Master’s Thesis of Forest Environmental Science

Comparison of Structural Characteristics among Different Types of Limestone Forests in Cat Ba Biosphere Reserve, Vietnam

February 2020

Department of Forest Sciences
Graduate School
Seoul National University

Tran, Hai Long

Abstract

Vietnam' s forests have long been known for their rich and diverse fauna and flora. However, the country has experienced significant deforestation and forest degradation due to human activities in the past decades. In response, various scientific works as well as technical solutions have been developed to reverse this trend. This study was conducted to assess the ecological characteristics of limestone forests with different management practices (no logging, post-selective logging, and post-clear-cut forests) and mixed plantations for the restoration and sustainable management of degraded natural limestone forests in the Cat Ba Biosphere Reserve, Vietnam. Structural characteristics of overstory as well as understory were investigated and then evaluated. The results showed that post-selective logging and post-clear-cut forests had much less number of tree species than no-logging forests. Several poor forest stands showed that the natural restoration of degraded limestone forests to the level of unimpacted primeval state could be very slow, or nearly impossible. Mixed plantations showed better signs of reasonable growth, the presence of various valuable species as well as higher biodiversity index than the naturally regenerated post-logged forests, and were nearly comparable to the no logged forest. Some limitation still existed in enrichment planting, such as high planting density and lower soil fertility than no-logged forests. These findings implied that further silvicultural and ecological techniques should be developed to improve the existing models as well as to be the basis for future measures in similar sites.

Keyword: Cat Ba Biosphere Reserve, natural limestone forest, forest restoration, mixed plantation.

Student Number: 2018-25329

Table of Contents

Abstract ... **i**
List of Tables ... **iv**
List of Figures ... **vi**
List of Abbreviations ... **vii**
Chapter 1. General Introduction ... **1**
1.1. Study Background ... 1
1.2. Objectives ... 2
Chapter 2. Literature review ... **3**
2.1. Structural characteristics of natural limestone forests ... 3
2.2. Natural regeneration in natural limestone forests ... 5
2.3. Restoration of degraded natural limestone forests ... 6
Chapter 3. Materials and Methodology ... **8**
3.1 Study area ... 8
3.2 Methodology ... 10
3.2.1. Field inventory ... 10
3.2.2. Data analysis ... 15
Chapter 4. Results and Discussion ... **19**
4.1. Structural characteristics of some typical natural forest types ... 19
4.1.1. Species composition and growth characteristics of the overstory in natural limestone forest ... 19
4.1.2. Natural regeneration, shrubs and herbaceous layer characteristics in natural limestone forests ... 31
4.2. Assessing some restoration models for degraded natural limestone forest ... 38
4.2.1. Species composition and growth characteristics of overstory layer in the restoration models ... 38
4.2.2. Natural regeneration, shrubs and herbaceous layer characteristics in restoration models ... 46
4.3. Comparison of soil properties in the secondary forest and the mixed plantation ... 53
Chapter 5. Conclusion ... **56**
References ... **58**

List of Tables

Table 1. General characteristics of sample plots in the study area 13

Table 2. Species composition (IV) of the overstory layer of three natural limestone forest types (Original forest, Post-selective logging forest, Post-clear-cut forest (P) in the study area 21

Table 3. Growth characteristics of overstory (density, DBH, Ht, Total basal area (G), Total timber volume (M) and Canopy cover) for three natural limestone forest types (Original forest, Post-selective logging forest, Post-clear-cut forest) in the study area. 25

Table 4. Species diversity index (Gini - Simpson, Shannon - Weiner and Evenness) of natural forest types' overstory layer in the study a rea. 30

Table 5. Natural regeneration characteristics including number of species, seedling density, density by height classes and origin of seedlings of natural limestone forest types (rich, post-selective logging and post-clear-cut) in the study area 32

Table 6. Influence of canopy cover, average height and cover percentage of shrub and herbaceous layer on prospective seedling percenta ge of natural forest types in the study area. 36

Table 7. Species composition (IV) of the overstory layer of restoration models 1 and 2 compared to post-clear-cut forests in the study area 38

Table 8. Species composition (IV) of the overstory layer of restoration model 3 compared to post-selective logging forests in the study area 40

Table 9. Growth characteristics of overstory (Density, DBH, Ht, Total basal area (G), Total volume (H) and Canopy cover) of restoration models 1 and 2 and post-clear-cut forest in the study area. 42

Table 10. Growth characteristics of overstory (Density, DBH, Ht, Total basal area (G), Total volume (H) and Canopy cover) of restoration model 3 and post-selective logging forest in the study area 43

Table 11. Species diversity index (Gini-Simpson, Shannon – Weiner and Evenness) of restoration models, post-clear-cut and post-selective logging forests' overstory layer in the study area. 44

Table 12. Natural regeneration characteristics including number of species, seedling density, density by height classes and origin of seedlings in RM1, RM2 and Post-clear-cut forest in the study area 46

Table 13. Natural regeneration characteristics including number of species, seedling density, density by height classes and origin of seedlings in RM3 and Post-selective logging forest in the study area 48

Table 14. Influence of canopy cover, average height and cover percentage of shrub and herbaceous layer on prospective seedling percentage of restoration model in the study area. 52

Table 15. Comparison of the soil properties (0-30 cm depth) between the forest types in the study sites 55

List of Figures

Figure 1. Map of the study site with sample plots and location in the Northeastern Region of Vietnam 9

Figure 2. Restoration treatments of post-logging forests in the study area 10

Figure 3. Sample plot layout in the study site 11

Figure 4. N/D distribution of natural forest types at the study area 28

Figure 5. Aggregated N/D distribution of natural forest types at the study area 29

Figure 6. Height distribution of regenerated trees of natural limestone forest types in the study area 34

Figure 7. Height distribution of regenerated trees at Post-clear-cut forest, RM1 and RM2 in the study area 48

Figure 8. Height distribution of regenerated trees at RM3 and Post-selective logging forest in the study area 50

Figure 7. Distribution of regenerated seedling height of 4 forest types 41

List of Abbreviations

ANOVA	Analysis of Variance
Cat Ba BR	Cat Ba Biosphere Reserve
CEC	Cation-exchange Capacity
D’	Gini – Simpson index
DBH	Diameter at breath height
FFI	Fauna and Flora International
G	Basal area
H’	Shannon – Weiner index
Hs	Average height of Shrub and Herbaceous layer
Ht	Average total height of overstory trees
IUCN	International Union for Conservation of Nature
IV	Importance value index
J’	Evenness
LDS	Least Significant Difference
M	Volume
MAB	Man and Biosphere Programme
MARD	Ministry of Agriculture and Rural Development
N/D	Distribution of trees by diameter class
UNESCO	The United Nations Educational, Scientific and Cultural Organization
VNFOREST	Vietnam Administration of Forestry
WB	World Bank

Chapter 1. General Introduction

1.1. Study Background

Vietnam is a tropical monsoon climate country with an extremely rich and diverse fauna and flora. However, Vietnam's forests, especially natural forests, are seriously degraded due to war, slash-and-burn cultivation and unreasonable exploitation, causing heavy loss of plant resources and ecological imbalance (WCMC, 1994; Thoa, 2000). According to the Ministry of Agriculture and Rural Development (MARD, 2019), the total forest areas of the whole country in 2018 were 14,491,295 ha, covering 41.65% of the total land area, of which 10,255,525 ha was natural forest, and 4,235,770 ha was plantation forest. Although the forest areas have increased in recent years, the quality of the forest is still declining due to many reasons such as deforestation, land degradation, biodiversity loss, and plantation forest increase at the expense of natural forest decline (Nguyen, 2000).

Cat Ba Biosphere Reserve (Cat Ba BR) in Vietnam is one of nine world biosphere reserves recognized by the UNESCO. The total area of the Cat Ba BR is over 26,000 ha, with 2 core zones (strictly conservation with no human impact), 2 buffer zones (allowing limited economic development in combination with conservation) and 2 transition zones (economic development). The vegetation in Cat Ba BR includes tropical limestone forests, mangroves, coral reefs, algae mats and cave systems (MAB Vietnam, 2016). It has a significant biodiversity value as it is home to a number of rare and endangered species of plants and animals with the world's rarest primates – the Golden-headed Langur (FFI - 2003), identified as one of the areas of the highest biodiversity in Vietnam and is recognized as a high priority for global conservation (WB, 2005; Zingerli, 2005; Brooks, 2006).

However, in the past decades, over-exploitation, land use changes as well as improper management and protection of forests have made limestone forest vegetation in the Cat Ba BR rapidly declining in both quantity and quality. These impacts have greatly affected the viability of forests and disturbed the structure and natural regeneration, and the forest succession has been negatively affected by the lack of valuable tree species, degraded land, leading to low and unstable forest capacity. Deforestation has led to degradation of other natural resources, especially water resource. Since then, the life and economic development of local communities in the Cat Ba BR are affected, making forest development activities become even more troubled (Thap, 2010).

Since the establishment of the Cat Ba BR, there have been some researches on plant resources and biodiversity in the area. However, there are no in-depth studies on the composition and current status of plant species here as well as structural and regenerative features, while the impacts and pressures from local people and tourism activities affecting the forests are still taking place daily. Therefore, identifying appropriate technical measures for restoring and developing limestone forest areas in the Cat Ba BR are necessary. However, in order to get accurate and effective technical measures, knowledge of the forestry characteristics, including structural and natural regeneration, as well vegetation biodiversity is considered to be the most important basis.

In this context, the study: ***"Comparison of structural characteristics among different types of limestone forests in Cat Ba Biosphere Reserve, Vietnam"*** is conducted to contribute to supplementing new understandings about forest characteristics, biodiversity and sustainable development of natural limestone forest ecosystems in the study area.

1.2. Objectives

The main objective of this study was to compare the structural and ecological characteristics of some natural forests and mixed plantations for the restoration and sustainable management of degraded limestone forests in the Cat Ba Biosphere Reserve, Vietnam.

The specific objectives were the following:

i) Identifying basic silvicultural and ecological characteristics of some natural limestone forest communities (Study I).

ii) Evaluating applicability of the mixed plantations as a tool in restoration of degraded natural limestone forests (Study II).

Chapter 2. Literature review

2.1. Structural characteristics of natural limestone forests

Forests on limestone are widely distributed in the tropics, especially in Southeast Asia, northern Central America, Brazil and the Greater Antilles. In Southeast Asia, limestone karsts cover an area of around 400,000 km^2 (Day & Urich, 2000). Karsts are the main focus for speculation and important biodiversity arcs (Clements et al., 2006). They form a particularly abundant endemic flora and have high environmental heterogeneity due to large-scale changes in substrate solubility (Perez-Garcia et al., 2009). However, limestone vegetation, or more particularly limestone forests has been destroyed as much as other vegetation types even through these limestone areas are much more difficult to access and farm due to dangerous topographic characteristics. Moreover, limestone forests are more vulnerable because its typical shallow soil horizon and relative dry habitat which are in many cases irreversible one damaged (Tuyet, 2001).

Studies on tropical rain forest in general has been thoroughly conducted in the past decades, with morphological structure being represented by the correlation between tree height and diameter at breast height (DBH), and between crown diameter and DBH by regression analysis (Penttinen et al., 1992). Bauer (1962; 1964) had focused on forest structural factors and silviculture technical measures applied to each type of natural rain forest. Meyer (1930) used a mathematical equation with a continuous decreasing curve to describe the tree distribution with diameter size, later known as the Meyer distribution. Tang et al. (2010), when studying the tropical limestone forest of Xishuangbanna, China, have pointed out that inventory and monitoring of forest structure and diversity are major prerequisites for understanding and managing forest ecosystems. Phuong (1970) showed the structural characteristics of the forest cover in Northern Vietnam, which Cat Ba BR is a part of, based on the results of a general survey of the situation of the forests of Northern Vietnam from 1961 to 1965. The foremost structural element studied was species composition through which a number of development rules of forest ecosystems were discovered and applied in practices.

However, few studies have intensively investigated natural tropical limestone forest partly because of the difficulty faced while working in tropical karst terrain (Kelly et al., 1988; Felfili et al., 2007). In Vietnam, Thuong et al. (1988) conducted analysis of natural limestone forest in Northern Vietnam and marked the relationship between the variation in silvicultural characteristics of natural limestone forests (even in the primary forest) with the variation of main terrain types. Hong (2010), when researching the natural evergreen limestone forest in Vu Quang National Park – Ha Tinh province - Vietnam, concluded that the poor natural limestone forest type in the area had a relatively low tree density with un-even distribution, occupied mainly by pioneer and light-tolerant species, low canopy cover reaching only 0.53% and none of the distribution of trees by diameter (N/D distribution) followed the Meyer distribution function. Hien et al., (2014) pointed out that the importance value index (IV%) of dominant species in Vu Quang National Park had a great variation from 11.9% to 48.4% and the distribution of trees by diameter (N/D distribution) did not follow the Meyer function but followed the Distance function with decreasing distribution of trees by higher diameter classes.

In the past decades, the research on natural limestone forest structure has made some progress and contributing to raising awareness on this type of forest, enhancing the management and development efforts. On the other hand, forest management and silvicultural practices not only require information on tree species composition and forest structure, but also the diversity of tree species (Bauer, 1962; Trung, 1999). Previous studies have emphasized the importance of field surveys to improve our understanding of tree diversity in tropical limestone forests, especially in Central and South America (Kelly et al., 1988; Brewer et al., 2003; Perez-Garcia et al., 2009).

While investigating the biodiversity of limestone forest timber communities in Than Sa - Phuong Hoang Natural Reserve, Vietnam, Thoa (2013) indicated that diversity indices in that area was only at a modest rate compared to other forest types in Vietnam and was on a reducing trend. Similar results were studied in Xishuangbanna limestone forest, China, where although the stem density was equal to that of other forest types, timber community diversity was much lower (Tang et al., 2010). However, information is scarce on basic aspects such as the range of environmental conditions where they grow and the extent and model of species diversity of such ecosystems worldwide.

2.2. Natural regeneration in natural limestone forests

Apart from structural characteristics, natural regeneration is also significanly important, representing the replacement of the old tree generation with the seedling generation to restore the basic composition of the forest, contributing to enriching the number and composition of species in the ecosystem (Lan, 1986).

Richards (1952) summarized the study of regeneration on standard plots of 1x1 m^2 and the natural regeneration distribution in tropical forests. Two common characteristics of rainforest regeneration including continuous scattering and hole regeneration. These two characteristics are not only found in primary forests but also in secondary forests - a fairly common forest object in many tropical countries (Steenis, 1956).

When studying the effect of ecological factors on natural regeneration, light factors (through forest canopy), soil moisture, soil structure, shrubs and herbaceous layer were often mentioned. Bauer (1962) speculated that the lack of light through dense canopy cover in rain forest had negative impact on natural regeneration; while shrubs and herbaceous layer had some degree of effect on this subject. Others found the relationship between species richness and light in natural limestone forests, claiming that the number of species dropped in areas of highest light supply (Schmidt et al., 1996; Gad et al., 1999).

In summary, the studies mentioned above partly shed light on the study of structural characteristics and regeneration of natural forests in general and natural limestone forests in particular. These are the basis for the selection of structural and regenerative forest research in this topic in order to restore degraded forest types in the study area.

2.3. Restoration of degraded natural limestone forests

Restoration ecology is one of the new areas of ecology, often focused on solving the problem of rebuilding natural ecosystems on degraded or modified soil (Miller et al., 1995). The goal of ecosystem restoration is to recover the composition, structure and function of the original ecosystem when it has not been affected (Bradshaw, 1990; MacMahon, 1997). In general, no impact completely destroyed the landscape, there would usually still some plant and animal propagules, some organic matter left from previous ecosystems or other residues as well as the abiotic characteristics of the area (Young et al., 1987). These remnants are essentially raw materials available to rebuild the ecosystem (MacMahon, 1997). In fact, according to Janzen (1988), habitat restoration is mainly initiation, growth and coalescence of remnant habitat fragments.

During the restoration process, natural succession is the main factor and ecological principles have been used to restore degraded sites in different ecosystems (MacMahon, 1997). Natural succession on degraded sites is accompanied by improved structure in terms of species composition and complexity, and function of the ecosystem, this leading to ecosystem development. Therefore, the purpose of restoration is to accelerate the natural succession. It is clear that these natural elements are rarely sufficient to allow rapid ecosystem development so that they need to be enhanced by human impacts. Restoring the ecosystem to its original state is difficult or even impossible, because detailed ecological information about the original ecosystem is not available, techniques for introducing the original species to the ecosystem might be insufficient although using restoration ecosystem for conservation of endangered species and biodiversity in general has been well established (Cairns, 1988).

Recent studies on tropical plantation forest have presented that plantations can accelerate natural succession of endemic timber species by acting as a nursery ecosystem (Parrotta, 1992, 1993, 1995; Otsamo, 2000). Planted forests established over long degraded areas may act as catalysts for succession, facilitating the reorganization of native flora through their influence to soil microorganisms and fertility (Parrotta, 1995). As this natural process is enhanced by silvicultural techniques to promote the development of native species, plantations can gradually be converted into natural forests (Fang and Peng, 1997; Kamo, 2002). Planted species, after facilitating the succession of vegetation, often cannot be regenerated in a rich-species environment, as they are predominantly not shade tolerant pioneer species that are eventually replaced by shade tolerant native species (Parrotta, 1995; Kamo, 2002).

In Vietnam, the studies on restoration of degraded natural limestone forest have long been conducted in various areas. Ngu and Lan (2000) has researched on biological characteristics and the ability to plant several high-value native trees species in Northern mountainous region of Vietnam. They identified some ecological characteristics and proposed techniques to plant these species in the above localities with some initial success. Vien et al. (2005) proposed some restoration models for degraded natural limestone forest such as plantation of *Acacia* with a native pioneer species and enhancement of natural regeneration.

Although these studies had been conducted in various regions of Vietnam, it has poorly been done for the Cat Ba area, which with its proximity to the sea, has been proven to be unique and vastly different in conditions from other in-land natural limestone forests in the country (Thap, 2010). Therefore, studying the characteristics of structural and natural regeneration, along with biodiversity of natural and restoration model for limestone forest would have meaningful contribution for future restoration efforts of similar landscapes in the world in general and in Vietnam in particular.

Chapter 3. Materials and Methodology

3.1 Study area

The study area is located in the Cat Ba BR (Lat. 20°44′50″-20°55′29″N, Long. 106°54′20″-107°10′05″E), Cat Hai district, Hai Phong city in the Northeastern region, Vietnam (Figure 1). The Cat Ba BR has a total area of 26,241 ha with 17,040 ha of landmass and 9,200 ha of marine environment (UNMAB, 2007). It is located in the tropical monsoon climate region with an average annual rainfall of 1,700-1,800 mm, mainly concentrated in the rainy season from July to October. The average temperature is 25-28^{o}C (max. 36^{o}C, min. 10^{o}C) and average humidity is around 85% (Government of Vietnam, 2018).

The Cat Ba BR is characterized by a unique variety of landscapes and ecosystems, including limestone karsts, tropical limestone forests, coral reefs, mangrove and sea grass beds, lagoons, beaches, caves and willow swamp forests (Viet & Lin 2001). The original vegetation in this study area was characterized by tropical evergreen broad-leaved forests developed on limestone bedrock (i.e. natural limestone forest) before degradation in the 1970s (Le, 1990). The forests were subjected to widespread over-harvesting, both legal and illegal logging, land-use shift to agriculture or annual crops (except for the core zone of the national park) and is partly in regeneration process since 1998 (Thap, 2010).

After logging operations, the post-clear-cut forests were either left for natural restoration or been applied with two main artificial restoration methods including soil improvement and high intensity additional planting of native and high valuable species. While the post-selective logging also faced two options, natural or artificial restorations by zoning for protection combined with enrichment planting of some native species. The detailed diagram of historical impact and restoration to forests in the study site was presented in Figure 2.

For the purpose of this study, the tropical limestone forests in the Cat Ba BR was selected because it is the most dominant ecosystem in the study area, affecting and regulating all the others.

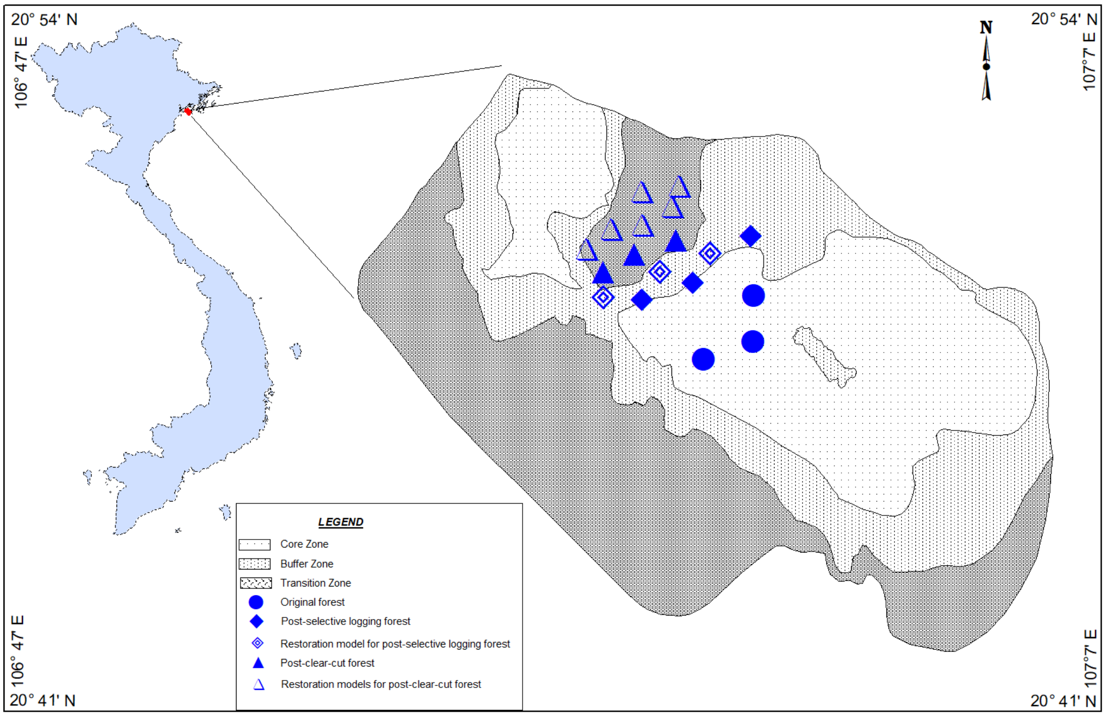

Figure 1. Map of the study site with sample plots and location in the Northeastern Region of Vietnam.

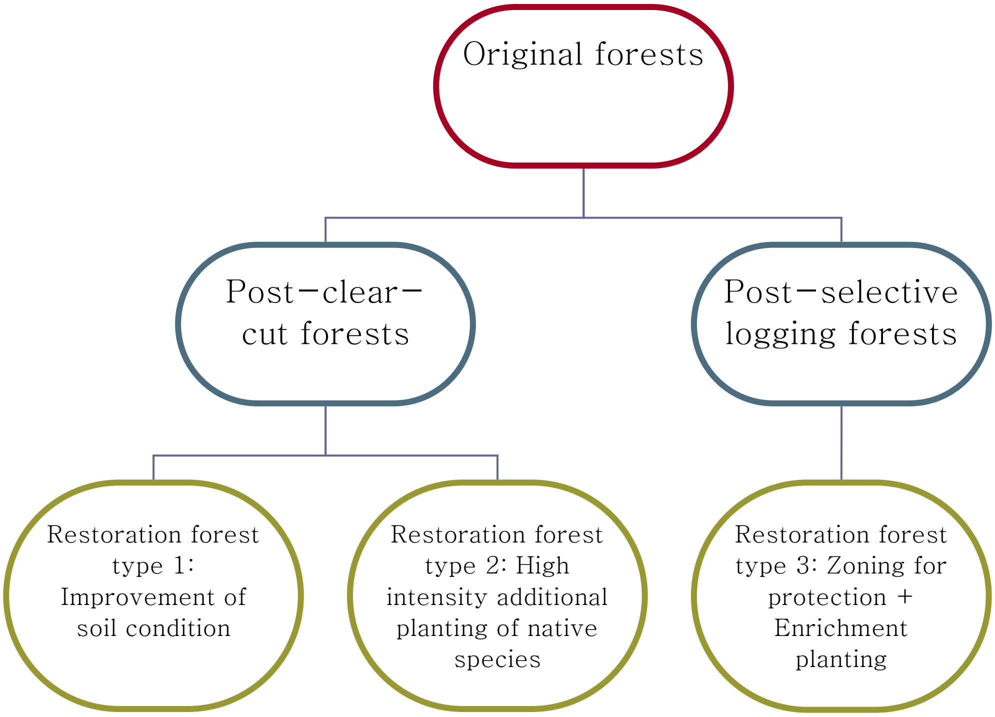

Figure 2. Restoration treatments of post-logging forests in the study area.

3.2 Methodology

3.2.1. Field inventory

Based on the collected information of Cat Ba BR Management Board and Cat Ba National Park such as forest status map, topography and administrative maps, etc., the transects were identified to represent the study areas, arranged through many forest types, forest status, habitats and terrains, especially through the highest peaks of the area.

From the official files and status of transect lines, the study selected sample plots that represent the forest status in the study area as the basis for conducting detailed surveys. Natural forest type classification was based on the national classification system of Vietnam (MARD, 2009), where:

- Original forest: primeval forest, no human impact, with total tree volume of >200 m^3/ha, or equivalent to Rich natural forest type in the national classification.
- Post-selective logging forest: forest with past human impact, mainly from selective logging in the 1970s. All logging activities ended and natural

restoration started in 1980. Total tree volume of between 100 and 200 m^3/ha, equivalent to Medium natural forest type in the national classification.

- Post-clear-cut forest: forest with past human impact, mainly from clear-cut in the 1970s through 1990s. Activities stopped and natural restoration started in 1995. Total tree volume of between 10 and 100 m^3/ha, equivalent to Poor natural forest type in the national classification.

Eighteen 20x20 m (400 m^2) sample plots were established: 3 for original forests (R1, R2 and R3), 3 for post-selective logging forests (M1, M2 and M3), 3 for post-clear-cut forests (P1, P2 and P3), and 9 for the dominant restoration models (RM1, RM2 and RM3) in the study site. In each restoration model, 1 plot was set up for survey and 2 others were inherited from previous study (Hung et al., 2016). The list of sample plots and their respective general characteristics were presented in Table 1. Plots for each types of natural forest were arranged in three positions: bottom, middle and top of the mountain.

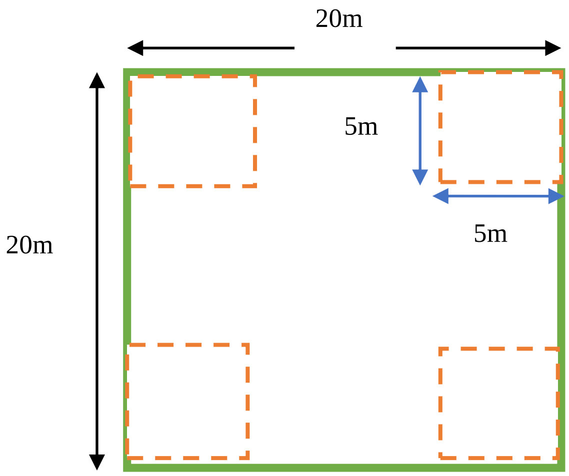

Figure 3. Sample plot layout in the study site

In each sample plots, the composition of all timber individuals in the overstory with DBH ⩾ 5 cm were investigated. DBH and total height of each trees (Ht) were measured. In addition, in each plot the data on canopy cover, slope, elevation, type of terrain and historical human activity were also recorded.

Four 5x5 m (25 m^2) standard plots were set up in each sample plot to survey the height, growth characteristics and origin of regenerated trees with

DBH < 5cm. The data of shrubs and herbaceous vegetation layer on their composition, quantity, average height and cover (%) were also collected.

Three soil sample plots were established at each site and a 10-cm diameter auger was used to randomly collect nine soil samples from 0–30 cm depth. The samples at 0–20 cm depth from each plot were aggregated into a composite. Preparation and analysis of the composite soil samples were carried out according to van Reewijk (2002). All soil samples would be analyzed in the Soil Ecology Laboratory Lab – Research Institute of Forest Ecology and Environment – Vietnamese Academy of Forest Sciences.

Table 1. General characteristics of sample plots in the study area

Plot	X coordinate	Y coordinate	Location	Sloping (degree)	Slope direction	Altitude (m)	Forest type	Historical human impact
R1	629743	2301148	Top of mountain	5	South West	108	Natural limestone forest	None
R2	631812	2300637	Middle	25	South	96	Natural limestone forest	None
R3	631100	2300763	Bottom	10	North East	43	Natural limestone forest	None
M1	632171	2303182	Top of mountain	20	East	122	Natural limestone forest	Selective logging completed in 1980- Natural regeneration
M2	629366	2305496	Middle	25	East	92	Natural limestone forest	Selective logging completed in 1980- Natural regeneration
M3	629311	2302878	Bottom	7	East	61	Natural limestone forest	Selective logging completed in 1980- Natural regeneration
P1	627872	2297025	Top of mountain	20	East	114	Natural limestone forest	Clear-cut completed in 1995 - Natural regeneration
P2	625409	2304823	Middle	38	South East	81	Natural limestone forest	Clear-cut completed in 1995 - Natural regeneration
P3	625644	2305091	Bottom	15	South	61	Natural limestone forest	Clear-cut completed in 1995 - Natural regeneration
RM1-1	627361	2303279	Bottom	23	South West	19	Artificial restoration to natural forest	Clear-cut completed in 1995 - Mixed plantation (*Acacia* and native species) started in 2004 - 2005

RM1-2	627721	2302164	Middle	42	West	27	Artificial restoration to natural forest	Clear-cut completed in 1995 - Mixed plantation (*Acacia* and native species) started in 2004 - 2005
RM1-3	627385	2303011	Bottom	18	North East	14	Artificial restoration to natural forest	Clear-cut completed in 1995 - Mixed plantation (*Acacia* and native species) started in 2004 - 2005
RM2-1	629718	2300648	Bottom	28	East	45	Artificial restoration to natural forest	Clear-cut completed in 1995 – Additional native species restoration planting in 1998-1999
RM2-2	629503	2300140	Bottom	17	South East	32	Artificial restoration to natural forest	Clear-cut completed in 1995 – Additional native species restoration planting in 1998-1999
RM2-3	630122	2298735	Bottom	20	East	30	Artificial restoration to natural forest	Clear-cut completed in 1995 – Additional native species restoration planting in 1998-1999
RM3-1	629491	2301201	Bottom	5	North	37	Artificial restoration to natural forest	Selective logging completed in 1975 - Enrichment planting in 1975-1976
RM3-2	629246	2301087	Bottom	12	North East	20	Artificial restoration to natural forest	Selective logging completed in 1975 - Enrichment planting in 1975-1976
RM3-3	630267	2300871	Middle	37	East	38	Artificial restoration to natural forest	Selective logging completed in 1975 - Enrichment planting in 1975-1976

3.2.2. Data analysis

a. Structural characteristics of the overstory

- Identifying the species composition and role in the community

In order to determine the composition of tall trees, the thesis used Daniel Marmillod's method of determining the importance level (IV%) (cited by Khanh, 1996).

$$IV_i\% = \frac{N_1\% + G_i\%}{2}$$

where: $IV_i\%$ is the importance value of species *i*th

$N_i\%$ is the % in the number of species ith in the forest community

Gi% is the % total basal area of species ith in the forest community

- Density:

Density is an indicator of the number of individuals of each species or all species involved in a unit of area (usually 1 ha), reflecting the utilization of nutrient space and the role of species in the forest community. The formula for determining the density is as follows:

$$N/ha = \frac{n}{S_p} * 10{,}000$$

where: n: Number of individuals of each species or all species in a sample plot

S_p: Sample plot area (m^2)

- Tree basal area and stand volume

The author calculated basal area and volume for each measured tree as follows:

$$G = 3.1416 \times \frac{\left(\frac{D}{400}\right)^2}{400}$$

where: G is basal area of tree in m^2,

D is diameter at breath height (DBH) in centimeter.

$$V = G \times h \times f$$

where: V is volume of tree in m^3

G is basal area in m^2

h is total height of tree in m and

f is tree form co-efficient, constant at 0.45 in this study

- Canopy cover of a forest community

The canopy cover is determined by the point investigation method with the calculation formula:

$$TC = \frac{n_1}{N}$$

where: TC is the canopy cover

n_1 is the point with foliage

N is the total point investigated.

- Diameter class distribution:

Based on field data of diameter measures and all stem numbers from both main and sub-plots, we group tree stems into diameter classes of 5-cm size; then the number of each diameter class is converted to per ha.

Based on the data of stem number per diameter class, the diameter class distribution will be constructed for analysis of its pattern to see whether the stand development is sustainable or not, then recommendations would be made for silviculture interventions. The two major distribution schemes used in this study were Meyer distribution (Meyer, 1930) and Distance distribution functions.

b. Species diversity

- Gini-Simpson index (D):

The Gini-Simpson index equals the probability that the two entities represent different types, and it can be represented by the equation (Jost, 2006):

$$1 - \lambda = 1 - \sum_{i=1}^{R} p_i^2 = 1 - \frac{1}{{}^2D}$$

where: R is richness (the total number of species in the plot).

p_i is the proportion of individuals belonging to the *i*th species in the dataset of interest.

- Shannon – Weiner index (H’):

This measure was originally proposed by Claude Shannon to quantify the entropy (uncertainty or information content) in strings of text (Shannon, 1948). It is calculated by the formula:

$$H' = -\sum_{i=1}^{R} p_i \ ln\, p_i$$

where: p_i is often the proportion of individuals belonging to the *i*th species in the plot

R is richness (the total number of species in the plot).

- The evenness index (J’):

It is the equality of abundances in the community. The maximum evenness is 1 when all species are equally abundant and in other cases, evenness will be less than 1 (Pielou, 1966). It is calculated by:

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

where: H is the Shannon – Weiner index

S is the number of species in the plot.

c. Natural regeneration

- Regeneration density:

It is the indicator representing the number of regenerated trees per unit area, determined by the following formula:

$$N / ha = \frac{10.000 \times n}{S_{dt}}$$

where: S_{dt} is the total area of standard plots in each sample plot (m^2)

n is the number of regeneration trees surveyed.

- Height class distribution of regeneration trees:

Regenerated trees were divided into 3 height class: less than 0.5m; 0.5-1m; and over 1m. On that basis, regenerated trees with a height of ≥ 1m were considered prospective seedlings, i.e. seedlings with high chance to develop into fully grown overstory layer trees (VNFOREST, 2013).

- Effect of some ecological factors to natural regeneration

- Canopy cover:

The effect of canopy on natural regeneration was assessed through the synthesis of regeneration research such as density, percentage of prospective trees and quality of regenerated trees according to different canopy cover in each plot studied.

- Shrub and herbaceous layer:

Based on the research results of shrubs and herbaceous layer, the topic summarized the relationship between the percentage of prospective trees according to different growth levels of the shrub and herbaceous height level and cover in each sample plot.

The IBM SPSS Version 22 software package was used for all statistical analysis. The difference in species richness and diversity among the study plots were determined by analysis of variance (ANOVA). Least Significant Difference (LDS) test ($p<0.05$) was also used.

Chapter 4. Results and Discussion

4.1. Structural characteristics of some typical natural forest types

4.1.1. Species composition and growth characteristics of the overstory in natural limestone forest

a. Species composition of the overstory

According to Daniel Marmillod (1982), only plant species with IV% value ≥ 5% had ecological significance in the forest community and took part in the composition formula. Results of overstory species composition of natural forest types in the study area are summarized in Table 2.

Woody species with DBH ⩾ 5 cm of the overstory in natural limestone forests comprised a total of 64 species in 38 families (Table 2). In which 7 species can be used for food or medicine, 3 were considered to have high value wood and 2 endangered species listed in the Vietnam Red Data Book (2007) or IUCN’s red list (1997).

According to the species importance value ranking, the total number of overstory species taking part in the composition in the original forest was 19, with 3 species that appeared in 2/3 plots (*Engelhardtia roxburghiana*, *Dracontomelum duperreanum* and *Dyoxylum loureirii*). The most dominant species was *Pterospermum diversifolium* (28.6%) in the Plot R1, followed by *Engelhardtia roxburghiana* (25.2%) and *Bischofia javanica* (19.5%) in the Plot R2, and *Dracontomelum duperreanum* (18.7%) in the Plot R3, respectively. Species with the highest IV% are those that can thrive and develop on poor nutrient soil condition with many visible rocks (Plot R1) or on high slope degree with relatively low nutrient level (Plot R2) or otherwise shade tolerant (Plot R3). At these plots, a number of rare and high value species were found such as *Sterculia lanceolata*, *Syzygium cumini* and *Garcinia oblongifolia* (Plot R1), *Dracontomelum duperreanum*, *Dyoxylum loureirii* (Plot R2) and *Dracontomelum duperreanum* , *Dyoxylum loureirii*, *Annamocarya sinensis*, *Canarium bengalensis*, *Castanopsis indica* (Plot R3), althouth their IV% values were low.

For the post-selective logging forest, 15 overstory species were present in the species composition, with one species appeared in all 3 plots (*Streblus* *macrophyllus*) and two species in 2/3 plots (*Diospyros susarticulata*, *Callicarpa longifolia*). The species with highest IV% value was *Sacara dives* (47.7%) in Plot M2; *Aesculus assamica* (31.7%) and *Acanthus ebracteatus* (19.4%) in Plot M1; and *Streblus macrophyllus* (31.5%) and *Homalium paniculiflorum* (24.1%) in Plot M3. In this forest type, species that became the most dominant are rather pioneer species preferable with the poor nutrient and high rock percentage (in Plot M1), high sloping degree with median soil erosion (in Plot M2), or light-tolerant as in Plot M3. There was no rare or valuable species in Plot M1, but some can be found in the other plots including *Aphanamixis grandifolia* (Plot M2) and *Goniothalamus macrocalyx* (Plot M3).

Regarding the post-clear-cut forest, the total number of overstory species in the species composition was 11 species, with only 1 species appreared in 2/3 plots (*Actephila* longipediculata). Species that dominated the landscape were *Actephila longipediculata* (44.2%) and *Vitex quinata* (34.2%) in Plot P1; *Ficus auriculata* (74.2%) and *Litsea verticillata* (22%) in Plot P2; and *Acanthus ebracteatus* (40.9%) in Plot P3. All these species were pioneer species with low value, median growth and could develop on harsh conditions such as extremely rocky topography (P1), very high slope and exessive erosion (P2) and poor soil nutrient (P3). Notably, no species of high value, rare or precious can be found in this forest type.

Table 2. Species composition (IV) of the overstory layer of three natural limestone forest types (Original forest, Post-selective logging forest, Post-clear-cut forest (P) in the study area

Forest type	Plot	Number of species	Number of family	Species composition (IV%)
Original forest	**R1**	12	12	28.6 *Pterospermum diversifolium* (Sterculiaceae) + 11.3 *Engelhardtia roxburghiana* (Juglandaceae) + 10.9 *Peltophorum tonkinensis* (Fabaceae) + 9.7 *Bridelia penangiana* (Phyllanthaceae) + 8.7 *Sterculia lanceolata* (Malvaceae)[+] + 6.9 *Syzygium cumini* (Myrtaceae)[*+#] + 6.5 *Garcinia oblongifolia* (Clusiaceae)[*] + 5.8 *Vatica odorata* (Dipterocarpaceae) + 11.6 Others
	R2	13	10	25.2 *Engelhardtia roxburghiana* (Juglandaceae) + 19.5 *Bischofia javanica* (Phyllanthaceae) + 16.8 *Elaeocarpus griffithii* (Elaeocarpaceae) + 11.0 *Flacourtia cataphracta* (Flacourtiaceae) + 8.1 *Dracontomelum duperreanum* (Anacardiaceae)[*] + 5.0 *Dysoxylum loureirii* (Meliaceae)[#] + 14.3 Others
	R3	15	12	18.7 *Dracontomelum duperreanum* (Anacardiaceae)[*] + 14.9 *Deutzianthus tonkinensis* (Euphorbiaceae) + 13.7 *Dysoxylum loureirii* (Meliaceae)[#] + 11.3 *Annamocarya sinensis* (Juglandaceae)[#] + 10.1 *Pterospermun truncatolobatum* (Fabaceae) + 6.2 *Sacara dives* (Fabaceae) + 6.9 *Canarium bengalensis* (Burseraceae)[*+] + 5.1 *Castanopsis indica* (Fagaceae)[*] + 20.0 Others
Post-selective logging forest	**M1**	9	8	31.7 *Aesculus assamica* (Sapindaceae) + 19.4 *Acanthus ebracteatus* (Acanthaceae) + 12.1 *Diospyros susarticulata* (Ebenaceae) + 8 *Pterospermum diversifolium* (Sterculiaceae) + 7.4 *Streblus macrophyllus* (Moraceae) + 6.3 *Ficus hispida* (Moraceae) + 6.2 *Callicarpa longifolia* (Lamiaceae) + 5.9 *Microcos paniculata* (Malvaceae) + 3.0 Others

	M2	7	5	47.7 *Sacara dives* (Fabaceae) + 12.8 *Streblus macrophyllus* (Moraceae) + 12.6 *Diospyros susarticulata* (Ebenaceae) + 10.8 *Symplocos glauca var. epapillata* (Symplocaceae) + 7.3 *Streblus indica* (Moraceae) + 5.7 *Aphanamixis grandifolia* (Meliaceae)*+ + 3.1 Others
	M3	9	7	31.5 *Streblus macrophyllus* (Moraceae) + 24.1 *Homalium paniculiflorum* (Salicaceae) + 13.7 *Callicarpa longifolia* (Lamiaceae) + 11.2 *Goniothalamus macrocalyx* (Annonaceae)* + 8.5 *Xerospermum noronhianum* (Sapindaceae) + 11.0 Others
Post-clear-cut forest	**P1**	7	6	44.2 *Actephila longipediculata* (Euphorbiaceae) + 34.2 *Vitex quinata* (Lamiaceae) + 7.6 *Lonicera japonica* (Caprifoliaceae) + 5.9 *Randia dasycarpa* (Rubiaceae) + 8.1 Others
	P2	3	3	74.2 *Ficus auriculata* (Moraceae) + 22.0 *Litsea verticillata* (Lauraceae) + 3.8 Others
	P3	7	6	40.9 *Acanthus ebracteatus* (Acanthacea) + 14.7 *Streblus macrophyllus* (Moraceae) + 12.9 *Callicarpa longifolia* (Lamiaceae)+ 12.0 *Actephila longipediculata* (Euphorbiaceae) + 10.5 *Aesculus assamica* (Sapindaceae) + 5.5 *Microcos paniculata* (Malvaceae) + 3.5 Others

*denotes species that can be used for food or medicine; + denotes species that have high value wood; # denotes species listed in the Vietnam Red Book or IUCN (1997).

Species composition is an important factor in the structure of forest stands and decisively influence other ecological features of the stand (Barbour et al., 1987; Parrotta 1995). Evenmore so in natural forests of Vietnam, with hot and humid climate, have created a complex forest ecosystem and constituted a diverse and abundant species of woody trees in the flora. Species composition denote the density of a particular species or group of tree species occupying the forest stand, which is an indicator used to assess biodiversity, stability and sustainability of ecosystems. It is the basis for orienting business and nurturing measures.

Therefore, the study of species composition is considered as the first task in the process of forest structure research in general and is the basis for proposing integrated silvicultural solutions for protection and zoning in forest restoration. The indicator showing the level of participation of each species in the forest stand is called the Importance Value (IV%). The set of composition factors of the corresponding tree species is called the species composition formula. In essence, the composition formula has profound biological significance, reflecting the reciprocal relationship between plants in a plant community and the relationship between plant communities and external conditions.

The result of species composition in the study area showed a large variation between forest types and within each forest type. In general, the original forest had a more uniform structure with the appearance of many valuable or rare species, species had low IV%, none of which dominated the bottom and middle positions of the mountain but there were species that dominated at the top position, this was similar to the research results in similar other non-affected natural limestone forests in Than Sa – Phuong Hoang Reserve, Vietnam (Thoa, 2013) and Xishuangbanna National Parks, China (Liu & Slik, 2014).

However, the number of valuable species decreased and there were 1 to 2 dominant species that overwhelm the growth of other species in post-selective logging and especially post-clear-cut forests where there were no rare, precious or valuable species but predominant pioneer species. These presented a significant reduction in plant resources in the two affected forest states, similar to results of other studies on secondary forests in Cat Ba (Thap, 2010) and Binh Dinh - Vietnam (Van et al., 2018).

Human impact on the Cat Ba BR, typically logging, was evident through the difference in the composition of the original forest at the core zone and the post-selective logging and post-clear-cut forests in the buffer zones. Many valuable timber species occurred in the original forest but very little in the post-selective logging forest and non-existence in post-clear-cut forest clearly showing that these species had been severely exploited in the past. The dominance of a number of species in the study areas had various causes, such as these species could develop well on poor nutrient soil, high steepness; human intervention causing the destruction and disappearance of other species (i.e. invasive cultivation, logging, ecotourism, etc.).

In addition, the natural limestone forest in Cat Ba had a much lower number of species that appear and the number of species participating in the formulation, including the original forests, than other limestone forests in Vietnam and China - which had similar natural conditions to the study area (Cao and Zhang, 1997; Thoa, 2013; Binh, 2014; Van et al., 2018). This could be explained by the relatively isolated topographic characteristics of the study area from other habitats and in each habitat in the study area together resulting in a shortage of seed dispersed from outside into the study area as well as species exchange between forest stands. Moreover, limestone karst site conditions were complex, poor in nutrition, with high percentage of exposed rocks, leading to the fact that many species did not had favorable growth context.

b. Growth indicators of the overstory

Growth indices for overstory vascular plants in the study are were presented in Table 3. The growth characteristics of overstory vegetation were significantly different ($p<0.05$) among natural forest types in the study area. Tree density raised steadily from original forest (800 trees/ha) to post-selective logging forest (817 trees/ha) and finally to post-clear-cut forest (1117 trees/ha), however the average density between original and post-selective logging forests were not statistically meaningful. In addition, the tree density in each type also varied by location, descending from the top to the bottom of the hill in original forest, specifically from R1 with 975 trees/ha to R3 with 625 trees/ha. While in the post-selective logging forest tree density was at the lowest figure in plot M2 at the slope (600 trees/ha) and highest in M3 at the bottom (950 trees/ha). Similarly, tree density in post-clear-cut forest was also the lowest at the slopes (1,000 trees/ha) and highest at the bottom (1,300 trees/ha).

Table 3. Growth characteristics of overstory (density, DBH, Ht, Total basal area (G), Total timber volume (M) and Canopy cover) for three natural limestone forest types (Original forest, Post-selective logging forest, Post-clear-cut forest) in the study area.

Forest type	**Plot**	**Density (trees/ha)**	**DBH (cm)**	**Ht (m)**	**G (m^2/ha)**	**M (m^3/ha)**	**Canopy cover (%)**
Original forest	R1	975	17.6 ± 9.6	14.8 ± 5.2	30.8	250.3	71
	R2	800	18.3 ± 14.2	11.9 ± 5.8	33.8	278.0	78
	R3	625	27.8 ± 15.8	16.7 ± 7.2	50.0	491.1	89
	Mean	**800[a]**	**20.6 ± 13.7[a]**	**14.3 ± 6.2[a]**	**38.2[a]**	**340.8[a]**	**79.3[a]**
Post-selective logging forest	M1	900	15 ± 7.6	10.6 ± 3.0	20.0	112.5	58
	M2	600	18.3 ± 11.4	14.2 ± 5.5	21.5	187.5	62
	M3	950	17.5 ± 10.2	11.4 ± 4.6	30.5	201.9	67
	Mean	**817[a]**	**16.9 ± 9.7[b]**	**12.1 ± 4.4[b]**	**24.0[b]**	**169.2[b]**	**62.4[b]**
Post-clear-cut forest	P1	1050	7.7 ± 2.4	4.7 ± 0.9	5.2	12.5	50
	P2	1000	12.1 ± 4.5	6.7 ± 2.0	12.9	45.0	47
	P3	1300	11.7 ± 4.5	7.7 ± 2.7	16.1	62.5	61
	Mean	**1117[b]**	**10.5 ± 3.8[c]**	**6.4 ± 1.9[c]**	**11.4[c]**	**40.0[c]**	**52.7[c]**

Means followed by different letters in the same collum are significantly different between forest types at $p < 0.05$ by t-test

Average DBH and Ht decreased sharply from original to post-selective logging and post-clear-cut forests. Moreover, there was a great variation in each forest type. At original forest, DBH increased steadily from R1 (16.4 ± 9.8 cm) to R2 (17.6 ± 15.3) and in R3 (27.8 ± 16.1), while Ht was the lowest in R2 (11.9 ± 6.2) compared to R1 (14.3 ± 5.2 m) and R3 (16.7 ± 7.2 m). For post-selective logging forest, DBH and Ht had the highest value in M2 (18.3 ± 11.4 cm and 14.2 ± 5.5 m respectively) and lowest in M1 (DBH = 15 ± 7.6 cm, Ht = 10.6 ± 3.0 m). In post-clear-cut forest, DBH was highest in P2 with 12.1 ± 4.5 cm, Ht was highest in P3 at 7.7 ± 2.7., both were lowest in P1 (DBH = 7.7 ± 2.4 cm, Ht = 4.7 ± 0.9 m).

Total basal area, total volume and canopy cover, were also significantly different among the forest types. Average total basal area of original forest was relatively high (38.2 m^2/ha) then declined to 24 m^2/ha in post-selective logging forest and 11.4 m^2/ha in post-clear-cut forest. Stand volume in original forest was particularly high, up to 340.8 m^3/ha, while it was 169.2 m^3/ha in post-selective logging forest and only 40.0 m^3/ha in post-clear-cut forest. Canopy cover likewise decreased steadily from original forest (79.3%) down to post-selective logging forest (62.4%) and post-clear-cut forest (52.7%).

The results represented the difference of tree community between the unimpacted core zone and the impacted buffer zone at Cat Ba BR. The density of trees between original and post-selective logging forests was not significantly different, while it was significantly different from post-clear-cut forests. Other indicators such as DBH, height, basal area, volume and canopy cover had significant differences between all 3 types, with original forest had much higher indicators than the other two showing human impact, especially logging for habitat in the study area. In addition, site conditions such as soil properties and topographic characteristics can also explain these differences. Original forest in the study area also had comparable growth characteristics with other natural limestone forest such as basal area in Xishuangbanna, China (33.5 m^2/ha), Bau Hill (28 m^2/ha) and Gunung Mulu National Park in Sarawak, Malaysia (37 m^2/ha) (Tang et al., 2011; Proctor et al., 1983; Adam & Mamat, 2005).

The aforementioned characteristics were also similar with other forest ecosystems in Vietnam. Typically, natural forests in An Lao district, Binh

Dinh, Vietnam, where natural conditions and human impact history were similar to that of Cat Ba BR, had tree density = 574-1122 trees/ha, DBH = 14.3-18.1 cm, G = 12.56-35.28 m^2/ha (Van et al., 2018). Another region with relatively similar conditions to Cat Ba BR was Dong Nai BR in southern Vietnam had post-selective logging forest with basal area of 25.7 m^2/ha and volume of 138.4 m^3/ha (Trung et al., 2016).

However, post-clear-cut forest in the study area had a much lower growth and development than many similarly affected forest conditions in other evergreen montane forests in Vietnam. Also, in Dong Nai BR, this forest type had basal area = 17.8 m^2/ha and volume = 65.4 m^3/ha. In the natural limestone secondary forest adjacent to Than Sa – Phuong Hoang BR, growth characteristics were DBH = 14.1 cm, Ht = 13.1 m and basal area = 13.0 m^2/ha (Chung & Hung, 2013).

The original and post-selective logging forest stands in Cat Ba BR had good plant species growth. Meanwhile, the post-clear-cut forest status had very low indicators when compared to the natural forests in Vietnam as well as in the region, requiring careful silvicultural measures to improve the vegetation development ability to restore the area to near the natural development threshold in the long term.

c. Diameter distribution (N/D) of the overstory in natural limestone forests

Research results of N/D distribution of natural limestone forest types in Cat Ba BR showed that the original forest had N/D distribution that followed the Meyer and Distance distribution laws, the post-selective logging forest that did not follow any distribution law, and the N/D distribution of the post-clear-cut forest state followed the Distance distribution law (Figure 4 and Figure 5).

By observing the distribution of the number of trees at each diameter class and analytical results, the study suggested the following conclusion, if the actual frequency line had a descending trend (Figure 4c) or a left skewed peak (Figure 4a), continuously in the adjacent class sizes, with or without 1-2 low peaks, N/D distribution usually follows the Meyer or Distance distribution. These types of distribution were typical for the forest that was minimally affected (as in original forest) or clear-cut exploitation and has undergone restoration process (with post-clear-cut forest). In contrast, the interrupted distribution range with many undulating peaks, which do not follow the two mentioned laws, characterized the forest object that has been affected many times with selective logging (Figure 4b - post-selective logging forest).

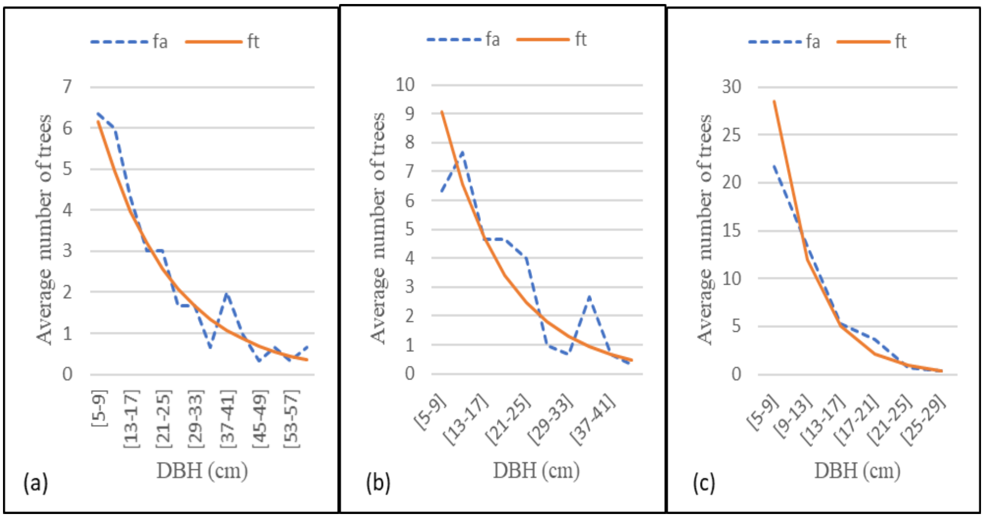

Figure 4. N/D distribution of natural forest types at the study area:
a. Original forest; b. Post-selective logging forest; c. Post-clear-cut forest
fa: actual frequency; ft: theoretical frequency.

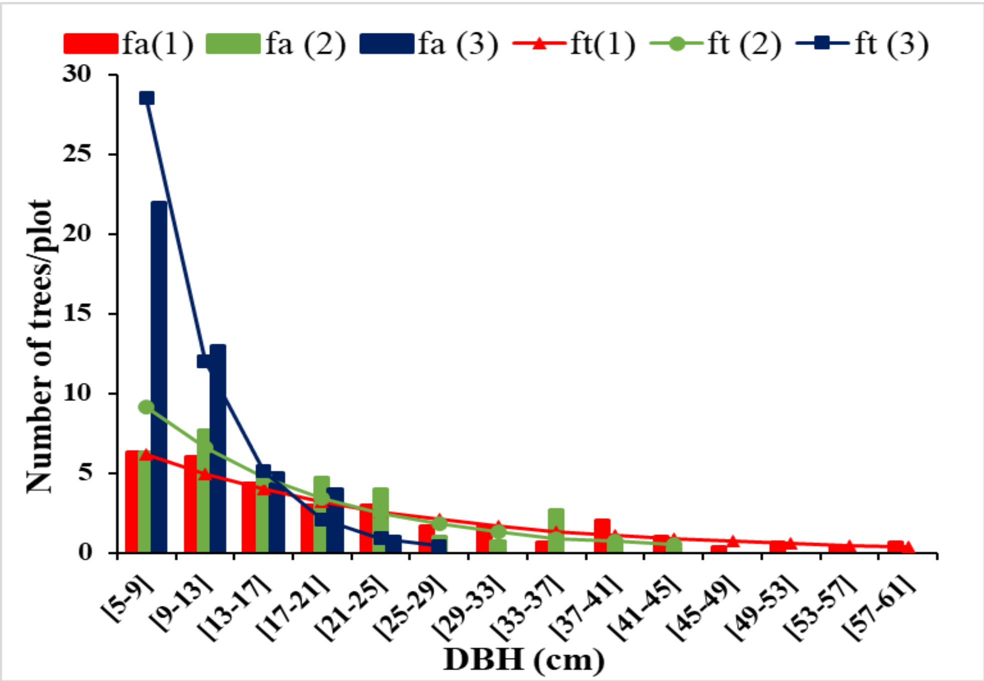

Figure 5. Aggregated N/D distribution of natural forest types at the study area

The study of N/D distribution helped determine the horizontal distribution of the number of trees, and the previous history of impact measures (clearcut or selective logging). In the forest stand, if the N/D distribution was continuously reduced in adjacent diameter sizes, and there were many large trees (> 40 cm), then it reflected that the forest was little or no impact, entering a phase of stability. Conversely, if the N/D distribution was interrupted, with high peaks protruding at large diameter sizes indicates that the forest has undergone selective logging. Thanks to this feature, the N/D distribution study provides a scientific basis for classifying forest objects, thereby proposing suitable impact measures towards the restoration of forests to premival state (Bryan et al., 1999; Jefferson et al., 2003).

In the study area, the original and post-clear-cut forests all follow the Meyer or Distance distribution, clearly showing that these stands were not affected or had undergone clearcut exploitation. The N/D distribution that many undulating and intermittent peaks, which do not follow any distribution rule in the post-selective logging forest was because it has undergone selective exploitation, valuable trees with large diameter were mostly exploited, resulting in the fact that only a few trees of large diameter remained. This result was consistent with previous studies on other forests in Vietnam (Hien et al., 2014; Trung et al., 2016; Van et al., 2018).

d. *Species diversity of the overstory in natural limestone forests*

The plant species diversity including Gini-Simpson, Shannon-Weiner and Evenness were summarized in Table 4. The results showed that there was a significant difference ($p < 0.05$) in biodiversity between forest types and within each forest type. In general, average D', H' and J' indices decreased from original natural forest (D'=0.880; H'=2.353, J'=0.910) to post-selective logging forest (D'=0.790, H'= 1.805, J'=0.855) and post-clear-cut forest (D'=0.567, H'=1.163, J'=0.679). In each type, these indices also varied by plot position with the highest at the bottom and lowest and the middle of the mountain for original and post-clear-cut forests, while for post-selective logging forest they decreased from the top to the bottom.

Table 4. Species diversity index (Gini-Simpson, Shannon-Weiner and Evenness) of natural forest types' overstory layer in the study area.

Forest type	Plot	Density (trees/plot)	Number of species (species /plot)	Gini – Simpson (D')	Shannon – Weiner (H')	Evenness (J')
Original forest	R1	39	12	0.873	2.278	0.917
	R2	32	13	0.854	2.215	0.864
	R3	25	15	0.912	2.567	0.948
	Mean	**32[a]**	**13.3[a]**	**0.880 [a]**	**2.353 [a]**	**0.910 [a]**
Post-selective logging forest	M1	36	9	0.833	1.976	0.899
	M2	24	7	0.792	1.723	0.885
	M3	38	9	0.744	1.716	0.781
	Mean	**33 [a]**	**8.3[b]**	**0.790[b]**	**1.805 [b]**	**0.855 [b]**
Post-clear-cut forest	P1	42	7	0.655	1.340	0.689
	P2	40	3	0.335	0.613	0.558
	P3	52	7	0.711	1.537	0.790
	Mean	**45[b]**	**5.7[c]**	**0.567[c]**	**1.163 [c]**	**0.679[c]**

Means followed by different letters in the same column are significantly different between forest types at $p < 0.05$ by t-test

The above analysis showed that the diversity of overstory species in original forest was higher than the two affected types, representing the fact that under natural and unaffected conditions, the diversity of forest community in the study area would be high and continuous. In contrast, the post-selective logging forest had a large variation with the indicators at plot M1, which had the least growth in this forest type (Table 3), had higher diversity indicators than the other two positions. This may be due to an unstable environment under the forest canopy, which is conducive to the formation and survival of many tree species.

The formation of gaps in the unstable forest canopy due to the impact of logging is a favorable condition for the growth of many species of timber. Many studies have shown that most woody trees in tropical rainforests regenerate in gaps. For post-clear-cut forests, these indicators are of low value due to the shortage of seedlings and the degradation of the soil environment under the forest canopy due to previous human activities (Richards, 1952; Bauer, 1962; Trung, 1999). It suggested that stronger actions are needed to ensure the stable development of forest stands, especially for post-selective logging and post-clear-cut forest areas that have been affected in the past.

However, the biodiversity indicators of natural limestone forest in the study area were much lower than that of other evergreen forests in Vietnam and in the region. The H' index in Xishuangbanna-China was 3.02 - 3.89; while in Ba Be National Park – Vietnam, a similarly affected area, it varied from 1.9 to 3.61 (Cao and Zhang, 1997; Hien et al., 2014). It was also lower than other limestone forests such as in Sarawak – Malaysia, H' = 3.0 -3.7 (Adam & Mamat, 2005). Meanwhile D' in Bidoup-Nuiba evergreen forest was 0.903, and at Binh Dinh was between 0.955-0.963 (Binh, 2014; Van et al., 2018). This could be due to the isolation of the study area and the historical human logging that destroy the majority of forest in the area, which create lack of seed sources both from outside and from within the study area, as previously suggested by Howe & Smallwood (1982) and Thomas (1999).

4.1.2. Natural regeneration, shrubs and herbaceous layer characteristics in natural limestone forests

a. Natural regeneration characteristics of natural limestone forests

The natural regeneration characteristics of natural limestone forest types in the study site were shown in Table 5.

There was a significant difference ($p<0.05$) on seedling species richness between unimpacted (32 species) and impacted, self-recovering forest types (12.6 species for post-selective logging forest and 4.7 species for post-clear-cut forest). Remarkably, the number of regenerated timber species in the original forest state was significantly higher than the overstory layer of the same type (32.0 – 13.3 species, or 240% higher than the overstory). While the post-selective logging forest also had higher number of regenerated species than it's overstory layer but the percentage was not as high as for original forest (12.6 – 8.3 species, or 150% higher than the overstory). This indicator was similar in post-clear-cut forest but the percentage was not as significant as the other two types (5.7 – 4.7 species, or 121% higher than overstory).

Table 5. Natural regeneration characteristics including number of species, seedling density, density by height classes and origin of seedlings of natural limestone forest types (rich, post-selective logging and post-clear-cut) in the study area.

Forest type	Plot	Number of species	Density (plants/ ha)	Density by height classes (m)			Origin (%)	
				< 0.5	0.5-1	> 1	Seed	Shoot
Original forest	R1	21	13360	7680	4480	1200	87.1	12.9
	R2	40	8480	5840	1520	1120	95.2	4.8
	R3	35	3280	1920	1040	320	86.4	13.6
	Mean	**32.0[a]**	**8373[a]**	**5147[a]**	**2347[a]**	**880[a]**	**89.6[a]**	**10.4[a]**
Post-selective logging forest	M1	11	27440	11680	9840	5920	97.2	2.8
	M2	9	20320	11360	5680	3280	89.3	10.7
	M3	18	17440	9840	5440	2160	91.8	8.2
	Mean	**12.6[b]**	**21733[b]**	**10960[b]**	**6987[b]**	**3787[b]**	**92.8[a]**	**7.2[a]**
Post-clear-cut forest	P1	6	66080	46560	16960	2560	47.4	52.6
	P2	3	35600	25360	8800	2400	73.6	26.4
	P3	5	29040	21440	5680	1920	68.5	31.5
	Mean	**4.7[c]**	**43573[c]**	**31120[c]**	**10240[c]**	**2293[c]**	**63.2[b]**	**36.8[b]**

Means followed by different letters in the same column are significantly different between forest types at $p < 0.05$ by t-test

The density of regenerated trees also varied from type to type, with the density decreasing from post-clear-cut forest (43,573 plants ha) to post-selective logging forest (21,733 plants/ha) and original forest (8,373 plants/ha). This indicator also varied by height level, concentrating more in <0.5m level and decreasing as the height level increases. Simulation of the regenerated trees distribution by height levels of the natural limestone forest types in the study area was shown more clearly in Figure 6.

It can be seen that the density of regenerated trees in the post-clear-cut forest state decreases rapidly from small to large height levels (31,120 at <0.5m to 2,293 at > 1m, or a 92.63% decrease). Meanwhile, in the post-selective logging forest, the level of reduction was slower and more stable (10,960 at level <0.5m to 3,797 at level> 1m, a 65.36% decrease). In the original forest type, this ratio increased to 82.91% (from 5,147 to 880 trees).

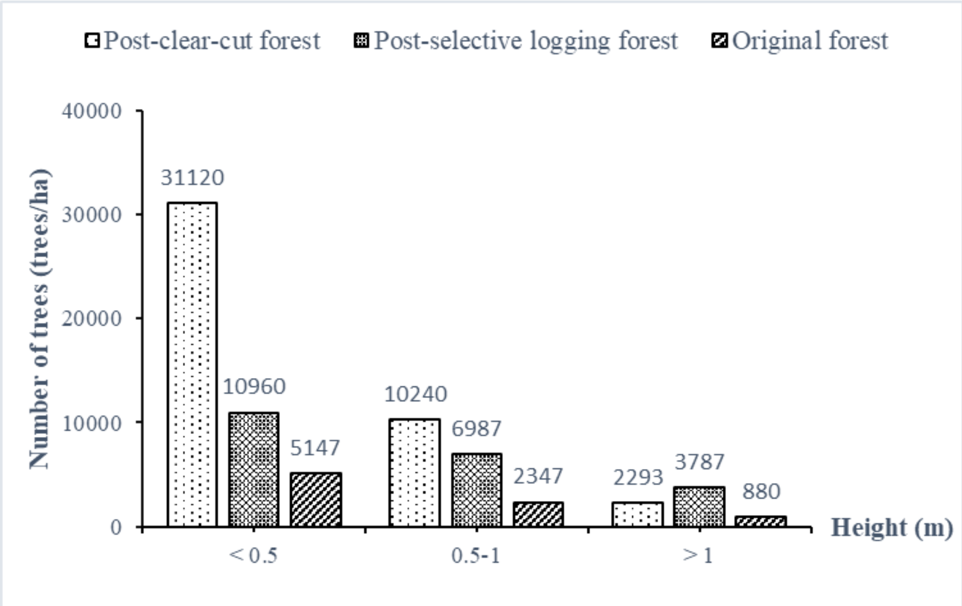

Figure 6. Height distribution of regenerated trees of natural limestone forest types in the study area.

The origin of regenerated trees was an important indicator determining the growth and development of forest trees and the characteristics and properties of the stand in the future. The majority of regenerated trees in the study area derived from seed regeneration. Seed/shoot origin ration between original forest (89.6-10.4%) and post-selective logging forest (92.8-7.2%) was not significantly different ($p < 0.05$), while there is a clear difference with post-clear-cut forests (63.2-36.8%). In P1 alone, the percentage of regenerated plants by shoots was higher than that of seeds (47.4-52.6%).

Regeneration is a particular biological process of forest ecosystems, it is the replacement of the old tree generation with the seedling generation in order to restore the basic elements of the forest, contributing to enriching the number and composition of the ecosystem (Lan, 1986). During the regeneration process, under the influence of external factors, not all regenerated trees have the opportunity to survive and grow to be able to join and replace trees in the overstory layer in the future.

The results of the study of regenerated tree layers in the study area showed the difference between the unaffected original forest and affected post-selective logging and post-clear-cut forests. The number of regenerated species in the former was much higher than in the remaining types because its condition was highly stable, with the addition seedlings from adjacent original forest stands that ensured gradual development of many species. The post-selective logging forest had lower number of regenerated species than the original forest due to the shortage of seed supply from surrounding areas as well as the human activities in the past that caused many species to disappeared in the stand. Post-clear-cut forest, on the other hand, had a dramatically lower number of regenerated species compared to the two other forest types, partly due to the lack of external seed supply and partly due to the very poor soil condition. This showed the unstable development and lack of potential to enhance biodiversity in the future for this forest type. These results were consistent with previous studies of Gad (1999) and Jeremy (1997), in which the authors argued that the original unimpacted forest type usually had higher number of regenerated tree species than the impacted types.

The density and distribution of regenerated trees by height levels in the study area represent the rules of forest structure: in the younger stage, the number of seedlings is high but through growth and development, due to natural selection, the number of regenerated trees decrease, to a period of stability and development, which is called closed canopy stage (Kramer H., 1966 1979; Oliver et al., 1996). However, the density of regenerated trees in post-clear-cut forest stand decreased rapidly when reaching higher height levels was because of this type had low canopy cover, leaving plenty of room for regeneration trees to grow, but when the seedlings reach a certain mature level, unfavorable environment, especially nutrient deficiency in the soil significantly increased the mortality of seedlings (Parrota 1993, 1997; Thinh et al., 2015; Nam et al., 2017).

The main regeneration origin in the forest stands was from seed, this feature facilitated the formation of the overstory layer in the future because although shoot regeneration would ensure that the seedlings in the plant community maintain the genetic characteristics of the parent tree, its disadvantage was that the growth and development process was short, quick maturity and prone to impact from the outside environment. Seed regeneration created plant communities with high rejuvenation, longevity and tolerance to adverse conditions of the external environment than shoot regeneration. Regeneration capacity of plants growing from seeds was better than that of shoots, thus forming more sustainable vegetation, in consistent with previous studies and findings of different forest ecosystems in Vietnam (Sim & Tan, 2013; Nam et al., 2017; Thanh, 2019).

In general, the original forest had high number of regenerated tree species, low seedlings density and gradually decreasing by larger height level, and most derived from seeds, ensuring stable growth and development into the overstory layer. post-selective logging forest also had relatively good regeneration development, greater density, also decreased progressively with larger height levels, mainly originated from seeds. However, the number of regeneration species in this type was much lower than that of the original forest, which might not guarantee the enhancement of biodiversity under natural circumstances in the near future. The post-clear-cut forest, on the other hand, had a very unstable regeneration process, with substantial concentration of regenerated trees at smaller height and declined dramatically when it became larger, much smaller number of species, and high percentage of shoot regeneration.

b. The influence of some stand's characteristics on natural regeneration

The characteristics used to assess the regeneration quality including Canopy cover, Average height (Hs) and Cover percentage of the Shrub and Herbaceous layer. Representative factor for regeneration layer was the percentage prospective seedlings, or seedlings with height >1m (VNFOREST, 2013). The result was shown in Table 6.

In original forest, with a canopy cover of 79.3%, shrub height of 0.97m and cover of 51% resulted in % prospective seedlings of 10.51%. In post-selective logging forest, canopy cover and shrub height decreased to 62.3% and 0.93m respectively, shrub cover increased to 66% leading to 17.42% of seedlings to be prospective. In post-clear-cut forest, the canopy cover reduced to 52.7%, shrub height raised to 1.04m while shrub cover declined to 63%.

Table 6. Influence of canopy cover, average height and cover percentage of shrub and herbaceous layer on prospective seedling percentage of natural forest types in the study area.

Forest type	Plot	Canopy cover (%)	Prospective seedlings (%)	Shrub and Herbaceous layer	
				Hs (m)	Cover (%)
Original forest	R1	71	8.98	0.95	54
	R2	78	13.21	0.96	47
	R3	89	9.76	1.01	53
	Mean	**79.3^{a}**	**10.51^{a}**	**0.97^{ab}**	**51^{a}**
Post-selective logging forest	M1	58	21.57	0.92	73
	M2	62	16.14	0.86	64
	M3	67	12.39	0.93	60
	Mean	**62.3^{a}**	**17.42^{a}**	**0.90^{a}**	**66^{a}**
Post-clear-cut forest	P1	50	3.87	1.00	59
	P2	47	6.70	1.10	75
	P3	61	6.61	1.03	56
	Mean	**52.7^{a}**	**5.25^{a}**	**1.04^{ab}**	**63^{b}**

Means followed by different letters in the same column are significantly different between forest types at $p < 0.05$ by t-test

The shrub and herbaceous layer's characteristics as well as canopy cover are important factors affecting the growth and development of regenerated trees, especially the competition for nutrition and light under the forest canopy. When the forest canopy cover is reduced, shrubs of shrubs grow, which is favorable for regenerating trees to be shade-proof at a young age, but it will be an obstacle when regenerated trees grow. At this time, fresh shrubs will crowd and compete with regenerated trees. Therefore, it is necessary to determine the characteristics of this layer to take appropriate measures to limit the damage caused to the regenerated trees (Lan, 1986; Van Auken and Bush, 1991).

The results, however, placed a conflicting picture of their influence on the prospective seedlings in the study site. In original and post-selective logging forests, reducing canopy cover, shrub and herbaceous layer height as well as increasing cover of this layer led to an increment of the percentage of seedlings > 1m. These findings were similar with study results of various forest ecosystems in Vietnam and around the world (Van Auken & Bush, 1991; O'Brien et al., 2007; Nam et al., 2017).

On the other hand, the post-clear-cut forest had a vastly different trend from the other two natural forest types, with a decreasing canopy cover and an increasing shrub and herbaceous layer height and cover from original forest, the percentage of prospective seedlings decreased. This suggested that development of seedlings in this forest type was unstable and the chance for them to become overstory trees was questionable.

This indicated that canopy cover, shrub and herbaceous layer were important but not dominating factors for the development of seedlings in the study area. Site conditions such as soil qualities, adjacent habitats as well as human activities also had some influence on the regeneration layer. While original and post-selective logging forests had good regenerated trees growth, post-clear-cut forest, however, demanded more silvicultural measures to improve the existing situation in order to restore it back to the original natural state.

In short conclusion, all of the indicators regarding canopy and regeneration layers of natural forest types in the study area showed that the post-selective logging and especially the post-clear-cut forest were greatly weakened by human activities. The post-selective logging still had some ability to reverse back into the original unaffected forest in terms of volume but for the species composition and biodiversity, it would be much more difficult. For post-clear-cut forests, every characteristic proved this forest type's incapacity to naturally recover to the original forest, requiring artificial restoration efforts. The study further compared the differences between post-selective logging and post-clear-cut forests with their respective artificial restoration models in the study area to understand how these models improved the conditions inside the impacted forests.

4.2. Comparing restoration models for degraded natural limestone forest with their respective natural forest types in the study area

4.2.1. Species composition and growth characteristics of overstory layer in the restoration models

a. Species composition of the overstory

As previously mentioned in Section 4.1.1.1., only plant species with IV% value ≥ 5% had ecological significance in the forest community and took part in the composition. The study compared post-clear-cut and post-selective logging forests with their respective restoration models.

- Between Post-clear-cut forests and Restoration models 1 and 2:

Results of comparing species composition of overstory layer in restoration models for post-selective logging forest were presented in Table 7.

Table 7. Species composition (IV) of the overstory layer of restoration models 1 and 2 compared to post-clear-cut forests in the study area

Forest type	Number of species	Number of family	Species composition (IV%)
RM1	2	2	56 *Acacia auriculiformis* (Fabaceae) + 44 *Canarium tramdeum* (Burseraceae)* + 0 Other
RM2	26	17	19.6 *Sterculia lanceolata* (Malvaceae)+ + 12.9 *Dracontomelum duperreanum* (Anacardiaceae)* + 10.4 *Canarium tramdeum* (Burseraceae)* + 8.7 *Vatica odorata* (Dipterocarpaceae) + 6.0 *Callicarpa longifolia* (Lamiaceae) + 5.8 *Deutzianthus tonkinensis* (Euphorbiaceae) + 5.4 *Actephila longipediculata* (Euphorbiaceae) + 31.2 Others
Post-clear-cut forest	11	7	26.9 *Ficus auriculata* (Moraceae) + 19.1 *Acanthus ebracteatus* (Acanthacea) + 17.4 *Actephila longipediculata* (Euphorbiaceae) + 7.8 *Litsea verticillata* (Lauraceae) + 6.9 *Vitex quinata* (Lamiaceae) + 6.2 *Streblus macrophyllus* (Moraceae) + 15.7 Others

*denotes species that can be used for food or medicine; + denotes species that have high value wood; # denotes species listed in the Vietnam Red Data Book (2007) or IUCN (1997).

Woody species with DBH ⩾ 5 cm of the overstory in restoration model comprised a total of 48 species in 27 families (Table 7). In which 6 species can be used for food or medicine, 3 were considered to have high value wood and 1 endangered species listed in the Vietnam Red Data Book (2007) or IUCN's Red list (1997).

The total number of overstory species taking part in the composition in the model RM1 was only 2, with *Acacia auriculiformis* comprised 56% and *Canarium tramdeum* made up 44%. These species were light tolerant and fast growing, appropriate for this model which was carried out on previously post-exploitation bare land. Especially, *Canarium tramdeum* is a valuable and endemic Vietnamese species of the genus *Canarium*.

According to the species importance value ranking, at RM2 model, the total number of species was 26 of which 7 participated in the composition. Species with the highest IV% value was *Sterculia lanceolata* (19.6%), *Dracontomelum duperreanum* (12.9%) and *Canarium tramdeum* (10.4%). These species were either light or shade tolerant, but all of them were valuable species with the former one being considered as to have high value hardwood, and the latter two often being used for variously purposes. Only one species presented in post-clear-cut forest also occurred in this model, which was *Actephila longipediculata*, but it did not take a high IV% value, reducing from 17.4% in the former to only 5.4% in the later.

The results of studying species composition at restoration models for post-clear-cut forest showed vastly different trends among them. RM1, because of its focus on improving the soil properties, restricted the plantation to only two species, of which *Acacia* would later be cut down in order to make way for future native species. While in RM2, which was additional plantation of many native species, the number of species significantly increased with the highest IV% species were valuable. This illustrated the manager's original idea of establishing a well-developed model with valuable and native species dominating the landscape.

In general, the species composition of RM2 in the study area showed a relative success at a number of points. Firstly, the number of species and number of families greatly increased from the post-clear-cut forest. Secondly, the species compositions comprised many native, valuable or rare species, with great biological significant to the area, whereas post-clear-cut forest had none. Thirdly, the composition participating proportion of these species was higher than most post-selective logging and post-clear-cut forest, and comparable to original forest of the study area. This finding was consistent with previous successful examples of different restoration forest models in the world and in Vietnam (Keenan et al., 1997; Trung et al., 2016; Tai et al., 2017).

- Between Post-selective logging forests and Restoration model 3:

Results of comparing species composition of overstory layer in restoration models for post-selective logging forest were presented in Table 8.

Table 8. Species composition (IV) of the overstory layer of restoration model 3 compared to post-selective logging forests in the study area

Forest type	Number of species	Number of family	Species composition (IV%)
RM3	19	16	17.5 *Peltophorum pterocarpum* (Fabaceae) + 13.9 *Aidia pycnantha* (Rubiaceae) + 12.1 *Annamocarya sinensis* (Juglandaceae)# + 9.0 *Peltophorum tonkinensis* (Fabaceae) + 8.1 *Dracontomelum duperreanum* (Anacardiaceae)* + 6.5 *Aphanamixis grandifolia* (Meliaceae)*+ + 5.0 *Sterculia lanceolata* (Malvaceae)+ + 28.9 Others
Post-selective logging forest	16	11	24.1 *Streblus macrophyllus* (Moraceae) + 17.4 *Sacara dives* (Fabaceae) + 14.9 *Diospyros susarticulata* (Ebenaceae) + 10.8 *Callicarpa longifolia* (Lamiaceae) + 7.7 *Acanthus ebracteatus* (Acanthaceae) + 25.1 Others

*denotes species that can be used for food or medicine; + denotes species that have high value wood; # denotes species listed in the Vietnam Red Data Book (2007) or IUCN (1997).

At model RM3, 7 out of 19 overstory species participated in the composition, in which the most dominant species were *Peltophorum pterocarpum* (17.5%), *Aidia pycnantha* (13.9%) and *Annamocarya sinensis* (12.1%). Species with the highest IV% are those that often well adapted to various site conditions and light tolerant. Many rare or valuable species were found such as *Annamocarya sinensis*, *Aphanamixis grandifolia*, *Dracontomelum duperreanum and Sterculia lanceolata*. Although they were not the most dominant species in this model, they otherwise made up all of the remaining positions in the species composition. There was no common species

There was a great difference in species composition between RM3 and post-selective logging forest as no common species was present in both types. Moreover, while RM3 had some valuable species, the accumulation formula for the whole post-selective logging plots in the study area had none. This further illustrated how human activities caused great losses the vegetation there as these species were all exploited or only existed in small percentage. RM3, on the other hand, established only a five years earlier than post-selective logging forest, still contained many pre-existing species of the original forest, with the enrichment planting of some others. These findings were similar to those of Doi (2013) and Hung et al. (2013) in which the authors found that enrichment planting would greatly enhance the appearance of species in natural forests although the restoration model was very close in cohort with the naturally restored stands.

b. Growth indicators of the overstory

- Between Post-clear-cut forests and Restoration models 1 and 2:

The results of comparing the growth indicators in the forest restoration models 1 and 2 and the post-clear-cut forest in the study area were presented in Table 9.

At RM1, tree density was low (683 trees/ha) while average DBH and average Ht were relatively high (13.6 ± 5.5 cm and 10.8 ± 3.6 m respectively) and canopy cover was 59.2%. At RM2, due to the addition of a large number of trees to the stand, the tree density was much higher (1,378 trees/ha), which also led to the increase in canopy cover, cross section and stand volume of the forest, while average DBH and Ht were not statistically different from the younger RM1. Moreover, all of these indices in RM1 and RM2 was significantly higher than that of post-clear-cut forest.

Table 9. Growth characteristics of overstory (Density, DBH, Ht, Total basal area (G), Total volume (H) and Canopy cover) of restoration models 1 and 2 and post-clear-cut forest in the study area.

Plot	Density (trees/ ha)	DBH (cm)	Ht (m)	G (m^2/ha)	M (m^3/ha)	Canopy cover (%)
RM1	683[a]	13.6 ± 5.5 [a]	10.8 ± 3.6 [a]	13.7[a]	67.6 [a]	59.2 [a]
RM2	1,378[b]	14.5 ± 6.4 [a]	11.3 ± 4.1 [a]	28.2 [b]	147 [b]	70.7 [b]
Post-clear-cut forest	1,117[c]	10.5 ± 3.8[b]	6.4 ± 1.9[b]	11.4[c]	40.0[c]	52.7[c]

Means followed by different letters in the same column are significantly different between forest types at $p < 0.05$ by t-test

The reason that RM1 had low tree density was due to the application of strict plantation regulations, which limited the number of overstory trees at the model. Meanwhile, the planting of many more native species led to a surge in tree density at RM2. DBH and Ht in RM1 was almost equal to RM2 was due to the fact that species in RM1, especially *Acacia*, were fast growing light-tolerant species suitable for reforestation and forest rehabilitation on bare land, similar with the initial condition of this model, plus the application of measures such as fertilizing, leading to their growth and development. While at RM2, many additional species were not fast-growing species like in RM1 and due to the massive planting of trees has led to fierce competition for nutrients and light, making individual in this model grew at a slow pace.

- Between Post-selective logging forests and Restoration model 3:

The results of comparing the growth indicators in the forest restoration model and the post-selective logging forest in the study area were presented in table 10. Density increased from 817 trees/ha in post-selective logging forest to 886 trees/ha in RM3. All other indicators in RM3 were also significantly higher compared to the post-selective logging forest in the study area with increment of DBH from 16.9 ± 9.7 to 21.9 ± 14.0 cm, Ht from 12.1 ± 4.4 to 15.1 ± 6.7m, G from 24.0 to 42.3m^2/ha, M from 169.2 to 358.3 m^3/ha and the canopy cover from 62.4 to 80.2%.

Table 10. Growth characteristics of overstory (Density, DBH, Ht, Total basal area (G), Total volume (H) and Canopy cover) of restoration model 3 and post-selective logging forest in the study area.

Plot	Density (trees/ ha)	DBH (cm)	Ht (m)	G (m2/ha)	M (m3/ha)	Canopy cover (%)
RM3	886[a]	21.5 ± 14.0[a]	15.1 ± 6.7[a]	42.3[a]	358.3 [a]	80.2[a]
Post-selective logging forest	817[b]	16.9 ± 9.7[b]	12.1 ± 4.4[b]	24.0[b]	169.2[b]	62.4[b]

Means followed by different letters in the same column are significantly different between forest types at $p < 0.05$ by t-test

The result indicated that although the enrichment planting increased the density of trees in the site, it did not hamper the development of individuals with increasing figures in all indices. The growth indicators in this model were quite optimistic, especially when the volume of the stand was higher than that of the post-selective logging sties and also of two original forest plots R1 and R2, and only lower than R3 (results from Table 3). This showed that the forest stand had grown relatively stable and had the ability to recover to the primeval state. The above results were relatively similar with the previous research results on restored forest models in Vietnam and around the world (Falk, 1990; Fang et al., 1997; Doi, 2013; Thinh et al., 2015).

On all restoration models in the study area, the fact that all growth indicators saw significant increment from the post-clear-cut and post-selective logging forests proved that these models were relatively successful in terms of improving the development of the overstory layer. Thus, making the models to be more sustainable than the impacted forest and ensuring their future development.

c. Species diversity of the overstory in restoration models

The results of analyzing the biodiversity indicators of overstory layer at the forest restoration model in the study area were summarized in the following table:

Table 11. Species diversity index (Gini-Simpson, Shannon – Weiner and Evenness) of restoration models, post-clear-cut and post-selective logging forests' overstory layer in the study area.

Plot	Number of species (species/ plot)	Gini – Simpson (D')	Shannon – Weiner (H')	Evenness (J')
RM1	2.0 [a]	0.443[a]	0.601[a]	0.960[a]
RM2	21.3 [b]	0.934[b]	3.011[b]	0.874[b]
Post-clear-cut forest	5.7[c]	0.567[c]	1.163 [c]	0.679[c]
RM3	17.4[d]	0.901[d]	2.584 [d]	0.908 [d]
Post-selective logging forest	8.3[e]	0.790[b]	1.805 [b]	0.855 [b]

Means followed by different letters in the same column are significantly different between forest types at $p < 0.05$ by t-test

The table above showed that in comparison between post-clear-cut forest and its respective restoration models, both Gini-Simpson and Shannon-Weiner index values were at their lowest in RM1 (D' = 0.443, H' = 0.601) and highest in RM2 (D' = 0.934, H' = 3.011), while post-clear-cut forest had median value compared to the previous two with all indicators significantly lower than RM2 and higher than RM1 (except for evenness). Adversely, Evenness index was highest in RM1 (0.961) and reduced in RM2 and post-clear-cut forest (0.874 and 0.679 respectively). For post-selective logging forest and RM3, the same story happened as all diversity values increased greatly from the former to the latter.

This result was consistent with the type of model apply at these stands.

RM1 only had 2 species, therefore the D’ and H’ were obviously low. Meanwhile at RM2, the addition of many species increased the vegetation biodiversity index considerably. The evenness index in phase 1 was the highest also because it had 2 species and none dominated the other, while the relativity of RM2 and RM3 showed that different species in these models shared a quite even number of individuals. In the RM3 model, however, relatively lower number of species planted compared to RM2 as well as a long period natural thinning and selection, led to decreasing diversity indices.

The findings in studying overstory diversity in the restoration model combined with the similar results from the natural forest types in the study area (Section 4.1) indicated that diversity indicators in RM2 and RM3 of the restoration model were approximately equal to or even higher than all their respective natural forest stands in the study area. Similar findings were also reached by other authors from various forest ecosystems (Fang et al., 1997; Thinh et al., 2015) where they argued that additional planting of native species in the stand appropriately would greatly increase the ecological and biodiversity values of the site, thus creating a more favorable condition for further restoration efforts.

This suggested that technical measures to restore forests showed their effectiveness, at least in increasing the biodiversity of these forest states to a level comparable to the original ecosystem in the study area. However, silvicultural and ecological techniques to maintain the stability of biodiversity, protect poorly developed but valuable species in the site and maintain the structure of the stands, ensuring the ability of uniform development of the species are still needed.

4.2.2. Natural regeneration, shrubs and herbaceous layer characteristics in restoration models

a. Natural regeneration characteristics

- Between Post-clear-cut forests and Restoration models 1 and 2:

The natural regeneration characteristics of RM1 and RM2 when compared to post-clear-cut forests were summarized in Table 12. The combined results showed that the number of regenerated species was the lowest in RM1 but this figure was not significantly lower than that of Post-clear-cut forest (4.4 and 4.7 species respectively), but it increased sharply in RM2 with 22.7 species. The density of regenerated trees was also at the lowest in RM1 (4,440 plants/ha) but increases rapidly to 12,320 plants/ha in and 43,573 plants/ha in Post-clear-cut forest.

Table 12. Natural regeneration characteristics including number of species, seedling density, density by height classes and origin of seedlings in RM1, RM2 and Post-clear-cut forest in the study area

Plot	Number of species	Density (plants/ ha)	Density with height classes (m)			Origin (%)	
			< 0.5	0.5-1	> 1	Seed	Shoot
RM1	4.4[a]	4440[a]	3320 [a]	800 [a]	320 [a]	100 [a]	0 [a]
RM2	22.7[b]	12320[b]	7680 [b]	2720[b]	1920[b]	90.5 [b]	9.5 [b]
Post-clear-cut forest	4.7[a]	43573[c]	31120[c]	10240[c]	2293[b]	63.2 [c]	36.8 [c]

Means followed by different letters in the same column are significantly different between forest types at $p < 0.05$ by t-test

The regenerated tree density also varied by height level, concentrating more in <0.5m level and decreasing as the height level increases. Simulation of the regenerated trees distribution by height levels of the Post-clear-cut forest and RM1 & 2 in the study area was shown more clearly in Figure 7.

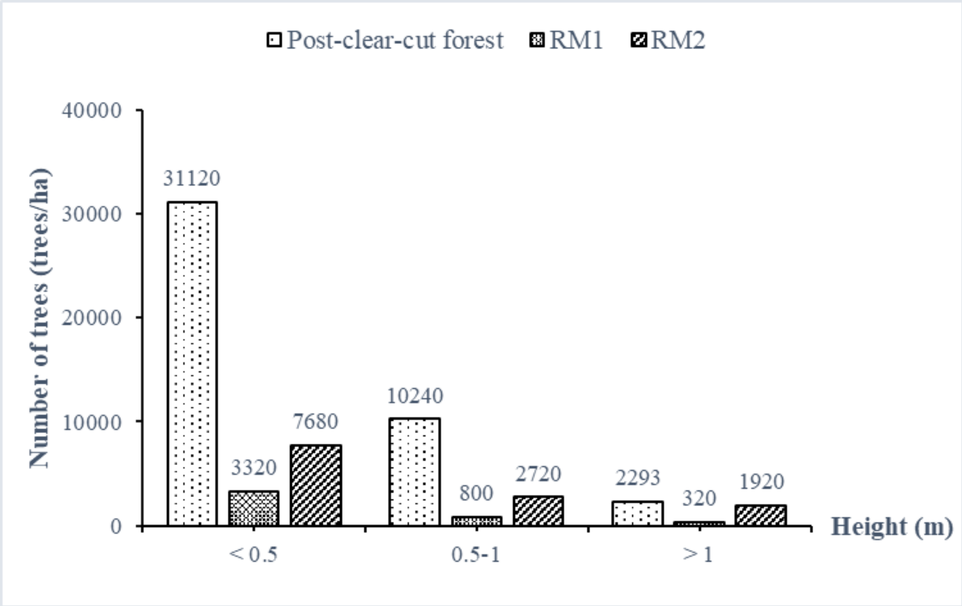

Figure 7. Height distribution of regenerated trees at Post-clear-cut forest, RM1 and RM2 in the study area.

It can be seen that the number of regenerated trees in Post-clear-cut forest was significantly higher than all restoration models at smaller height classes, but dropped dramatically when reaching larger classes, finally reaching a value not significantly higher than that of RM2 (2,293 to 1,920 plants/ha at >1m class respectively).

The majority of regenerated trees in the restoration models and post-clear-cut forest derived from seed regeneration. Seed/shoot origin ration, however, reduced gradually from RM1 (100-0%) to RM2 (90.5-9.5%) and Post-clear-cut forest (63.2-36.8%).

- Between Post-selective logging forest and Restoration model 3:

The comparison of natural regeneration characteristics between RM3 and Post-clear-cut forests were summarized in Table 13. The result showed that the number of regenerated species was much higher in RM3 than in the Post-selective logging forest (24.3 to 12.6 species). The density of regenerated trees was also lower in RM3 (6,290 plants/ha) compared to Post-selective logging forest (21,733 plants/ha).

Table 13. Natural regeneration characteristics including number of species, seedling density, density by height classes and origin of seedlings in RM3 and Post-selective logging forest in the study area

Plot	Number of species	Density (plants/ ha)	Density with height classes (m)			Origin (%)	
			< 0.5	0.5-1	> 1	Seed	Shoot
RM3	24.3[a]	6,290[a]	4,080[a]	1,680[a]	530[a]	82.1[a]	17.9[a]
Post-selective logging forest	12.6[b]	21,733[b]	10,960[b]	6,987[b]	3,787[b]	92.8[b]	7.2[b]

Means followed by different letters in the same column are significantly different between forest types at $p < 0.05$ by t-test

The regenerated tree density by height classes also varied with more concentrating more in <0.5m level and decreasing with larger height class. However, this index was also significantly lower in RM3 than in Post-selective logging forest. Simulation of the regenerated trees distribution by height levels of the Post-selective logging forest and RM3 in the study area was shown more clearly in Figure 8.

The main regeneration origin in RM3, similar with Post-selective logging forest, was from seed, but it was lower in the former than in the latter. In RM3, 82.1% of regenerated trees developed from seeds while in Post-selective logging forest, this figure was 92.8%.

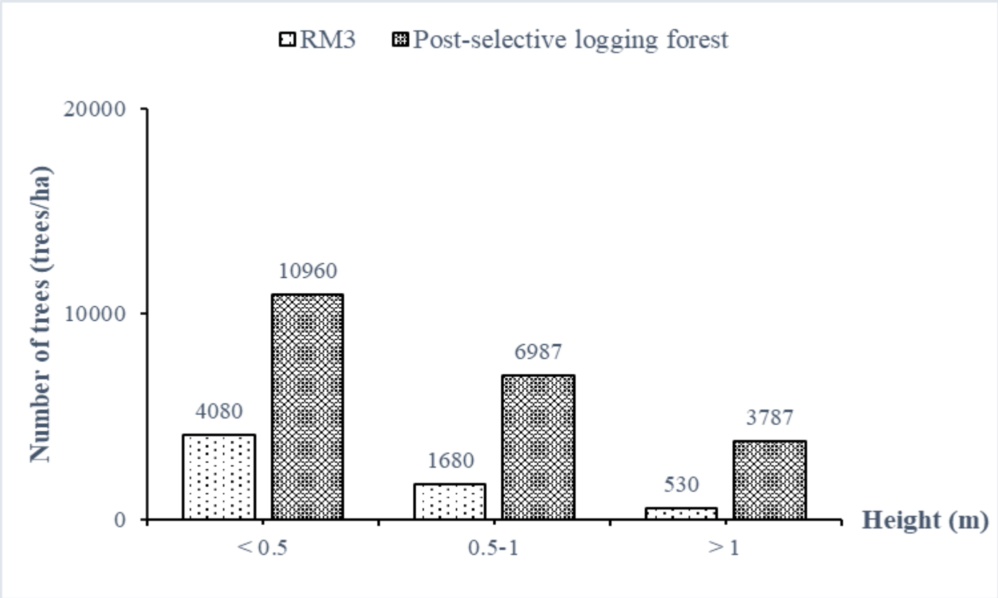

Figure 8. Height distribution of regenerated trees at RM3 and Post-selective logging forest in the study area.

In general, as mentioned in Section 4.1.4, natural regeneration is an essential biological process of forest ecosystems, it is the replacement of the old tree generation with the seedling generation in order to restore the basic composition of the forest, contributing to enriching the number and composition of forests species part in the ecosystem (Lan, 1986). In the regeneration process, under the influence of external factors, not all seedlings have the opportunity to survive and grow to be able to join and replace the top layer of trees in the future.

The low number of species and density of regenerated trees found in RM1 could be attributed to restrictive measures applied in this model limited the growth of seedlings in order to promote the growth of overstory layer as well as not letting the species in this period to become dominant in the latter succession stages. In RM2, the number of species and density increased rapidly because additional planted trees provided seed pool for regeneration. For RM3, the increment in number of regenerated tree species indicated that there were more newly regenerated species formed after the protection and zoning period, either from dispersal of overstory trees in the stand or from adjacent natural forests. However, the density of regenerated trees at this model was much lower than RM2 because the canopy closure of the tall tree layer creates less space for regenerated trees to grow (Kramer, 1966; 1979; Oliver et al., 1996).

In general, for all restoration models and their natural forest types in the study area, which facilitated the formation of the overstory layer in the future because although shoot regeneration would ensure that the seedlings in the plant community maintain the genetic characteristics of the parent tree, its disadvantage was that the growth and development process was short, quick maturity and prone to impact from the outside environment. Seed regeneration created plant communities with high rejuvenation, longevity and tolerance to adverse conditions of the external environment than shoot regeneration. Regeneration capacity of plants growing from seeds was better than that of shoots, thus forming more sustainable vegetation, in consistent with previous studies and findings from other natural forests as well as restoration models in the region (Lubbe et al., 1991; Sim & Tan, 2013; Doi, 2013; Thanh, 2019).

Natural regeneration in restoration model when compared to their respective natural forests showed positive signs. All indicators show relatively stable development. However, there were still some less than desirable points in these models. Firstly, the fact that the number of regenerated tree species at RM2 was less than that of the overstory in the same stand, in contrast to the other researched sample plots, indicated that not all species here had a chance for continued regeneration and development. This may be due to the intense competition among species in the same forest stand due to tight planting density. Secondly, with a lower percentage regeneration from seed in RM3 when compared to Post-selective logging forest, it showed a potentially more questionable future development of this restoration model because as mentioned before, regeneration from seed was lower but much more stable than that of shoot origin.

All of these negative signs again presented the need for adjustments of the silvicultural solutions currently being applied to this model to ensure that every species has the opportunity to grow, increasing the effectiveness of the models.

b. The influence of some stand's characteristics on natural regeneration

The characteristics used to assess the regeneration quality including Canopy cover, Average height (Hs) and Cover percentage of the Shrub and Herbaceous layer. Representative factor for regeneration layer was the percentage prospective seedlings, or seedlings with height >1m (VNFOREST, 2013). The result was shown in Table 14.

When comparing Post-clear-cut forest and its respective restoration models, RM2 had significantly higher percentage of prospective seedlings than the others while also having the highest canopy cover. Height and cover of the shrub and herbaceous layer had conflicting effects on the prospective seedlings, with the lowest figures also found in RM1, but theirs almost identical values in RM2 and post-clear-cut forest could not explain the difference in prospective seedlings rate in both sites. The average height and coverage of the shrub and herbaceous layer did not have clear effect on the rate of prospective regeneration trees. RM2 had the highest coverage (63%) and also had the highest rate of prospective seedlings (14.77%), while RM1 with the lowest coverage (48%) also had the lowest rate of prospective seedlings (3.98%). However, Post-clear-cut forest had a similar coverage of shrub and herbaceous layer but had a low prospective seedling rate of only 5.25%.

For Post-selective logging forest and RM3, the same trend as in post-selective logging forest was found where the canopy cover, shrub and herbaceous layer's height and cover somewhat influenced the rate of prospective seedlings. The canopy directly affected the growth of regenerated trees, RM3 had higher canopy cover but had the lower rate of prospective regenerated trees. While height of shrub and herbaceous layer also did not significantly on seedlings development, their coverage did. Post-selective logging forest had higher rate of prospective seedlings and also had higher shrub and herbaceous coverage.

Table 14. Influence of canopy cover, average height and cover percentage of shrub and herbaceous layer on prospective seedling percentage of restoration model in the study area.

Plot	Canopy cover (%)	Prospective seedlings (%)	Shrub and Herbaceous layer	
			Hs (m)	Cover (%)
RM1	59.2 [a]	3.98[a]	0.84[a]	48[a]
RM2	70.7[b]	14.77[b]	1.01[b]	63[b]
Post-clear-cut forest	52.7 [c]	5.25[c]	1.04[b]	63[b]
RM3	80.2[d]	8.96[d]	0.94[d]	55[d]
Post-selective logging forest	62.3[e]	17.42[e]	0.90[d]	66 [e]

Means followed by different letters in the same column are significantly different between forest types at p <0.05 by t-test

The shrub and herbaceous layer's characteristics as well as canopy cover are important factors affecting the growth and development of regenerated trees, especially the competition for nutrition and light under the forest canopy. When the forest canopy cover is reduced, shrubs of shrubs grow, which is favorable for regenerating trees to be shade-proof at a young age, but it will be an obstacle when regenerated trees grow. At this time, fresh shrubs will crowd and compete with regenerated trees. Therefore, it is necessary to determine the characteristics of this layer to take appropriate measures to limit the damage caused to the regenerated trees (Lan, 1986; Van Auken & Bush, 1991).

The findings indicated that in RM1 with its special conditions, such as the application of regeneration inhibition measures, made prospective seedlings rate became abnormal compare to other stands in the study area, meaning that canopy cover, shrub and herbaceous layer, though important, did not become the decisive factor for the growth and development of regenerated trees at this stage. Meanwhile at RM2 and RM3, the fact that previously mentioned measures were not applied made these factors became more important in influencing the regeneration layer in the restoration model, similar with the natural forest types in the study area as well as other forest ecosystems in Vietnam (Van Auken & Bush, 1991; Doi, 2013; Nam et al., 2017).

4.3. Comparison of soil properties in natural forest and restoration models in the study area

The results of soil sample were presented in Table 15. All soil components in the original forests showed higher value than that in the remaining forest types, both natural and artificial. Between post-clear-cut forest and its restoration models 1 and 2, these indices all had positive trend as they increased steadily from the former to the latter. Especially in restoration model 1 where soil improvement was the main focus, the N% index even became higher than that of the older model 2, while others such as pH, extractable potassium (Ex-K) and CEC approached closely.

When comparing post-selective logging forest and restoration model 3, conflicting results were found where organic matter (OM%), Ex-K and CEC were higher in the former while pH, N% and Ex-P were higher in the latter. The texture of both sites was not significantly different from each other but was somewhat poorer than that of original forest.

Study on soil properties is necessary to understand its role to successful forest management. Generally, the soil in the degraded and restoration forests in the study site had been strongly degraded. The content of humus and nitrogen in the post-clear-cut forest and restoration models was lower than that in the original and post-selective logging forests. Both organic matter (OM%) and nitrogen (N%) are most significant factors for plants but they are easily eroded in the cultivation process. This make the soil becomes infertile, reducing the ability to provide nutrient for plants.

The soil is poor in terms of organic substance but still soft and has light texture at preliminary types having bush cover. However, soil is highly acidic but poor in available substances. Therefore, to build the restoration models with silviculture combination, it is necessary to increase the fertility of soil by planting leguminous trees and shrubs before planting crops. These species are also needed as a measure of reducing erosion. Highly extensive cultivation methods for increasing productivity are important as well.

Table 15. Comparison of the soil properties (0-30 cm depth) between the forest types in the study sites

Site	pH_{H2O}	Organic matter (%)	N (%)	Ex-P (mg/1kg)	Ex-K (mg/100g)	Texture			CEC (me/100g)
						Sand	Silt	Clay	
Original forest	6.57±0.18	3.65±0.212	0.638±0.05	118.12±31.65	33.85±2.21	25.49±3.931	37.12±1.470	38.29±2.485	26.97±2.68
Post-clear-cut forest	5.31±0.19	1.67±0.283	0.253±0.11	21.84±07.73	12.62±0.83	42.63±4.670	29.07±3.633	28.31±5.390	14.5±2.09
Restoration model 1	5.73±0.13	1.80±0.128	0.450±0.18	54.85±18.21	14.05±1.81	35.18±2.095	30.10±1.119	34.72±3.206	16.35±2.81
Restoration model 2	5.77±0.21	1.97±0.201	0.371±0.12	70.57±31.05	15.20±3.07	28.85±2.681	32.83±2.130	38.32±2.871	18.05±3.02
Post-selective logging forest	6.41±0.26	2.85±0.009	0.512±0.04	83.61±39.29	16.56±5.92	22.89±2.877	38.18±1.504	38.94±2.218	18.37±4.85
Restoration model 3	6.88±0.14	2.73±0.213	0.598±0.09	96.68±33.27	16.00±2.11	24.76±3.007	35,58±1.460	39,66±3.654	17.38±3.11

Chapter 5. Conclusion

The results obtained from this study showed that the stand structure of post-selective logging and especially post-clear-cut forest has been deeply weaken because of historical human activities in the study area. Post-clear-cut forest had weak and unstable growth both in overstory and regeneration layers as well as low biodiversity, dominated by mostly pioneer species as the result from clear-cut exploitation. The post-selective logging forest had better development than the post-clear-cut forest with the appearance of some valuable species, but the biodiversity level was still low. All original forest stands were characterized by good growth and development parameters, which were superior to the other two forest types, but low species richness here represented that the site condition in the study area, possibly limestone bedrocks, in the study area was not as favorable for plants as other forests in Vietnam.

The natural restoration of degraded limestone forest in the study area into unimpacted primeval state could be very slow as in post-selective logging forest, or nearly impossible as in post-clear-cut forest stands, due to weak structural characteristics as well as poor soil conditions which do not guarantee the growth of various species as well as fragmentation and isolation between stands in the study area, reducing the possibility of seed dispersal from original forest into the others.

The comparison of forest restoration models and their respective natural forests in the study area showed some highly positive results, such as the growth indicators, both of overstory and regeneration layers, were relatively good in every model compared to natural forest types. Except for RM1 model, which was still at the early stage of restoration, biodiversity indicators of the native species additional planting (RM2) and the enrichment (RM3) models were in general higher than all natural forest types, including the untreated original forest. In addition, the increasing participation of valuable species showed the relative success of the forest restoration model in the study area.

However, the current models still have some limitations. High planting density in RM2 resulted in excessive competition for nutrients among species, reducing the growth of most individuals in the stand. The low number of regeneration species compared to the overstory in this model would also have negative influence on the model, as this low figure do not guarantee that the stand in the future could maintain the biodiversity it was enjoying. All restoration models' soil components were lower than that of natural forests in the study area, except for the post-clear-cut forest.

Therefore, in order to improve the existing models and to develop future restoration models with silviculture combination, it is necessary to adjust the planting density to reduce the competition among species, planting leguminous trees and shrubs before planting other species in order to increase soil fertility and reduce soil erosion. Highly extensive cultivation methods should also be applied for increasing the productivity of planted species.

In conclusion, natural forest types in the study area had shown significantly different results in terms of growth, composition, biodiversity and regeneration. Natural restoration of post-clear-cut forests showed not highly appreciable results, requiring further silvicultural and ecological measures to enhance the development of this forest type. The analytical results of the applied forest restoration models indicated that it could be a meaningful approach to recover the degraded natural limestone forests in the study area, although some adjustment measures were still needed to ensure its future success.

Future studies should focus more deeply on analyzing the impacts of natural conditions, biotic as well as abiotic, such as site qualities, soil nutrients, and seed dispersal capacity among different forest stands, etc., in order to obtain a more multi-dimensional view of the ecological features in the study area.

References

Adam J.H. and Z. Mamat. 2005. Floristics composition and structural comparison of limestone forest at three different elevations in Bau, Kuching, Sarawaj, Malaysia. Journal of Biological Science 5: 478–485.

Barbour, M.G., J.H. Burk and W.D. Pitts. 1987. Terrestrial Plant Ecology (2nd Ed). Benjamin Cummins Publishing Co, Menlo Park, CA, USA. pp. 191-193.

Bauer, G.N. 1962. The ecological basis of rain forest management. For. Comm. New South Wales, Aust., 1961-1962, Rome. FAO, Andre Meyer Fellowship Prog. Rep. 499 pp.

Bauer, G.N. 1964. Rain forest treatment. Unasylva (FAO) 72:1826.

Binh, N.T. 2014. Some Structural characteristics and Biodiversity of mixed tropical evergreen forest in Bidoup-Nuiba National Park. Journal of Forest Science and Technology 2:3255-3263.

Bradshaw, A.D. 1990. The reclamation of derelict land and the ecology of ecosystems. In: Jordan, W.R., Gilpin, E. and Aber, J.D. (Eds.). Restoration Ecology: A Synthetic Approach to Ecological Research. Cambridge University Press, Cambridge, UK. pp. 53-74.

Brewer, S.W., M. Rejmanek, M.A.H. Webb and P.V.A. Fine. 2003. Relationship of phytogeography and diversity of tropical tree species with limestone topography in southern Belize. Journal of Biogeography 30: 1669-1688.

Brooks, A. 2006. Enhancing the effectiveness of projects on Cat Ba Island - an evaluation of ten years of international support. IUCN Vietnam Country Office: Hanoi, Vietnam.

Cairns, J.J. 1988. Increasing diversity by restoring damaged ecosystems. In: Wilson, E.O. and F.M. Peter (eds.): Biodiversity. National Academy Press, Washington, D.C. 333- 343.

Cao, M. and J. Zhang. 1997. Tree species diversity of tropical forest vegetation in Xishuangbanna, SW China. Biodiversity and Conservation 6: 995–1006.

Chung, D.H. and N.T. Hung. 2013. Structural, living mass and carbon sequestration characteristics of natural forests in Sang Moc commune, Than Sa – Phuong Hoang Natural Reserve. The Fifth National Scientific

Convention on Ecology and Species Resources.

Clements, R., N.S. Sodhi, M. Schilthuizen and P.K.L. Ng. 2006. Limestone karsts of southeast Asia: imperiled arks of biodiversity. Bioscience 56: 733–742.

Day, M.J. and P.B. Urich. 2000. *An assessment of protected karst landscapes in Southeast Asia*. Cave and Karst Science 27: 61–70.

Do, K.H. and L.N. Cong. 2013. Classification of natural vegetation and the causes of forest degradation in Vi Xuyen, Ha Giang. The Fifth National Scientific Convention on Ecology and Species Resources.

Falk, D.A. 1990. *Restoration of endangered species: A strategy for conservation*. In: Berger, J.J. (ed.). Environmental restoration: Science and strategies for restoring the earth. Island Press, Washington, D.C. 328-334.

Fang, W. and S.L. Peng. 1997. Development of species diversity in the restoration process of establishing a tropical man-made forest ecosystem in China. Forest Ecosystem and Management 99: 185-196.

Felfili, J.M., A.R.T. Narcimento, C.W. Fagg and E.M. Meirelles. 2007. Floristic composition and community structure of a seasonally deciduous forest on limestone outcrops in central Brazil. Revista Brasileira de Botanica 30: 611-621.

FFI. 2003. *Annual Technical Report: Report on BP - Vietnam Funding, Ha Long/ Cat Ba Conservation Project and Coastal Biodiversity Support Project Preparation Phase*. Fauna and Flora International (FFI), Hanoi, Vietnam.

Finegan, B., M. Camacho and N. Zamore. 1999. Diameter increment patterns among 106 tree species in a logged and silviculturally treated Costa Rican rain forest. Forest Ecology and Management Volume 121, Issue 3, 23 August 1999, Pages 159-176.

Government of Vietnam. 1986. Decision No. 79-CP of the Council of Ministers on the Establishment of the Cat Ba National Park.

Government of Vietnam. 2018. National Census of Vietnam in the year 2018.

Hall, J.S., D.J. Harris, V. Medjibe and P.M.S. Ashton. 2003. The effects of selective logging on forest structure and tree species composition in a Central African forest: implications for management of conservation areas. Forest Ecology and Management Volume 183, Issues 1–3, 15

September 2003, Pages 249-264.
Hien, N.T.T and T.T.T. Ha. 2014. Some structural characteristics of natural evergreen forests in Vu Quang National Park - Ha Tinh. Journal of Forestry Science and Technology, (No. 3), pp. 3408 - 3416. ISSN: 1859 – 0373.
Hien, N.T.T. 2014. Structural dynamics of evergreen broadleaves forest in Babe National Park. Journal of Forestry Science and Technology 3/2014 (3417 - 3423).
Hong, N.V. 2010. Characteristics of forest structure and the relationship between the composition of tree species, between regenerated trees and timber trees, non-timber forest product species in the Huong Son Special Use Forest Management Board of, Ha Tinh. Master of Science thesis, Vietnam Forestry University, Hanoi.
Howe, H.F. and J. Smallwood. 1982. Ecology of seed dispersal. Annu. Rev. Ecol. Syst. 13: 201-228.
IUCN. 1997. IUCN red list of threatened plants. Gland, IUCN.
Janzen, D.H. 1988. Management of habitat fragments in a tropical dry forest: growth. Annals of the Missouri Botanical Garden 75: 105-116.
Jeremy. H., M. Kevyn and F. Richard. 1997. The potential of plantation to foster woody regeneration within a deforested landscape in lowland Costa Rica. Forest Ecology and Management 99: 55-64.
Jost, L. 2006. Entropy and diversity. Oikos 113: 363–375.
Kamo, K., T. Vacharangkura, S. Tyianon, C. Viriyabuncha, S. Simpila and B. Duangsrisen. 2002. Plant species diversity in tropical planted forests and implication for restoration of forest ecosystems in Sakaerat, Northeastern Thailand. JARQ 36(2): 111-118.
Keenan, R., D. Lamb, O. Woldring, T. Irvine and R. Jensen. 1997. Restoration of plant diversity beneath tropical tree plantations in Northern Australia. Forest Ecology and Management 99: 117-131.
Kelly, D.L., E.V.J. Tanner, V. Kapos, T.A. Dickinson, G.A. Goodfriend and P. Fairbairn. 1988. Jamaican limestone forests: floristics, structure and environment of three examples along a rainfall gradient. Journal of Tropical Ecology 4: 121-156.
Khanh D.C. 1996. Some structural characteristics of evergreen broadleaf forests in Huong Son - Ha Tinh as a basis for proposing silvicultural

measures for forest exploitation and nurturing. Dissertation of Forestry Science PhD, Vietnamese Academy of Forest Sciences, Hanoi.

Kramer, H. 1966. Crown development in conifer stands in Scotland as influenced by initial spacing and subsequent thinning treatment. Forestry 39:40-58.

Kramer, P.J., and T.T. Kozlowski. 1960. Physiology of Trees. McGraw-Hill, New York, 642 pp.

Kramer, P.J., and T.T. Kozlowski. 1979. Physiology of Woody Plants. Academic, New York, 811 pp.

Lan, P. N. 1986. Principles of bio-forestry in Vietnam. Agriculture Scientific Publisher, 1986.

Langenheder, S., M.T. Bulling and J.I. Prosser. 2012. Role of functionally dominant species in varying environmental regimes: evidence for the performance-enhancing effect of biodiversity. BMC Ecol 12, 14 (2012) doi:10.1186/1472-6785-12-14

Le, T.C. 1990. Vietnam nature. Science and Technical Publishing House. Hanoi, Vietnam.

Liu, J.J. and J.W.F. Slik. 2014. Forest fragment spatial distribution matters for tropical tree conservation. Biological Conservation 171 (2014) 99-106.

Lubbe, W.A. and C.J. Geldenhuys. 1991. Regeneration patterns in planted and natural forest stands near Knysna, southern Cape. S. Afr. For. J. 159: 43-50.

MAB Vietnam. 2016. Cat Ba Archipelago Biosphere Reserve. http://mabvietnam.net/khu-du-tru-sinh-quyen-the-gioi-quan-dao-cat-ba

MacMahon, J.A. 1997. Ecological Restoration. In: Meffe, G.K. and Carroll, C.R. (Eds.). Principles of Conservation Biology. Second edition. Sinauer Associates, Inc. Publishers, Sunderland, Massachusetts, USA. 479-511.

Meyer, W.H. 1930. Diameter Distribution Series in Even-aged Forest Stands. Yale School of Forestry Bulletin 28. 105 pp.

Marmillod, D. 1982. Methodik und Ergebnisse von Untersuchungen über Zusammensetzung und Aufbau eines Terrassenwaldes im perauanischen Amazonien. Georg-August-Universität zu Göttingen.

Miller, K., M. H. Allegretti, N. Johnson and B. Jonsson. 1995. Measures for conservation of biodiversity and sustainable use of its components. In:

Heywood, V.H. and R.T. Watson. (Eds.). Global Biodiversity Assessment. The United Nations Environment Programme and Cambridge University Press, Cambridge, UK. 915- 1061.

Ministry of Agriculture and Rural Development of Vietnam. 2009. Circular No. 34/2009/TT-BNNPTNT on Criteria Regulation for Identifying and Classifying forests.

Ministry of Agriculture and Rural Development of Vietnam. 2019. Decision No. 911/QĐ-BNN-TCLN on publishing the Forest Status of Vietnam in 2018.

Ministry of Science, Technology and Environment. 2007. Vietnam Red Data Book. Part II. Plants. Scientific Publishing House, Hanoi, Vietnam.

Nam, V. Q. 2017. Some natural regeneration characteristics of vegetation types in Go Doi – Yen Mo – Ninh Binh – Vietnam. Journal of Forestry Science and Technology 3 – 2017.

Naveh, Z. and R.H. Whittaker. 1979. Structural and floristic diversity of shrublands and woodlands in Northern Israel and other Mediterranean areas. Vegetation 41:171-190.

Ngu, H.K. and P.N. Lan. 2000. Forest ecology. Agriculture Science Publisher, Hanoi.

Nguyen, N. B. 2000. Forest management in the uplands of Vietnam: social, economic and environmental perspectives. 104 pp.

Nguyen, S.T., J.J. Pigram and B.A. Rugendyke. 2002. Tourism development and national parks in the developing word: Cat Ba island national park, Vietnam. In D. G. In Pearce & R. Butler (Eds.), Contemporary issues in tourism development (pp. 211-231). New York, USA: Routledge Advances in Tourism.

O’Brien, M.J., K.L. O’Hara, N. Erbilgin and D.L. Wood. 2007. Overstory and shrub effects on natural regeneration processes in native Pinus radiata stands. Forest Ecology and Management, 240(1-3), 178-185.

Oliver, C.D., B.C. Larson and C. D. Oliver. 1996. Forest stand dynamics. New York: Wiley, 1996.

Otsamo, R. 2000. Secondary forest regeneration under fast growing forest plantations on degraded Imperata cylindrica grasslands. New Forests 19: 69-93.

Parrotta, J.M., H.K. Oliver, M. Joseph and J. Wunderle. 1997. Development of floristic diversity in 10-year-old restoration forests on a bauxite mined site in Amazonia. Forest Ecology and Management 99: 21-42.

Pandey, P.K., S.C. Sharma and S.K. Banerjee. 2002. Biodiversity studies in a moist temperate Western Himalayan forest. Indian Journal of Tropical Biodiversity 10:19-27.

Parrotta, J.A. 1992. The role of plantation forests in rehabilitating degraded tropical ecosystems. Agriculture Ecosystem and Environment 41: 115-133.

Parrotta, J.A. 1993. Secondary forest regeneration on degraded tropical land, the role of plantation as "foster ecosystem". In: Leith, H. and M. Lohmann. (Eds.). Restoration of Tropical Forest Ecosystems. Kluwer Academic, Nertherlands. 63-73.

Parrotta, J.A. 1995. Influence of overstory composition on understory colonisation by native species in plantations on a degraded tropical site. Journal of Vegtation Science 6: 627-636.

Peet, R.K., and N.L. Christensen. 1987. Competition and tree death. BioScience 37:586-595

Penttinen, A., Stoyan, D. and Henttonen, H.M. 1992. Market point process in forest statistics. For. Sci. 38, 806-824.

Perez-Garcia, E.A., A.C. Sevilha, J.A. Meave and A. Scariot. 2009. Floristic differentiation in limestone outcrops of southern Mexico and central Brazil: a beta diversity approach. Boletin de la Sociedad Batanica de Mexico 84: 45-58.

Perry, G. and J.M. Morton. 1999. Regeneration rates of the woody vegetation of Guam's Northwest Field following major disturbance: land use patterns, feral ungulates, and cascading effects of the brown treesnake. Micronesica 31(2):125–142. 1999.

Pielou, E.C. 1966. The measurement of diversity in different types of biological collections. Journal of Theoretical Biology. 13: 131–144.

Phuong, T.N. 1970. Initial research on forests of Northern Vietnam. Science and Technology Publisher, Hanoi.

Proctor, J., J.M. Anderson, P. Chai and H.W. Vallack. 1983. Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak. Journal of Ecology 71: 237–260.

Quan, N.V. 2010. Landscapes and Ecosystems of Tropical Limestone: Case

Study of the Cat Ba Islands, Vietnam. J. Ecol. Field Biol. 33 (1): 23-36, 2010.

Richards, P.W. 1952. The tropical rain forests. Cambridge. Cambridge Univ. Press. Richardson, AR (1929) North-west History. J. and Proc. WA Hist. Soc, 1, 68-74.

Schmidt, W., M. Weitemeier and C. Holzapfel, 1996. Vegetation dynamics in canopy gaps of a beech forest on limestone - the influence of the light gradient on species richness. Verhandlungen - Gesellschaft fur Okologie, 25, 253-260.

Shannon, C.E. 1948. A mathematical theory of communication. The Bell System Technical Journal, 27, 379–423 and 623–656.

Sim, M.A. and L.D. Tan. 2013. Understory regeneration characteristics in Na Hang – Tuyen Quang – Vietnam. The Fifth National Scientific Convention on Ecology and Species Resources.

Singh, A.N., A.S. Raghubanshi and J. S. Singh. 2002. Plantations as a tool for mine spoil restoration. Current Science 82(12): 1436-1441

Steenis, C.V. 1956. Basic principles of rain forest sociology. In Proceeding of the Kandy Symposium on Study of Tropical Vegetation (pp. 159-63).

Tang, J., X. Lu, J. Yin and J. Qi. 2011. Diversity, composition and physical structure of tropical forest over limestone in Xishuangbanna, Southeast China. Journal of Tropical Forest Science 23(4): 425–433 (2011).

Thanh, L.T. 2019. Some structural characteristics of natural forests in Thuong Xuan – Thanh Hoa. Scientific Journal of Hong Duc University, 44/2019.

Tuyet, D. 2001. Characteristics of karst ecosystems of Vietnam and their vulnerability to human impact. Acta Geologica Sinica 75: 325–329.

Thoa, M.P. 2000. Forests in Viet Nam and Partnership for Forestry Development. Online http://www.rinya.maff.go.jp/codeh2003/PART_4/Pham_Minh_Thoa_(Vietnam).pdf

Thoa, N.T. 2013. Analysis of some biodiversity indicators of limestone forest in Than Sa – Phuong Hoang Natural Reserve, Thai Nguyen, Vietnam. Journal of Forestry Science and Technology 4/2013 (2961 - 2967).

Thap, N.V. 2010. Proposing some technical solutions for rehabilitation of poor limestone forest in Cat Ba National Park, Vietnam. Doctor of

Philosophy Thesis.
Thinh, N.V. et al. 2015. Comparison of floristic composition in four sites of a tropical lowland forest on the North-Central Coast of Vietnam. Journal of Nature and Science, Vol.1, No.8, e144.
Trung, P.D. et al. 2016. Structural characteristics and biodiversity of post-exploitation restoration forest in Dong Nai Natural Reserve. Journal of Forestry Science and Technology 4/2016 (4637 - 4645).
Trung, T.V. 1999. Vietnam forest vegetation from the perspective of ecosystems. Science and Technology Publisher, Hanoi, 297 pages.
Van Auken, O.W. and J.K. Bush. 1991. Influence of shade and herbaceous competition on the seedling growth of two woody species. Madrono, 149-157.
Van, P.Q. 2018. Structural characteristics and species diversity of canopy layer vegetation in natural forest of An Lao, Binh Dinh. Journal of Forestry Science and Technology 01/2018.
Van Reewijk, L.P., 2002. Procedures for soil analysis (sixth ed.). Technical Paper No. 9, Wageningen: International Soil Reference and Information Centre.
Verma, R.K. 2000. Analysis of species diversity and soil quality under Tectona grandis L.f. and Acacia catechu (L.f.) Wild. plantations raised on degraded bhata land. Indian Journal of Ecology 27(2):97-108.
Vien, T.H. 2005. Scientific basis for establishing technical and economic solutions for sustainable natural limestone forest development. Vietnam national priority project. Agriculture Science Publisher, Hanoi.
Viet, H., and C.K. Lin. 2001. Cat Ba National Park, Viet Nam. ITCZM Monograph No.2: AIT, Thailand.
Vietnam Administration of Forestry. 2013. Decision No. 689/QD-TCLN-KL dated 23/12/2013 on Guiding the Principles of Forest Survey.
Thomas, J.G. 1999. On the causes of gradients in tropical tree diversity. Journal of Ecology 87: 193-210.
World Bank. 2005. Vietnam environment monitor 2005: Biodiversity. Hanoi, Vietnam: Vietnam World Bank (WB).
WCMC (The World Conservation Monitoring Centre). On line http://www.wcmc.org.uk/infoserv/countryp/vietnam/chapter3-.html
Yachi, S. and M. Loreau. 1999. Biodiversity and ecosystem productivity in a

fluctuating environment: The insurance hypothesis. Proc Natl Acad Sci U S A. 1999, 96 (4): 1463-1468. 10.1073/pnas.96.4.1463.

Young, K.R., J.J. Ewel and B.J. Brown. 1987. Seed dynamics during forest succession in Costa Rica. Vegetatio 71: 157-173.

Zingerli, C. 2005. Colliding understandings of biodiversity conservation in Vietnam: Global claims, national interests, and local struggles. Society & Natural Resources, 18(8), 733-747.

ABSTRACT
(in Korean)

베트남의 산림은 오랫동안 생물의 종 풍부성과 다양성이 높은 것으로 알려져 왔으나 지난 수십년 동안 산림의 무분별한 이용으로 훼손과 퇴화 과정을 겪고 있다. 최근에는 훼손된 산림을 복원하고 회복하기 위한 과학 연구와 기술 개발에 많은 노력을 기울이고 있다. 이 연구는 베트남 Cat Ba Biosphere Reserve의 훼손된 석회암 천연림의 복원 및 지속 관리를 위한 산림복원기술 (무벌채, 택벌, 개벌)과 혼합조림기술의 생태학적 특성에 대해 평가하고자 진행하였다. 연구에서는 산림의 상층 구조와 더불어 하층 식생의 구조적 특성에 대해 조사 및 평가하였다. 그 결과, 택벌 (selective logging)과 개벌 (clear-cut)을 실시한 산림은 무벌채 (no logging) 지역의 산림에 비해 나무의 종수가 적었다. 특히, 건강하지 못한 임분에서는 자연복원 방식을 통해 원시림 수준까지 도달하기에는 시간이 많이 소요되거나 일부 지역에서는 불가능할 것으로 보였다. 한편, 복합 조림 (mixed plantation)을 시행한 임분은 재적 성장량이 양호하고 경제 수종이 다수 서식하고 있으며, 생물다양성 지수가 높게 나타나, 생태적으로 무벌채 임분과 유사하였으나 인위적으로 벌채를 시업한 임분 보다는 좋은 결과를 보였다. 또한, 보식 식재 방법 (enrichment planting)은 무벌채 지역에 비해 높은 임목 밀도와 낮은 토양 비옥도 등의 한계를 가지고 있었다. 이 연구는 베트남 훼손 산림의 복원 및 회복을 위한 산림 복원 기술 개발에 필요한 기초 자료를 제공하고, 조림 기술, 생태 복원 기술 등의 적용 및 평가를 위한 과학적인 연구방법을 제시하고 있다.

Keyword: 캇 바 생물권보호지역, 석회암 천연림, 산림복원, 복합 조림

학 번: 2018-25329