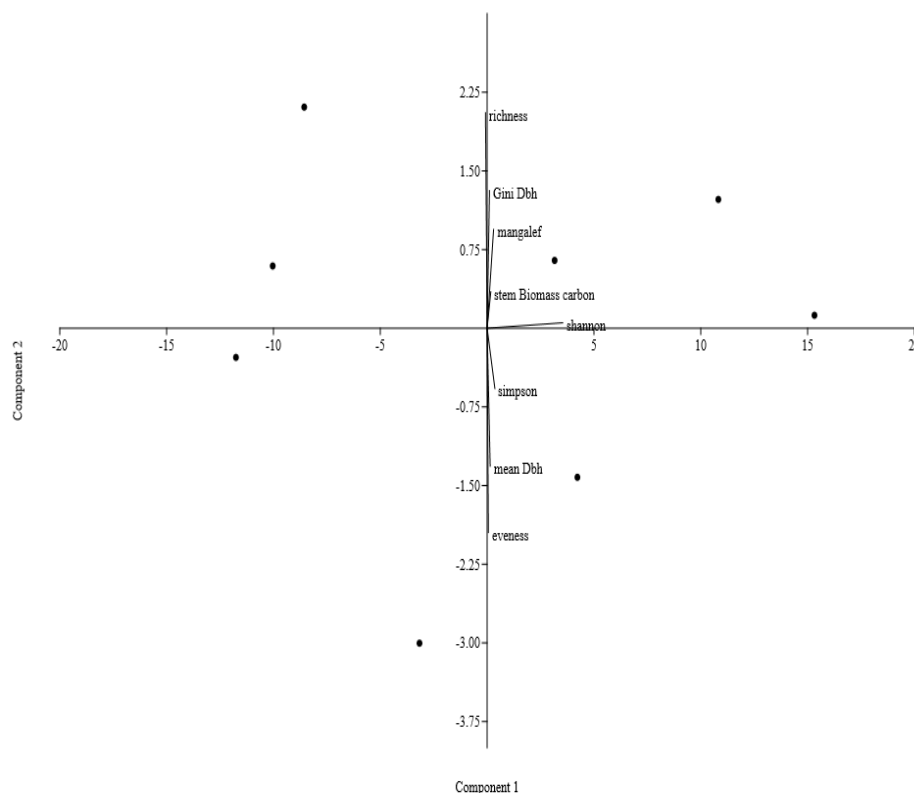


Figure 3a. Principal component analysis of species in the Hilltop of Elephant Camp Natural Forest

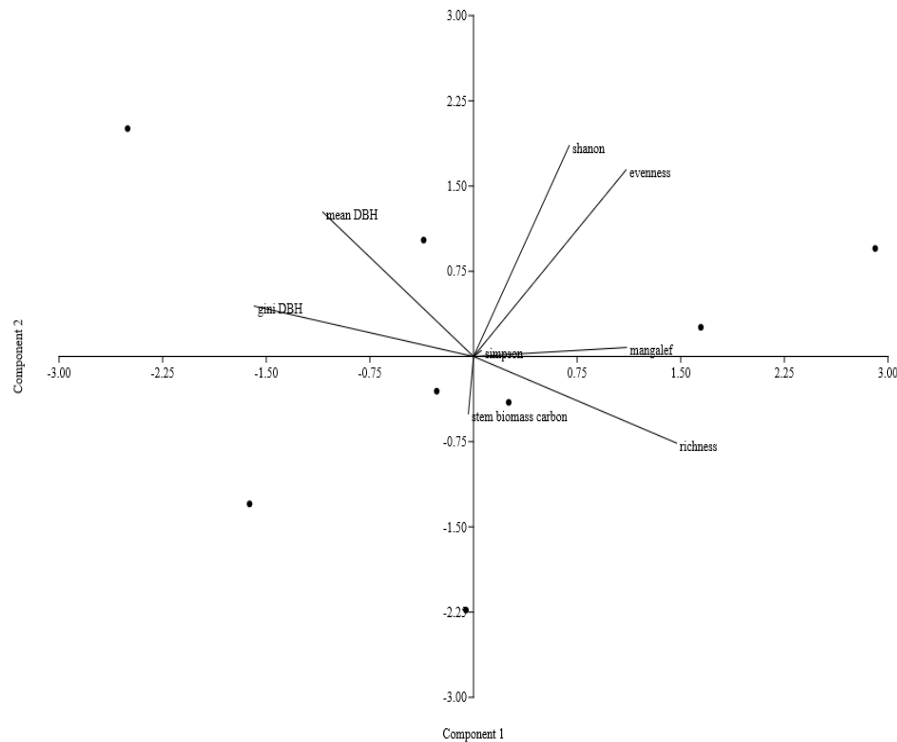


Figure 3b. Principal component analysis of species in the Valley-Bottom of Elephant Camp Natural Forest

Table 1. Statistics of Diameter Stand Distribution of Hilltop and Valley-Bottom Stands in Elephant Camp Natural Forest

Stand	Minimum (cm dbh)	Maximum (cm dbh)	Mean±std (cm dbh)	Gini	CV (%)	Skewness	Kurtosis	Stand-density (stems/ha)
HT	4.50	97.00	21.39±15.30	0.36	71.52	1.72	3.48	655.55
VB	6.00	319.00	24.35±32.11	0.47	98.0	5.74	40.38	490.27

Minimum; Min, Maximum; Max, Skewness Coefficient; Skew, Coefficient of Variation; Coff. V., Gini-Coefficient; Gini, Biomass Carbon; BC, Valley-Bottom; VB, Hilltop; HT.

Table 2. The Values of Diversity Indices for Hilltop and Valley-Bottom Stands of Elephant Camp Natural Forest

Statistics	Sh_H	Sh_V	Simp_H	Simp_V	Even_H	Even_V	Margalef_H	Margalef_V
Species richness	60.00	67.00	60.00	67.00	60.00	67.00	60.00	67.00
Mean	1.47	1.67	0.70	0.74	0.61	0.67	1.64	1.99
Median	1.45	1.66	0.71	1.66	0.64	0.66	1.63	1.89
Mode	1.07	1.14	0.60	1.14	0.41	0.51	0.73	0.80
CV	0.20	0.19	0.11	0.10	0.20	0.16	0.38	0.37
Skewness	0.31	-0.21	0.18	-0.28	-0.42	0.17	0.44	-0.05
Kurtosis	-1.32	-1.02	-1.07	-1.22	-1.29	-0.94	-0.23	-0.80

Shannon index for Hilltop stand, Sh_H; Shannon index for Valley-Bottom stand, Sh_V;
Simpson index for Hilltop stand, Simp_H; Simpson index for Valley-Bottom stand, Simp_V;
Evenness index for Hilltop stand, Even_H; Evenness index for Valley-Bottom stand, Even_V;
Margalef index for Hilltop stand, Marg_H; Margalef index for Valley-Bottom stand, Marg_V;

Table 3a. Correlation Statistics of Stem Size Inequality and Species Diversity Measures in Hilltop Stand

Index 1	Index 2	r	p≤0.05
Gini-DBH	Skewness-DBH	0.959	0.000
Shannon-Weiner	Simpson index	0.956	0.000
Shannon-Weiner	Margalef index	0.840	0.009

Correlation Coefficient; r: p≤0.05; Significant at 0.05 two tails

Table 3b. Correlation Statistics of Stem Size Inequality and Species Diversity Measures in Valley-Bottom Stand

Index 1	Index 2	r	p≤0.05
Shannon-Weiner	Evenness	0.916	0.001
Margalef index	Skewness-DBH	-0.850	0.007
Simpson index	Skewness-DBH	-0.848	0.008

Correlation Coefficient; r: p≤0.05; Significant at 0.05 two tails

Table 4. The Eigen-value of Principal Component Analysis

PC	Hilltop stand		Valley-Bottom stand	
	Eigenvalue	% variance	Eigenvalue	% variance
1	100.265	95.561	2.903	41.472
2	2.550	2.430	1.852	26.452
3	1.266	1.206	1.187	16.963
4	0.554	0.528	0.872	12.460
5	0.207	0.198	0.158	2.269
6	0.072	0.069	0.021	0.305
7	0.005	0.005	0.005	0.075

5. Discussion

There was similarity between tree size-density distribution of Hilltop and Valley-Bottom stands. The size-density distribution was positively skewed with many small and intermediate sized tree stems and a few very large stem size. This represented good reproductive success and regeneration for the two stands. The inequality based on dbh (Gini-coefficient, Skewness and Coefficient of Variation) of Valley-Bottom stand were higher than Hilltop stand. Metsaranta and Lieffers (2008) stated that high inequality in size may be due to large numbers of trees with low growth rate or due to small numbers of trees with high growth rate at sites with sporadic supply of specific plant growth resource. In the case of Valley-Bottom of Elephant Camp Natural Forest, there is seasonal flooding and supply of water through the tributaries of Omo river. Mohler *et al.* (1978) and Turner and Rabinowitz (1983) reiterated that high skewness of diameter distribution of stand is due to exponential growth rate of individual stems and may not be due to dominance and suppression of individual stems. This suggests asymmetric in the absence of competition. Hence, expression of high size inequality of Valley-Bottom stand may not be due to competition because of its stand stem density compared to Hilltop stand. Stem size distribution may become asymmetric in the absence of competition due to variance in exponential growth rates of individual stems. Therefore, change in elevation has cause changes in the forest structure of Elephant Camp Natural Forest. Structural diversity of tree size contributes to ecosystem services.

Strong positive correlations between Gini and Skewness Coefficients was more pronounced in Hilltop stand and it indicate size variability among tree communities. High size inequality among neighbouring trees of the same or different species contributed to the mechanisms regulating coexistence of trees in Hilltop stand (Keren *et al.*, 2020). High tree size inequality predicts high proportion of specific stem sizes. Microsite variability caused size variability. Also, positive correlation between tree species diversity indices was more pronounced in Hilltop stand. The Shannon-Weinner index emphasize evenness and richness of tree species while Simpson index emphasize abundance and richness of tree species (Young *et al.*, 2011). Margalef index emphasize richness of tree species. Species mingling is when

large tree is surrounded by different tree species (Wang *et al.*, 2021a). Therefore, relationship between Shannon-Weinner and Margalef indices in Hilltop stand indicated that the species mingling was basically regular among different tree species but sizes do not differ. Wang *et al.* (2021a) stated that different species-size correlation patterns could be observed in a forest ecosystem. However, the dominant correlation will determine the functional mechanism. This indicated that quantification of forest structure require species identity. Apart from species enrichment, manipulating of tree sizes could be a practical tool for increasing biodiversity in Hilltop stand (Lian *et al.*, 2007). This confirmed the study of Young *et al.* (2011) that increase in structural diversity is associated with increase in the species diversity.

Strong negative correlations between size inequality and spatial species diversity in Valley-Bottom stand suggested high size diversity within the same species (Wang *et al.*, 2021a). This effect is also associated with low stem inequality in plots of higher tree species diversity. This could be a consequence of high mortality in the tree communities with high size inequality. According to Magurran (1988), effect of low recruitment could lead to high tree species diversity and high tree species evenness in forest stand. Conversely, positive relationship between species diversity and evenness indices indicated that tree species mingling component were more regularly distributed in Valley-Bottom. According to Magurran, (1988), Shannon-Weinner index reflects both richness and evenness of tree species. Wang *et al.* (2021a) reported that high species mingling is more likely to be associated with large trees.

Shannon-Weiner index of species diversity was strongly associated with tree species evenness in Valley-Bottom stand. Also, relationship between skewness-coefficient and Margalef and Simpson indices were moderately strong and negative in Valley-Bottom stand. Therefore, Margalef and Simpson indices were negative predictors of Skewness coefficient in Valley-Bottom stand. Tree size inequality was strongly associated with regular distribution of individual tree species in Valley-Bottom stand. Skewness is basically determined by the proportion of stem in the diameter classes while Simpson index emphasize abundance and richness of tree species (Young *et al.*, 2011). This effect was associated with low stem inequality in plots of higher tree species diversity.

The measures of size inequality and tree species diversity were significantly and negatively associated with each other in Valley-Bottom stand (Keren *et al.*, 2020). Simpson and Skewness were significantly negatively correlated only in Valley-Bottom stand. Margalef and Skewness were significantly negatively correlated only in Valley-Bottom stand. The measures of tree size inequality and species diversity were strongly negative related with each other in Valley-Bottom stand. Therefore, the increase of structural diversity is associated with an increase in species diversity (Young *et al.*, 2011).

Tree species richness could be used as an indicator of tree

biomass in Hilltop and Valley-bottom stands of Elephant Camp Natural Forest.

6. Conclusions

Asymmetric distribution in the absence of competition indicated that elevation gradient is the major controlling factor of forest structure in Elephant Camp Natural Forest. Microsite variability may enhanced high tree species diversity and size inequality in Valley-Bottom stand. Variability in the significance and sign of the coefficient of the associated variables indicated that the relationships between predictors were site-specific. Spatial pattern of tree size and species diversity determined the structure of tree communities in Hilltop stand while size diversity determined structure of Hilltop stand. Overall, high size inequality among neighbouring trees of the same or different species determined the mechanisms regulating coexistence of trees in Hilltop stand while high size diversity within the same species determine determined the mechanisms regulating coexistence of trees in Valley-Bottom stand. These relationships were site-specific and the basis for the natural mechanisms for maintaining of plant diversity in forest ecosystem. Understanding the mechanisms necessary to maintain high species diversity under climate change condition is a major challenge of the present time.

REFERENCES

- [1] Bhatta, S. P., Sharma, K. P., Balami, S. 2018. Variation in carbon storage among tree species in the planted forest of Kathmandu, Central Nepal. *Current Science* 115(2): 274-282.
- [2] Bendel, R. B., Higgins, S. S., Teberg, J. E., Pyke, D. A., 1989. Comparison of skewness coefficient, Coefficient of Variation and Gini coefficient as inequality measures within populations. *Oecologia* 78: 394-400.
- [3] De Luis, M., Novak, K., Cufar, K., Raventos, J., 2009. Size mediated climate-growth relationships in *Pinus halepensis* and *Pinus pinea*. *Tree-Structure and Function* 23: 1065-1073.
- [4] Graz, F. P. 2004. The behavior of the species mingling index Msp in relation to species dominance and dispersion. *European Journal of Forest Resources* 123: 87-92.
- [5] Heip, C., and Engels, P., 1974. Comparing species diversity and evenness indices. *Journal of Mash Biology Association of Uk* 54: 559-569.
- [6] Keren, S., Svobod,a M., Janda, P., Nagel, T. A., 2020. Relationships between structural indices and conventional stand attributes in an Old-growth forest in SoutheastEurope. *Forest* 11.4. doi: 10.3390/f11010004.
- [7] Liang, J., Buongiorno, J., Monserud, R. A., Kruger, E. L., Zhou, M., 2007. Effects of diversity of tree species and size on forest basal area growth, recruitment, and mortality. *Forest Ecology and Management* 243: 116-127.
- [8] Lopez, J. G., Tor-ngern, P., Oren, R., Kozil, N., Laudon, H., Hasselquist, N., 2021. How tree species, tree size, and topographical location influenced tree transpiration in northern boreal forests during the historic 2018 drought. *Global Change Biology* 00: 1-13. doi: 10.1111/gcb.15601.
- [9] Luo, Y., and Chen, Y. H., 2011. Competition, species interaction and ageing control tree mortality in boreal forests. *Journal of Ecology* 99 (6): 1470-1480.
- [10] A. E. Magurran, 1988. *Ecological diversity and measurement*. Princeton University Press, Princeton. 354p.
- [11] Mao, Z., Wang, Y., Jourdon, C., Cecillon, L., Nespoulous, J., Rey, H., Saint-ndre, L., Alexia, S., 2015. Characterizing above- and belowground carbon partitioning in forest trees along an altitudinal gradient using area-based indicators. *Artic, Antarctic and Alpine Research* 47 (1): 59-69.
- [12] Mensah, S., Pienaar, O. L., Kunneke, A., du Toit, B., Seydack, A., Uhl, E., Pretzsch, H., Seifert, T., 2018. Height-diameter allometry in South Africa's indigenous high forests: Assessing generic models performance and function forms. *Forest Ecology and Management* 410:1-11.
- [13] Metsaranta, J., and Lieffers, V. J., 2008. Inequality of size and size increment in *Pinus banksiana* in relation to stand dynamics and annual growth rate. *Annals o Botany* 101: 561-571.
- [14] Mohler. C. L., Marks, P. L., Sprugel, D. G., 1978. Stand structure and allometry of trees during self-thinning of pure stands. *Journal of Ecology* 66: 599-614.
- [15] Ojo, L. O., 2004. The fate of a tropical rainforest in Nigeria: Abeku sector of Omo Forest Reserve (PDF). *Global Nest International Journal* 6: 116-130.
- [16] Pommerening, A., Zhang, G., Zhang, X., 2021. Unravelling the mechanisms of spatial correlation between species and size diversity in forest ecosystem. *Ecological Indicator* 121: 106925.
- [17] Rathgeber, C. B. K., Rossi, S., Bontemps, J. D., 2011. Cambial activity related to tree size in a mature silver-fir Plantation. *Annals of Botany* 108: 429-438. doi: 10.1093/aob/mir/68.
- [18] Sharma, K. P., Bhatta, S. P., Lamsal, S. K., 2020. Species diversity and regeneraton of community-managed hill sal (*Shorea robusta*) forest in Central Nepal. *Current Science* 119(1): 81-92.
- [19] Turner, M. D., and Rabinowitz, D., 1983. Factors affecting frequency distributions of plant mass: the absence of dominance and suppression in competing monocultures of *Festuca paradoxa*. *Ecology* 64(3): 469-475.
- [20] Uria-Diez, J., Gazol, A., Ibanez, R., 2014. Drivers of a riparian forest specialist (*Carex remota*, Cyperaceae): it is not only a matter of soil moisture. *American Journal of Botany* 101(8): 1286-1292.
- [21] Wang, B.C., and Smith, T. B., 2002. Closing the seed dispersal loop. *Trends in Ecology and Evolution* 17(2): 379-385.
- [22] Wang, H., Zhao, Z., Myllymaki, M., Pommerening, A., 2020. Spatial size diversity in natural and planted forest ecosystems and extending the concept of spatial size inequality. *Ecological Informatics* 57: 101054.

- [23] Wang, H., Zhang, X., Hu, Y., Pommerening, A., 2021a. Spatial patterns of correlation between conspecific species and size diversity in forest ecosystems. *Ecological Modelling* 457: 109678. doi. org/10.1016/j.ecolmodel.2021.109678.
- [24] Wang, H. X., Huang, S. X., Zhang, S. S., Peng, H., Cao, K. F., 2021b. Localized neighborhood species mingling is correlated with individual tree size inequality in natural forests in South China. *Annals of Forest Science* 78: 102. doi.org/10.1007/s13595-021-01111-x.
- [25] Weiner, J., and Solbrig, O. T., 1984. The meaning and measurement of size hierarchies in plant population. *Oecologia* 661: 334-336.
- [26] Weiner, J., and Thomas, S. C., 1986. Size variability and competition in plant monocultures. *Oikos* 47: 211-222.
- [27] Wichmann, L., 2001. Annual variation in competition symmetry in even-aged Sitka spruce. *Annals of Botany* 88: 145-151.
- [28] Young, B., Liang, J., Chapin, III F.S., 2011. Effects of species and tree size diversity on recruitment in the Alaskan boreal forest: A geospatial approach. *Forest Ecology and Management* 262: 1608-1617.