Chapter 4

Discussion

The present study utilizes a combination of field-based and remote sensing approaches to estimate tree species diversity and find a correlation between species and spectral diversity of three PAs in India, a country known for its extensive tropical biodiversity. It carries significant implications for effective forest management and conservation practices. The results of this study are discussed here with appropriate references.

4.1 Tree species diversity and distribution dynamics

Field inventories at three PAs have unveiled distinct variations in both tree species diversity and density. The findings show high tree species diversity at MTR, where a total of 80 species were recorded. This feature is attributed to higher mean annual rainfall (Chaurasia et al., 2020; Joseph et al., 2012; Parmar et al., 2022). Among the list of tree species recorded (70-80 species) at each PA, approximately a quarter of these species are abundant as indicated by the field-based metrics. This observation aligns with a well-established characteristic of ecological communities, as discussed by Avolio et al., (2019). The dominance of the Fabaceae family can be attributed to its high species richness, constituting approximately 27% of the total species in SWS and VNP, and 18% in MTR, highlighting their ecological significance in these PAs. This observation of the dominance of the Fabaceae family in tropical forests was reported earlier (Addo-Fordjour et al., 2009; Kacholi et al., 2015; Sen et al., 2021).

At MTR, a higher proportion (~26% of total recorded species) of singleton species (species represented by only one individual) is observed compared to SWS and VNP (Table 3.2). This indicates that MTR harbors a greater number of species contributing to its unique biodiversity profile. In contrast, SWS and VNP exhibited lower occurrences of singleton species, suggesting a higher degree of overlap in species composition. This finding aligns with a study conducted by Cazzolla Gatti et al., (2017) in Ghana, where the Ankasa site, characterized by higher rainfall, exhibited a higher number of singletons compared to the other two sites. Furthermore, a study by Chazdon et al., (2022) revealed that the Cuatro Rios site exhibited the highest proportion of singleton species among various sites in northeastern Costa Rica. Additionally, Hubbell, (2015) highlighted that 13% of species in Amazonia are singletons, based on a comprehensive analysis of 1,170 inventory plots (ter Steege et al., 2013).

Drier PAs (SWS & VNP) showed a greater proportion of deciduous species. In contrast, wetter PA (MTR) exhibited a comparatively higher proportion of evergreen species. This distinction in vegetation characteristics underscores the influence of climatic conditions on the composition of tree species (Ge & Xie, 2017; Pennington et al., 2004). Within MTR, distinct vegetation types were discernible between its northern and southern regions. The northern part of MTR prominently featured a higher abundance of deciduous and semi-evergreen species as highlighted by Suresh et al., (2010). Conversely, the southern part was characterized by a dominance of evergreen species. This spatial variation in vegetation types within MTR highlights the ecological heterogeneity across its landscape. The proportion of PA-specific species among the recorded tree species was higher at MTR (Table 3.2). This finding implies a distinctive local biodiversity contribution, reaching nearly 53% of the total species recorded at MTR. This emphasizes the importance of considering PA-specific ecological factors while addressing biodiversity conservation within PAs.

Among the 37 abundant species identified across three PAs, 22 species were common (at two or three PAs) and 15 were PA-specific, indicating dynamic inter-specific interactions across these PAs. These results are consistent with earlier research (Ricklefs, 2008) highlighting the influence of PA-specific factors and climatic variability on inter-species interactions, contributing to diverse community compositions. The sparse distribution of certain species, such as *Gmelina arborea* across all three PAs, suggests that some species inherently exhibit limited geographical spread. These shifts in community composition can have long-term implications for the growth rates and productivity of the PAs (Zhang et al., 2018). These changes can significantly impact the overall structure and functioning of the forests within these regions.

The observed trend of higher singleton species proportion in MTR and the dominance of PA-specific species highlight the importance of local ecological factors in shaping biodiversity patterns, emphasizing the need for tailored conservation strategies

4.1.1 Expected number of species

The examination of expected species numbers in three PAs revealed that all nonparametric estimators (Chao, Jackknife 1, Jackknife 2, and Bootstrap) used in this study projected a higher number of expected species richness than what was observed during the field survey (Table 3.5). In terms of estimator performance, the Bootstrap method produced estimates closely resembling the observed values. This aligns with previous research conducted by Chiarucci et al., (2001, 2003), who suggested that the Bootstrap method is a robust estimator, especially suitable for larger areas with a substantial number of samples. Contrasting this observation on Bootstrap’s efficacy, other studies, such as those by Brose et al., (2003), Chiarucci et al., (2003), and Skov & Lawesson, (2000), showed Jackknife 2 as a superior estimator.

The observed discrepancy in the performance of estimators highlights the intricate nature of biodiversity assessment methodologies. While some studies have favored Jackknife 2, the findings of this study emphasize the applicability and reliability of the Bootstrap method, particularly in the context of having larger study areas and an extensive sampling framework. This adds depth to the ongoing discourse on the selection of appropriate estimators for biodiversity assessments, highlighting the need for a nuanced understanding of field survey limitations. It also underscores the challenges in accurately assessing biodiversity, urging for continued refinement of estimation methods to better capture ecological realities.

4.1.2 Rank abundance curves

Analysis of rank abundance curves reveals significant shifts in species composition across the PAs. There was a steep decline in rank abundance curves, indicating the dominance of a few species (e.g. *Tectona grandis*) in all three PAs. This dominance contributed to a less even distribution of tree species within these areas as reported earlier (Kindt & Coe, 2005). The width of the rank abundance curves served as an additional indicator, suggesting that areas with broader curves exhibited greater species richness (Kindt & Coe, 2005). Conversely, the sharp descending and shorter curves implied a less or similar distribution of tree species among the plots within the PAs. The flat tails in all curves suggested the existence of singletons.

Consequently, it became evident that the community structure of tree species underwent significant changes among the three PAs. *Tectona grandis* remained as the most abundant species across all PAs, attributed to its utility as timber, economic value, and adaptability to these PAs. The prevalence of this species in all PAs was also could be because of its inclusion in silvicultural practices and ecological characteristics.

Timber-yielding species showed abundance across the three PAs. In MTR, *Lagerstroemia lanceolata*, *Terminalia tomentosa*, and *Anogeissus latifolia* were the top abundant species. This observation showed similarity with the findings of Kishore et al., (2020) who recorded *Tectona grandis* as the most abundant species in MTR, followed by *Anogeissus latifolia, Eucalyptus globulus,* and *Terminalia tomentosa.* The presence of distinct dominant species and the varying abundance of other species underscored the complexity of these ecosystems and the need for conservation and management strategies for each PA.

4.2 Spectral profiles of abundant species

The spectral analysis conducted in this study reveals variations in the spectral response of tree species across three PAs in different spectral regions. The study effectively utilized 226 out of 425 spectral bands spanning four distinct regions (VIS, NIR, and SWIR), successfully distinguishing tree species across the PAs. These results align with findings from previous studies. The visible (VIS) region, spanning from 550 to 650 nm, is associated with photosynthetic pigments (Chlorophyll). The near-infrared (NIR) region ranges from 750 to 1250 nm and is associated with biomass, LAI, and protein. Additionally, two regions within the short-wave infrared (SWIR) region (1500 to 1750 nm and 2000 to 2250 nm) are associated with nitrogen, carbon, cellulose, lignin, and moisture absorption. These associations emphasize the significance of selecting appropriate spectral regions for accurate tree species classification (Alonzo et al., 2014; Fassnacht et al., 2016; Ferreira et al., 2016; Thenkabail et al., 2004, 2021).

Moreover, within these selected spectral regions, differences in reflectance patterns among tree species were observed, even within the same species, potentially influenced by the climate gradient from SWS to MTR. For instance, *Tectona grandis*, the most abundant species across all three Pas, exhibited higher spectral separability in the SWIR region in both SWS and MTR, reflecting the species' adaptability and ecological significance. Oldeland et al., (2017) observed a significant degree of variability within tree species classes, suggesting that this variability in reflectance could be attributed to the influence of metabolites, particularly proteins, and water content resulting in the reflectance dynamics in the SWIR region that assist in discriminating tree species.

Further analysis highlighted specific spectral regions playing key roles in discriminating among tree species, with the NIR region showing significant differences in VNP and MTR, while the VIS region showed better discrimination among species in SWS. Oldeland et al., (2017) also indicated that reflectance in the VIS region predominantly revealed associations with the absorption characteristics of the leaf pigments present in the trees. This underscores the significance of considering VIS, NIR, and SWIR regions for discriminating tree species, aligning with prior studies emphasizing the importance of VIS (van Aardt & Wynne, 2001), NIR (Cochrane, 2000), NIR, and SWIR1 (Clark et al., 2005) in tree species classification.

Additionally, the study demonstrates the pivotal role of critical spectral bands in enhancing tree species classification accuracy, not only improving mapping precision but also streamlining model complexity by reducing training time, data dimensionality, and the risk of overfitting (Paz-Kagan et al., 2021). These findings contribute to the ongoing discourse on optimizing spectral analysis techniques for accurate tree species classification, offering valuable insights for future biodiversity monitoring efforts.

4.3 Abundant species maps

In the realm of hyperspectral data analysis for tree species classification, managing high dimensionality becomes a crucial consideration. Before classification, it is recommended to eliminate redundant data and identify essential bands for accurate classification (Ballanti et al., 2016). This study, in line with existing literature, employs Minimum Noise Fraction (MNF) as a robust dimension reduction method for AVIRIS-

NG data (Priyadarshini et al., 2019). The better performance of MNF can be attributed to its ability to reduce noise while minimizing signal loss, thereby enhancing the overall classification precision (Fassnacht et al., 2016; Ghosh et al., 2014; Zhang & Xie, 2012).

This study tested two machine learning algorithms, Random Forest (RF) and Support Vector Machine (SVM), for the pixel-level classification of abundant tree species in three PAs using airborne hyperspectral data. This approach is consistent with methodologies employed in other studies. For instance, Cao et al., (2018) utilized field hyperspectral data to identify eight mangrove species on Qi’ao Island in Zhuhai, China while Raczko & Zagajewski, (2017) employed hyperspectral data to map tree species in Poland. Similarly, Adam & Mutanga, (2009) and Murеriwa et al., (2016) employed hyperspectral data for spectral discrimination and classification of vegetation species in South Africa.

The resultant maps from both classifiers in this study showed fair overall accuracy, closely resembled the field-observed data, with validation indicating a match of over 85% through additional field visits. While SVM and RF classifiers showed similar performance in SWS and VNP, RF performed better than SVM by approximately 4% in MTR. These findings align with previous studies, highlighting the variability in classifier performance across different ecosystems and classification tasks (Dalponte et al., 2012; Fassnacht et al., 2014). Some studies reported higher accuracy with the RF classifier, while others observed superior performance with the SVM classifier. For example, Dalponte et al., (2012) found that SVM outperformed the RF classifier in mapping trees in the Southern Alps. In contrast, Sun et al., (2019) reported that the RF classifier outperformed SVM in the classification of the tropical dry forest in Costa Rica.

The findings of this study align with those of Ghosh et al., (2014), who reported similar performance for both SVM and RF when applied to hyperspectral data. However, this stands in contrast to the results reported by Ballanti et al., (2016), where SVM exhibited superior performance over RF. The accuracies achieved in this study surpassed those reported for tropical semi-deciduous forests (Ferreira et al., 2016), and for seven tree species in the Santa Genebra forest reserve, Brazil (Wagner et al., 2018). Although slightly lower than the accuracies reported for mangrove patches (Hati et al., 2021), the classifiers in this study exhibited a marginal improvement compared to the białowieża forest (Modzelewska et al., 2020), underscoring the advancement in hyperspectral data analysis techniques.

The abundant species maps produced by the RF classifier in this study exhibited a visually sharper image compared to those generated by the SVM classifier. Classification accuracy was found to be primarily influenced by intra- and inter-species spectral variability, as documented by Ferreira et al., (2016) and Zhang et al., (2006). This variability was evident in the spectra of abundant species, leading to classification maps with >77% accuracy for ~23 tropical tree species covering around 86% of the forest area in the three PAs. This highlights the advantage of using AVIRIS-NG in tree enumeration studies across expansive tropical regions. The distribution and spread of canopies of abundant species, as well as the quality of extracted endmember spectra, played a crucial role in achieving better accuracy in the developed abundant species maps (Ustin & Gamon, 2010; Wang & Gamon, 2019). In a similar context, Paz-Kagan et al., (2017) mapped 23 tree species in Israel with 82%–87% accuracy using imaging spectroscopy. Raczko & Zagajewski, (2017) achieved a 62% accuracy for five tree species in a temperate region with the RF classifier. Marconi et al., (2022) classified tree species in the United States forest covers using hyperspectral data from the National Ecological Observatory Network (NEON), achieving 77% accuracy with their general model.

An additional metric used by the RF classifier, the Out-of-Bag (OOB) error rate (Schonlau & Zou, 2020), was minimal, ranging from 9% to 11% across the three PAs, reflecting the accuracy of the resulting classification map. This finding aligns with the research of Piri Sahragard et al., (2018), who demonstrated an OOB estimate of the error rate between 3.33% and 13.3% for five plant species. Furthermore, the evaluation of the area under the curve (AUC) statistic indicated that the accuracy of the RF classifier for all three PAs was highly satisfactory, with mean AUC values > 0.95. To provide context, Moisen et al., (2006) reported an average AUC of 0.87 while modeling 13 tree species. Another study, conducted by Carvalho et al., (2017), found that the RF classifier performed better than other classifiers in terms of AUC.

The user's accuracy values obtained from the RF classifier in this study, ranging from 76.97% to 80.18% for ~23 tropical tree species with 4-meter spatial resolution data, are deemed reasonable. Given the number of abundant species considered and the spatial resolution of the sensor used, the accuracy of species classification in this study is considered satisfactory. The distribution maps of abundant species generated using high-resolution sensors offer valuable inputs for forest ecological studies (Vaglio Laurin et al., 2016) and forest management.

4.4 Relationship between species and spectral diversity

4.4.1 CHV values of plots and species derived from classification maps

The CHV values derived from plots and species identified through classification maps revealed that principal component-based metrics of diversity (CHV) in hyperspectral imagery can effectively distinguish between low and high alpha-diversity plots. This observation aligns with the findings reported by Hernández-Stefanoni et al., (2012), demonstrating a strong connection between species richness, community composition, and remotely sensed data.

The results of this study showed that species diversity is strongly associated with spectral diversity, as evidenced by high R^2 values (Figure 3.11). This suggests that CHV serves as a robust indicator of spectral diversity, offering valuable insights into the tree diversity aspect of studied PAs. This finding contrasts with those of Gholizadeh et al., (2018), who identified Convex Hull Area (CHA) as a superior metric for assessing spectral diversity in prairie ecosystems among five spectral diversity metrics (CV, CHV, SAM, SID and CHA).

The observed patterns in spectral CHVs across the three PAs of this study suggest that local factors play a significant role in influencing species assemblages. These patterns also unveil a strong alignment of co-occurrence patterns along climatic gradients as highlighted by Chaurasia et al., (2020). Building upon the findings of Randin et al., (2020) and Chadwick et al., (2020), this study emphasizes the potential of integrating ecological and remote sensing products to enhance the accuracy of ecological models. This integration, in turn, contributes to the development of more effective forest management strategies.

4.4.2 Diversity-area curves

The assessment of species accumulation in relation to sampling area is visually represented through species diversity-area curves. In this study, this was augmented by incorporating spectral diversity-area curves alongside species diversity-area curves.

Distinct patterns emerged from the analysis of both species diversity- and spectral diversity-area curves across the three PAs, reflecting variations in richness consistent with the research conducted by Jayakumar & Nair, (2013) within the tropical forests of the Western Ghats in India. Concurrently, disparities were also identified in the spectral diversity-area curves. Both the diversity-area curves showed a clear increasing trend from drier PAs (SWS & VNP) to wetter PA (MTR). This trend aligns with the results presented in Table 3.5, where the species richness estimator predicted a higher number of species in all three PAs compared to the recorded number. This alignment underscores the importance of considering both species and spectral diversity metrics in assessing ecosystem dynamics along climatic gradients.

These diversity-area curves showed that the sampling effort of field plots was sufficient to make comparisons of both species and spectral diversity across the studied PAs. This aligns with the study of Vaglio Laurin et al., (2014) at the Sierra Leonean national park in West Africa. In that study, the species-area curve demonstrated that the sampled area sufficiently encapsulated the majority of large-tree diversity within the site.

The flattening of species diversity-area curves occurred first for abundant species, followed by all the recorded species. In contrast, spectral diversity-area curves exhibited a reverse pattern, highlighting the impact of intra-species spectral variability, particularly among abundant species, on remote sensing-derived biodiversity estimations (Wang et al., 2019). Therefore, it is crucial to consider this factor when predicting biodiversity estimates for tropical regions utilizing remote sensing.

The observed consistency between diversity metrics derived from field observations and remote sensing, coupled with the proportional increase in the measured CHV corresponding to abundant species per unit area, emphasize the practical effectiveness of spectral diversity metrics in assessing biodiversity. Rocchini et al., (2011) showed a similar relationship between species diversity and spectral diversity. The increased rainfall seen at MTR resulted in a higher number of recorded tree species (~15%) and a considerable increase in spectral diversity. This is reflected in the CHV values of species (almost twice to those in SWS), in comparison to the other two PAs (Table 3.15). This positive association between spectral diversity and the climate gradient reinforces the influence of rainfall on biodiversity (Chaurasia et al., 2020).

The increased intra-species variability observed among abundant species of the three PAs, as evidenced by CHVs, could contribute to their extensive distribution. As highlighted by Avolio et al., (2019), this study contributes to estimating the distribution of abundant species across broader spatial scales through remote sensing and communicates functional diversity using spectral diversity metrics, aspects that might not be fully captured by conventional field-based studies.

A wide range of spectral diversity values were found in randomly selected plots from classification maps of each PA (Figure 3.12a), which differs from the results published by Dahlin, (2016), whose study focused on forests in southwestern Michigan, USA. This highlights the efficacy of spectral data obtained from AVIRIS-NG in establishing correlations with the observed tree species diversity within the studied PAs. Aligning with the observations of Wang & Gamon, (2019), this work reinforces the effectiveness of high-resolution remote sensing data in assessing biodiversity variables related to forest cover using spectral diversity metrics.

4.4.3 Bray-Curtis dissimilarity

This study focused on Bray-Curtis dissimilarity indices based on abundance data, demonstrating their resilience to sampling differences and robustness in characterizing changes in species composition. Bray-Curtis dissimilarity is chosen for its resilience to the number of null values between samples, in contrast to Euclidean distance. This approach aligns with the intuitive ordering of plots (Kindt & Coe, 2005).

An evaluation of beta diversity at three PAs using Bray-Curtis dissimilarity reveals different patterns. In MTR, both species and spectral diversity (as CHVs) exhibit the highest mean values of Bray-Curtis dissimilarity, indicating substantial variation in tree species composition within this area. This observation also suggests a congruence in the beta-diversity patterns between field and spectral data, aligning with the findings of Chraibi et al., (2021). Conversely, SWS and VNP showed slightly lower values, suggesting a strong similarity in tree species composition and a significant number of common species within these two PAs.

Given that Bray-Curtis dissimilarity characterizes changes in species composition between plots (Oksanen, 2018), the results indicate substantial differences in individual tree species composition of MTR. In contrast, plots in the SWS and VNP exhibit a high degree of uniformity in tree species composition. The similar mean dissimilarity values for SWS and VNP plots further suggest a similarity in species composition, supported by the nonsignificant difference in species diversity between these areas (Table 3.2). These findings highlight relatively lower tree species and spectral diversity in the VNP compared to the other PAs.

The Bray-Curtis dissimilarity measures in this study indicate that spectral diversity metrics (as CHVs) offer a more comprehensive understanding of tree species diversity when juxtaposed with metrics obtained through conventional field-based sampling methods. In contrast to the localized and often limited scope of field-based sampling, spectral diversity metrics obtained from remote sensing data provide a holistic perspective across larger spatial scales.

4.5 Intra- and Inter-species spectral variability

Spectra can unveil the biochemical and structural characteristics of vegetation, and Jetz et al., (2016) provides significant insights into this process, enabling the remote tracking of plant functional diversity. Building on this foundation, Schweiger et al., (2018) highlighted the pivotal role of plant spectral diversity in projecting ecosystem functionality of Cedar Creek. These studies collectively augment the findings of this study, where the spectral diversity metric (CHV) effectively captures the multivariate range of trait values, thus assessing species diversity indirectly. This methodology aligns with the approach outlined by Cornwell et al., (2006) in a similar context, reinforcing the reliability and relevance of the spectral analysis in understanding the diverse traits and functionalities within the studied PA.

The intricate trends of intra- and inter-species variability in CHVs seen across the three PAs elucidate the diverse nature of canopy traits and offer valuable insights into trait variations along a climate gradient (Chaurasia et al., 2020). Albert et al., (2011) emphasized the significance of acknowledging intra-specific variability in plant ecology, while Siefert et al., (2015) found that 25% of trait variation in a community is attributed to intra-species variability. The observed intra-species variability among abundant species in CHVs (Figure 3.15), coupled with its influence on species assemblages across the three PAs, aligns seamlessly with these established findings.

The consistent increase in the CHVs of common abundant species across the three PAs demonstrates that functional variability may be investigated at the individual, species-based, and community levels. Poorter et al., (2018) found 44% trait variation within the most abundant species, paralleling the significant levels of intra-specific variability observed in this study. Moreover, species-specific variation in CHV values indicates that intra-specific trait variation can shape species abundance and interaction, thus influencing community dynamics (Bolnick et al., 2011). This reasoning applies to the dynamics observed in the distribution of abundant species across the three PAs in this study.

The findings of this study not only align with published literature but also offer subtle insights into the intricate relationships between intra-specific variability, functional traits, and species distribution dynamics. This highlights the complex interplay that shapes the biodiversity landscape within these tropical ecosystems, and how it can be gauged by using contemporary remote sensing data.