ASSESSMENT OF STRATEGIC FOREST MANAGEMENT SYSTEM IN THE SUBTROPICAL FOREST OF OKINAWA MAIN ISLAND

(沖縄本島の亜熱帯森林における戦略的森林管理システムの評価）

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By

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This thesis is dedicated to my husband, parents

and kids for their endless support, love,

and encouragement

Assessment of strategic forest management system in the subtropical forest of Okinawa Main Island

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Abstract

The 27,161ha of the Yambaru Forest is managed by various stakeholders, which includes the Japanese government, Okinawa Prefecture, individuals and three municipalities – Kunigami, Ogimi and Higashi – with different management goals. The critical issue occurs in Yambaru is on how to improve society's perception and understand the sustainable use of forest resources for a stable and efficient forest management system. Therefore, this study was carried out to assess the potential management systems of Yambaru Forest, which is subject to diverse vegetation and land use conditions. The three main parts of the study consist of i) the dynamics of Yambaru forest, ii) elevation-based zonation for conservation forest, and iii) strategic management option for production forest.

Firstly, the vegetation structure and forest land use and land cover (LULC) attributes were assessed to explain the existing forest conditions. Vertical vegetation structure assessed within 20 sample plots showed that *Shima walichii* were the dominant species with mean diameter-at-breast height (dbh) and tree height of 10.3cm and 8.4m respectively. Major trees were concentrated in the middle layer (5-10m), and trees of smaller in height (<5m) significantly contribute to the high forest diversity. The

forest canopy structure, as delineated from Light Detection and Ranging (LiDAR), yielded a low accuracy due to the complex vegetation and topographical conditions. In addition, the forest LULC was evaluated using high-resolution satellite image of IKONOS with different image classification methods. Pixel-based classification derived the highest accuracy of 83.7% compared to the object-based classification of 81.3% in detecting the land cover attributes of logged-over forest and the adjacent areas. The study discovered that the post-harvest activity by silvicultural treatment of replantation had a positive impact through the reduction of bare area and increased amount of vegetation cover.

Secondly, the potential forest management by zoning system was introduced based on elevation gradients. The Potential Conservation Areas (PCAs) at different elevation levels were evaluated using digital terrain data along with information concerning forest ownership, protected parks, watershed areas, vegetation and forest accessibility. The PCAs decreased with an increased of elevation. The optimum PCAs at the middle-peak level illustrated the continuous connection of forest area with fewer forest patches. From the Digital Canopy Height Model (DCHM), the mean tree height was higher at this altitude than at other levels. The result was then compared with the zoning plan by the Okinawa Prefecture. The feasible measure of elevation gradients integrated with various consideration factors provide a better understanding of site selection for PCAs in the Yambaru Forest.

Finally, strategic timber management options produced by HARVEST allocation model were examined on the different harvesting procedures. With the small clear-cutting method, the estimated volume of timber production was 12% higher compared to the selective-cutting method. Mean patch sizes and forest edges were the significant factors that interacted with harvesting practice. For a long-term forest planning, the model is indispensable to predict cost-effective, appropriate and relevant timber harvesting options to improve timber management strategy towards a sustainable yield of timber production.

The result from this study is expected to improve community perception and comprehension on sustainable resource management in a practical approach. It could also be beneficial to support decision-making process for strategic forest management in the Yambaru Forest.

沖縄本島の亜熱帯森林における戦略的森林管理システムの評価

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要約

やんばる森林 27,161ha は、国、県、国頭村・大宜味村・東村の 3 村及び個人と、それぞれ異なった経営目標を持つ主体により管理されている。やんばる地域において、安定的かつ効果的な森林管理システムのために、森林資源の持続的利用をいかに地域が受容・理解するかが重要な問題となっている。そのため本研究は、多様な植生や土地利用条件下でのやんばる森林の将来的な管理システムを検討することを目的とした。本論文は、ｉ）やんばる森林の動態、ⅱ）保全森林地域の標高階別ゾーニング、及びⅲ）生産森林の戦略的管理選択肢の 3 部分から構成した。

まず、現在の森林状態を把握するため植生構造、林地利用・土地被覆属性(LULC)について検討した。設定された 20 プロットから垂直植生構造を評価した結果、いずれのプロットもイジュが優占樹種で、平均胸高直径及び平均樹高は、それぞれ 10.3cm、8.4m であった。多くは林分の中層階（5-10m）に集中し、林内の多様性は下層階（< 5m）に生育する低木類に依存している。複雑な地形や植生状態に起因して、航空搭載型レーザー(LiDAR)による樹冠構造解析精度は低値を示した。次に、IKONOS の高解像度画像データを用いて、LULC 判別精度を異なった二つの画像判別法（ピクセル法及びオブジェクト法）で比較した。伐採跡地を含む森林区域での判別結果は、オブジェクト法の 81.3%に

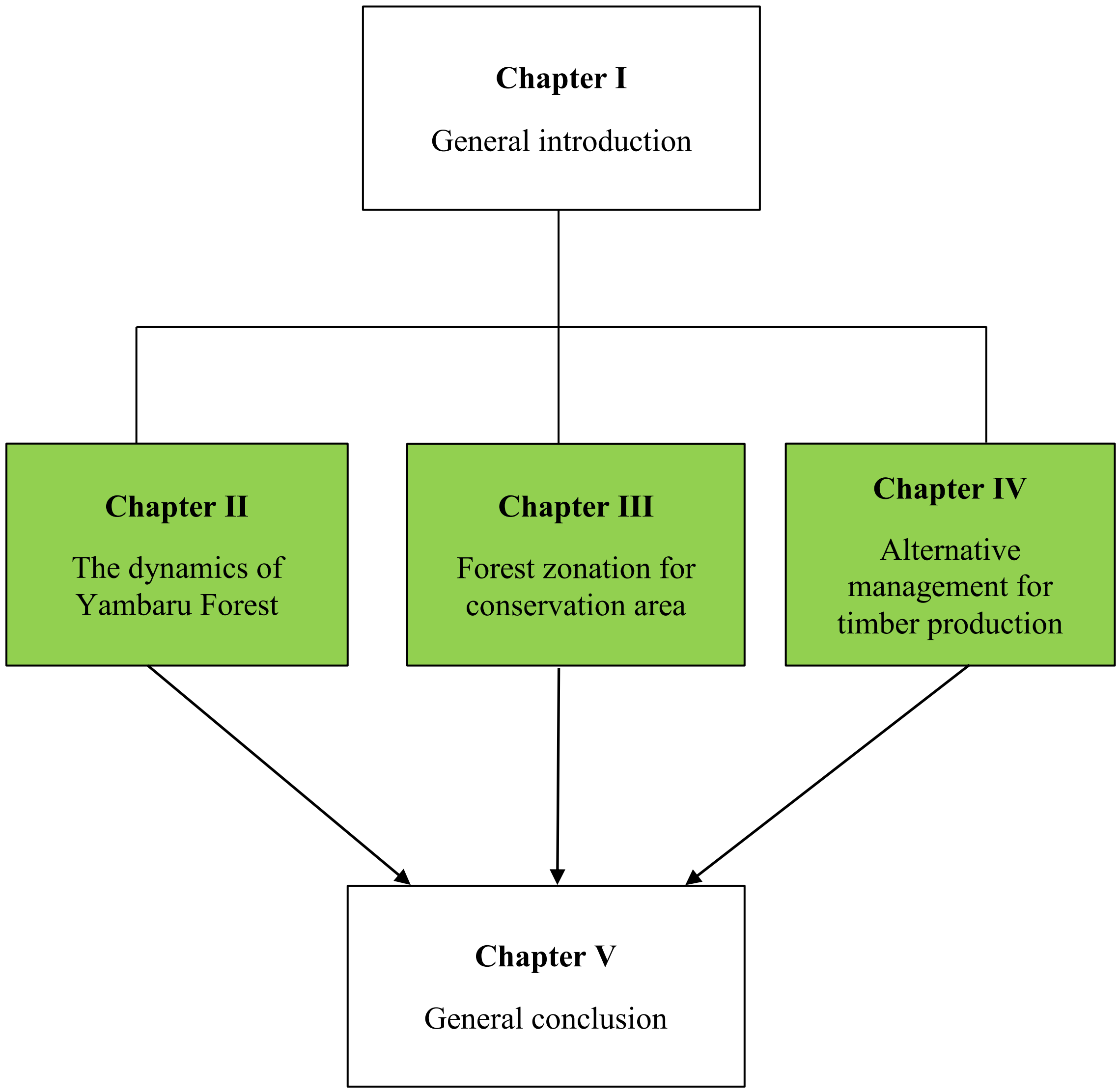
比べて、ピクセル法は 83.7%と相対的に高い精度を示した。本研究から、森林伐採後の速やかな育林作業が林地面の裸地化を抑え、被覆植生量を増加させることが明らかとなった。

次に、標高勾配に基づくゾーニングシステムを導入して将来的な森林管理法にいて検討した。森林所有、保護公園区域、流水域、森林・林内路網等の情報を付加した数値地形データを使って、標高階別の保全区域(PCAs)を評価した。標高が高くなるに従い保全区域面積は減少した。土地利用やその他の人為的な活動に伴う競合的要求の許容度を評価する上で重要な要因となる森林の連続性や断片化の程度から、最適な保全区域が中間標高階レベルで現れることが示された。当該標高での平均樹高は、他の標高階レベルより高いことが数値樹冠高モデル DCHM から明らかとなった。これらの結果を沖縄県により策定されたゾーニング計画と比較した。その結果、森林の諸状況を包括した標高勾配による本手法は、やんばる森林における保全区域選定をより理解しやすいものとすることが考察された。

HARVEST 配分モデルを用いて設定した戦略的木材管理手法について、異なった収穫方式による効果を比較検討した。小面積皆伐方式によれば、択伐方式に比べて木材生産量は 12%増加した。平均パッチサイズや生息域は収穫方式と相互に密接に関係していた。長期的な森林計画の観点から、持続的な木材資源生産を志向した管理戦略を改善するための費用対効果、適切かつ連携した収穫案を予測する上で、当該モデルは不可欠であると考えられる。

持続的な資源管理に関する地域社会の認識や理解を改善するための現実的な手法として本研究の結果は期待される。また、やんばる森林における戦略的な森林管理のための意思決定を支援するためにも有効である。

Research Layout and Thesis Flow



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List of Abbreviations

ALS	Airborne Laser Scanner
DAFF	Department of Agriculture, Forestry and Fisheries
Dbh	Diameter-at-breast height
DCHM	Digital Canopy Height Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
FT	Forest Type
GIS	Geographical Information Technology
GPS	Global Positioning System
IUCN	International Union for Conservation of Nature
JSI	Japan Space Imaging
LiDAR	Light Detection And Ranging
LULC	Land use and land cover
MA	Management Area
MOE	Ministry of Environment
NDVI	Normalized Difference Vegetation Index
NFI	National Forest Inventory
NIR	Near Infra-Red
PCAs	Potential Conservation Areas
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
VHR	Very High Resolution
WGS	World Geodetic System

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In the name of Allah, the Most Gracious and the Most Merciful.

You have given me the power to belief in myself and to pursue my dreams. I could never have done this without the faith I have in you, the Almighty.

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Finally, I would like to acknowledge the most important person in my life - my husband, Idi Shah Rizal. He has been a constant source of strength and inspiration, who is always been by my side throughout the inevitable ups and downs of this Ph.D. journey and living every single minute of his time just to make sure this study accomplished with flying colours. And to my lovely sons Ashraf and Adam, thank you for being such a good boy and always cheering me up. Without them, I would not have had the courage to embark on this journey through the end.

30 January 2015
University of the Ryukyus
Okinawa, Japan

Chapter I

General Introduction

"*It might be appropriate to develop a long term resource management strategy for the Ryukyuan Island forests. This can provide a land use framework within which the production and conservation functions of the forest are brought into balance...*"

- T. Shinohara 1996

1.1 The Yambaru Forest of Okinawa

The only subtropical forest formation in Japan is restricted from the southwest of Kagoshima to the Ryukyu Islands, including Okinawa Main Island (Sasse 1998). The forest spreads in area of latitude between 20º and 25ºN. The subtropical evergreen broadleaved forest in Okinawa is concentrated at the northern region of the island called Yambaru Forest. Yambaru (in Japanese: 山原) means the continuous mountains of forested areas in the northern region of Okinawa. The area is characterized by a subtropical climate with a mean annual temperature of 22.5ºC and an annual average rainfall of 2,127 mm, which is higher compared to the capital city of Naha (Japan Meteorological Agency; retrieved on December 2013). Forty percent of the precipitation is directly or indirectly contributed by heavy rainfall during regular typhoon outbreaks, mainly between August and October (Xu et al. 2008). The forest is located on steep slopes and rugged terrain with the highest peak of 502 m, which is located at Yonaha Mountain.

The Yambaru area comprises three neighbouring villages, named Kunigami, Ogimi and Higashi. It covers the entire area of 27,161 ha with a total population of 10,000 people. The natural and artificial forests cover 80% of the area. The preeminent broadleaved species are *Castanopsis sieboldii* and *Schima wallichii* (Aramoto et al. 1992; Xu et al. 2008) and only native pine trees were artificially planted. Although Yambaru only covers 0.1% of Japan's forest area, this woodland is well-known for its species diversity and high density of flora and fauna (Ito 1997; Kubota et al. 2005; Feroz et al. 2006), including the IUCN Red List Threatened Species – Okinawa spiny rat (*Tokudaia osimensis*), Okinawa woodpecker (*Dendrocopos noguchii*), Ishikawa frog (*Rana ishikawae*) and Okinawa rail (*Gallirallus okinawae*) – that dwell in the forest areas (IUCN 2012).

The nomination of Yambaru Forest as a candidate for the World Natural Heritage site in 2012 confirms the action to conserve the remarkable forest area (Ryukyu Shimpo 2013). Forest assessment and monitoring efforts are currently being conducted by the Department of Agriculture, Forestry and Fisheries of Okinawa Prefecture (DAFF), and the Ministry of Environment (MOE) together with other related non-profit organizations (NPOs) to uphold the proposal. The protection of endangered animal and endemic plant species has been a great issue for various stakeholders that pressed for rapid protection and conservation of the forest area. Therefore, strengthening the forest management system, particularly to maintain the balance between conservation and production functions, is urgently required.

1.2 Forest management system

The Yambaru Forest area belongs to two main stakeholders – public and private forest management. The public forest refers to the National Forest of Japan with an area of 7,493 ha (28% from a total forest of Yambaru). The area is leased to the government of the United States of America for military training sites. The private forest is managed by three different entities namely: i) prefectural forest, ii) individually owned forest and iii) village or municipal forest (DAFF 2012). **Figure 1-1** presents the overall view of forest distribution and ownership pattern in the Yambaru Forest.

During the Ryukyu Dynasty period, the Yambaru Forest was managed by a Somayama system introduced by Sai On, the council member of the Ryukyu Kingdom. Within this system, timber from the Yambaru was transported mainly for the construction of Shuri castle and reforestation was carried out to maintain the natural resources (Takeshi 2009). However, after World War II, there has been no stable forest management system. Timber was extensively harvested without the implementation of silviculture treatment, which caused destruction of the forest ecological system and had a severe impact on the environment (Shinohara 2003). Domestic timber production has changed drastically in that, in 1970, the mean harvested area reached to 586 ha/year, whereas, recently, only 8.7 ha is allowed to be cut each year (DAFF 2012). The reduction of forest area by farmland expansion, wood price crisis and illegal logging activity (Shinohara 2000) restricted the utilization of forest resources as well as the prospects for commercial timber activities. These are among the alarming issues that require prompt action in order to maintain the sustainability of the forest.

Besides the importance of the forest for local communities and domestic timber production, Yambaru Forest is a habitat of many wildlife and plant species. For that reason, a viable forest management practice is necessary to balance the forest usage for conservation and production purposes. To date, the Yambaru Forest is mainly managed by the DAFF of Okinawa Prefecture, which recently proposed to introduce forest management planning using a zoning system. In this management plan, the area was classified by the specific land use functions, which include conservation areas, protection areas for water and soil, timber production areas and National Forest areas (DAFF 2013).

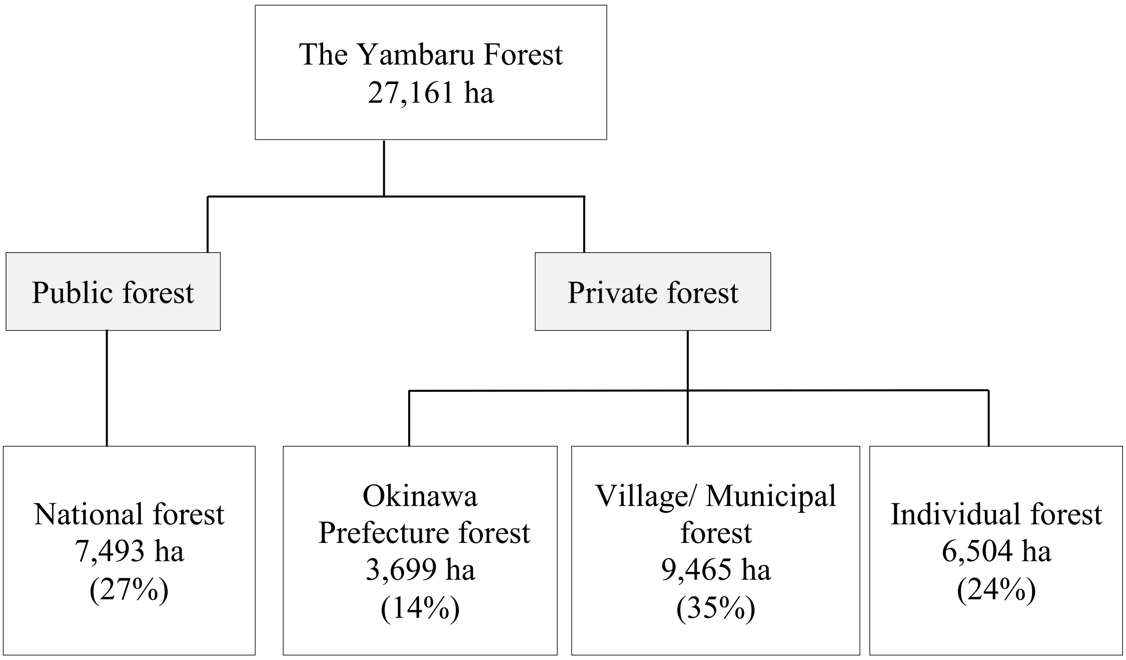

Figure 1-1. The distribution of forest area and ownership pattern in the Yambaru Forest.

(Source: Okinawa Forest and Forestry Report, published in 2013)

Strategic management is a long-term planning, monitoring and assessment which consider a systematic, aligned mission with strategy and the application is realistic with time and cost (Anderson & Eriksson 2007). The forest zoning system is one of the strategic management plans that aim to give an effective and clear direction concerning each zoned area, which, potentially, decreases land use conflict and eases communication with the public. Forest zonation is not a new topic in forestry. Numerous studies have attempted to explain the application of zoning in forestry based on various parameters, such as diversity of flora and fauna, land use and land cover, site quality, climate and altitude (McCain & Grytnes 2010; Hemp 2006; Lee et al. 2004; Chang et al. 2006; Ohsawa 1993; Colak & Rotherham 2007; Sugimura & Howard 2008; Hsieh et al. 1998). The Japanese forest zoning process used to be simple with a single forest management goal (Sugimura & Howard 2008), but has become more complicated after the introduction of multiple forest uses. Although there are drawbacks and limitations from zoning (Walther 1986), it has been strongly emphasized as a practical system for achieving long-term management goals.

The lack of zoning in forest areas leads to the failure to achieve particular management goals. However, the risk is lower if practical and feasible parameters are chosen in the site selection process. Detailed information about the management regime together with realistic plans are the key factors for the successful zoning process regardless for the conservation or production purposes.

1.3 Integration of forest management and technology

Forest management depends on complete, accurate and concise information concerning the condition, extent and productivity of forest resources (Corona 2010). Therefore, forest monitoring and resource assessment are required to help forest managers in developing tactical and strategic management planning for the forest. In principle, forest inventory is based on a complete census that measures samples in a given region (Kangas & Maltamo 2006). Traditional forest inventory, multiple sampling strategy and typology forest inventory are all sample-based inventories over a large area that are restricted in terms of time, financial and workers (Gregoire & Valentine 2008; Mandalaz 2008). In the case of Yambaru, the existence of poisonous snakes of *Trimeresurus flavoviridis* (local name: Habu), rugged terrain and unpredictable weather have limited accessibility to carry out forest inventory work.

The capabilities of Geographical Information System (GIS) and remote sensing technologies have been acknowledged globally, including in the forestry sector. This is an effective solution to assess forest environmental characteristics for monitoring, spatial planning, estimating forest resources as well as detecting land cover and vegetation changes (Bolstad & Lillesand 1991; Lillesand & Kiefer 1994; McRobert et al. 2002; Wulder & Franklin 2003).

Nowadays, various satellite data are utilized in forest monitoring including the very high-resolution (VHR) images from IKONOS, QuickBird and LiDAR. The spatial resolution of an image is an important consideration in selecting the image processing method and depends on the user's specific objective (Suarez et al. 2005). It is generally expected that the use of high spatial resolution data will improve the classification accuracy of land cover type. Various methods can be used to classify an image depending on the capabilities offered by the software providers. There are several suggested classification techniques to process VHR image data (<10meter). Among them are multiple agents of segmentation and classification, object-based analysis, decision tree, principle component analysis, maximum likelihood and hybrid classification methods (Lilles and & Kiefer 1994; Xu et al. 2001; Yuan & Buer 2006).

The integration of forest management and technology advancement has led to an effective framework to support sounds and practical forest management system.

1.4 Problem statement

The leading issue in Yambaru Forest is on how to maintain a balance between conservation and timber production forest, in order to improve the public perception and understanding concerning the importance of the forest. Forest zonation is an option to manage a forest strategically. However, it is a sensitive topic that involves many stakeholders with various forest management objectives. Forest zoning based on practical parameters is suggested for the site selection process to avoid land use conflicts and to ease public communication on forest information. For timber production, the integration of timber allocation and GIS models received less attention even it has been practically proven for future forest prediction. Alternative timber management options are required for a sustainable timber yield production in the Yambaru Forest.

1.5 Research objectives

The main objective of this study is to evaluate potential forest management options in Yambaru, primarily for conservation and timber production areas. In order to achieve the main objective, the study is divided into three main parts with specific objectives as follows:

i) to assess and monitor the dynamics of Yambaru Forest based on ground and space based data of forest vegetation structure and physical conditions.

ii) to evaluate the potential conservation areas based on elevation gradients considering other factors, such as area availability, forest ownership, water resource area, forest access road, forest vegetation, wildlife sanctuary and protected prefectural parks.

iii) to examine the strategic timber management options with a relevant and cost-effective technique for a sustainable timber yield production.

Chapter II

The Dynamics of Yambaru Forest

2.1 Introduction

In this chapter, the Yambaru Forest condition is examined. The objective is to assess and monitor the dynamics of the forest based on forest structure and physical conditions. Forest resources, areas, stakeholders and management systems are described based on a comprehensive literature review, published data and forest information from the DAFF of Okinawa Prefecture. Then, using ground-based inventory and space-based data, Yambaru Forest structure is analysed. The forest diversity and degree of concentration of individual species is calculated based on the inventory data, and the upper-storey canopy area is estimated using LiDAR data. Lastly, the land use and land cover (LULC) attributes of the Yambaru Forest are assessed using finer spatial resolution of IKONOS imagery by comparing the effectiveness of two different classification methods.

2.1.1 Okinawa forest settings

The total forest area in Okinawa Main Island is 106,400 ha, of which 30% is located in the Yambaru Forest. **Figure 2-1** briefly explains the situation of Okinawa forest. The Yambaru area consists of three villages where Kunigami occupies the largest area, of which 84% is forested, while in Ogimi and Higashi, the village occupy 76% and 72% of forest, respectively. The share of forest ownership of each village is presented in **Figure 2-2**.

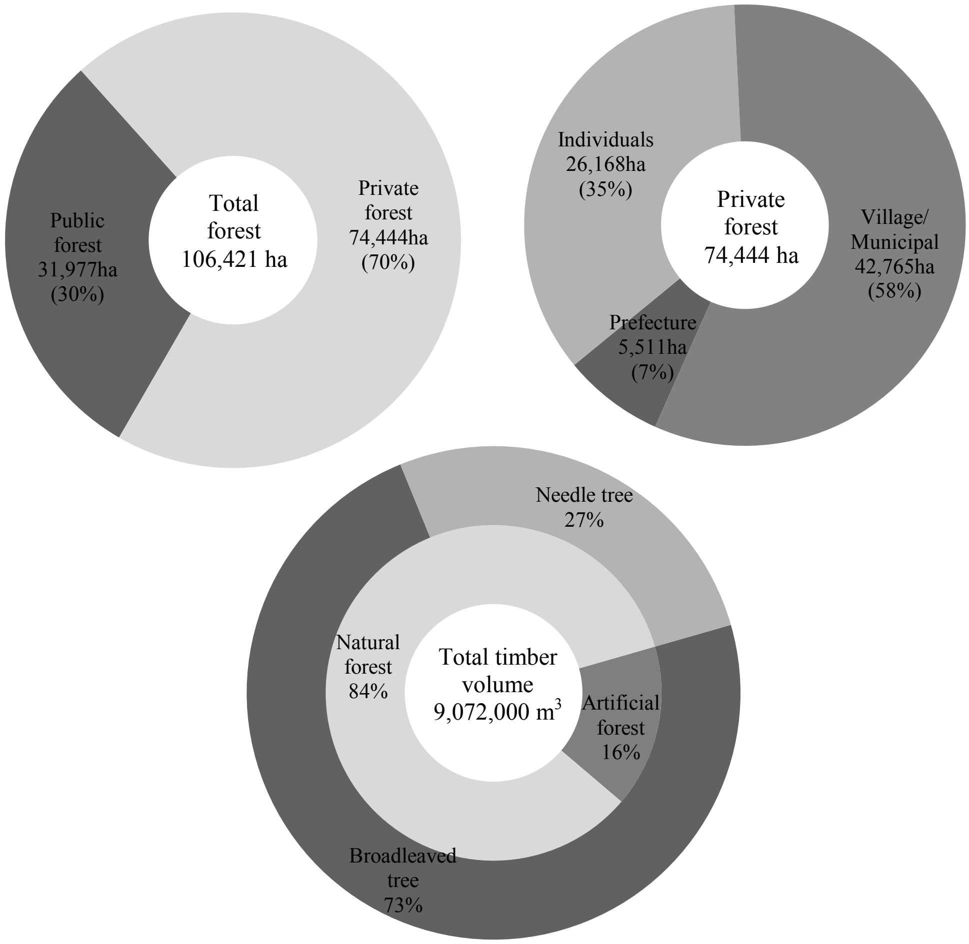

Figure 2-1. Brief introduction to the forest situation in Okinawa
(Source: Okinawa Forest and Forestry report published in 2013)

The diverse flora and fauna of Yambaru Forest has been acknowledged in many studies (Ito 2003; Shifley et al. 2008). The natural vegetation of broadleaved species constituting about 90% of the forest area, and the remaining forest area is belong to native pine stand (Shinohara et al. 1996). The forest consists of high species diversity and relatively low canopy height with a large number of small diameter trees (Xu et al. 2008). In particular cases, the maximum tree height and diameter-at-breast-height (dbh) can reach up to 20 m and 80 cm, respectively, depending on the topographic, soil and forest conditions. The existence of large trees is essential for the survival of wildlife species. For instance, a suitable nesting place for the Okinawa woodpecker is in a large *C.seiboldii* (local name: Itaji) and the old-growth of *Q.miyagii* (local name: Okinawa urajirogashi) is a home for the endangered species of the long-arm beetles (Takeshi 2009).

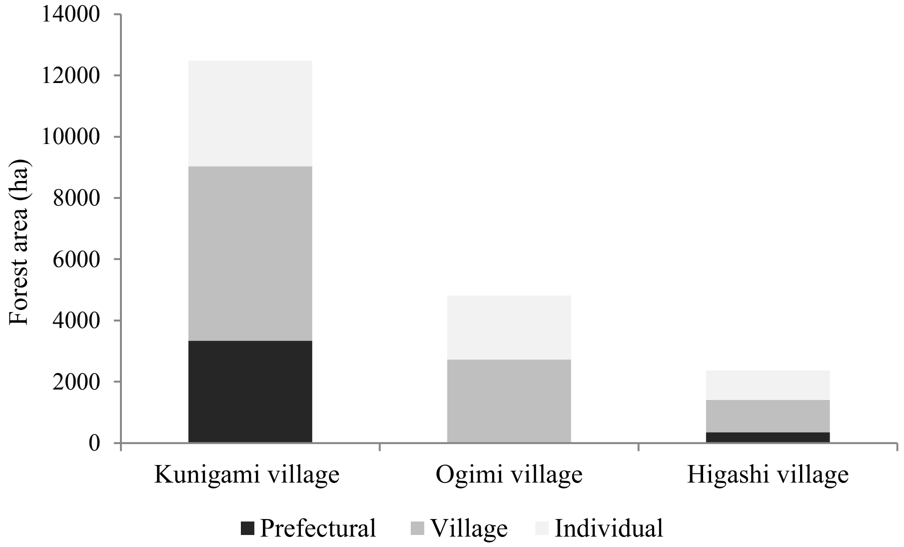

Figure 2-2. Forest ownership of each village in Yambaru Forest area
(Source: Okinawa Forest and Forestry Report, published in 2013)

The Yambaru Forest provides multiple forest functions and services, including biological conservation, timber production, education, recreation and eco-tourism. It also provide the main watershed area in which major dams are located that supply water to the south and central regions of Okinawa Main Island (Okinawa Development Agency 2003). Forestry-related activities such as timber production provide the primary source of income for local communities and play a major role in economic development. **Figure 2-3** shows the historical data concerning the local timber production from Okinawa forest areas. In addition, certain forest areas were conserved in order to preserve the historical and traditional value.

The remarkable forest functions offered by the Yambaru Forest led to the nomination of the forest as a candidate for a UNESCO Natural World Heritage site in 2012 (Ryukyu Shimpo 2013). For that reason, any forest-related activity in or adjacent to the forest area should pay attention to the forest and nature conservation, water and soil protection, as well as wildlife habitats.

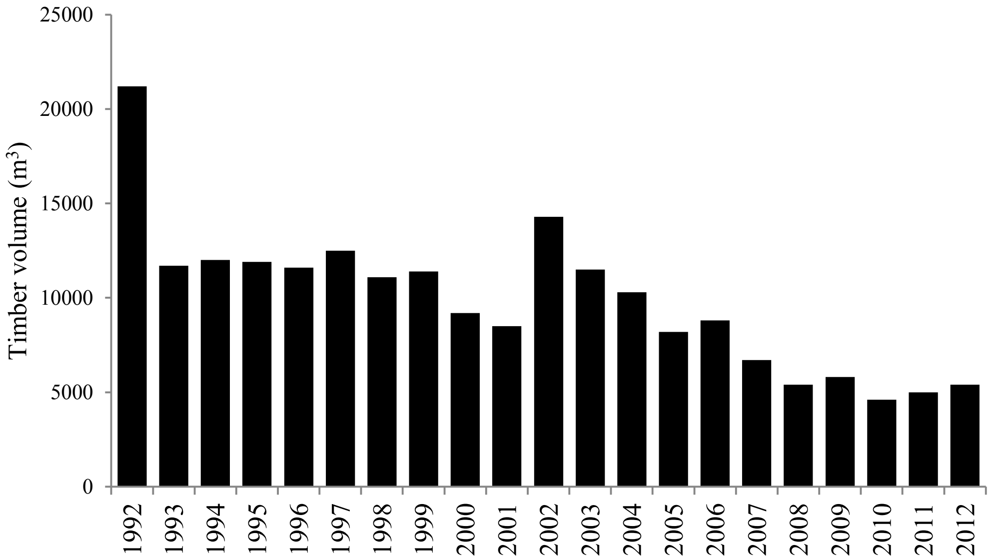

Figure 2-3. The historical data of domestic timber production in Okinawa Island
(Source: Okinawa Forest and Forestry Report, published in 2011)

2.1.2 Forest assessment and monitoring

Monitoring and assessment studies in Yambaru Forest have mainly conducted on the diversity of plants (Ito 1997; Kubota et al. 2005; Fujii et al. 2010), insect and wildlife (Ito et al. 1997; Winkler et al. 2005; Karasawa & Hijii 2006), forest stand structure (Feroz et al. 2006; Wu & Shinzato 2004; Xu et al. 2008), and litter decomposition (Xu & Hirata 2002; Xu et al. 2004; Xu & Hirata 2005). A detailed botanical assessment of the forest area commenced in 1987 (Niiro et al. 1988; Miyagi &

Shinjo 1989) with deficient information related to species diversity. According to Ito (1997), plant species diversity in Yambaru was strongly influenced by the vegetation at near-climax forest, aged more than 50 years. Further analysis showed that the forest diversity was also related to the distribution of under storey vegetation (Xu et al. 2001) and tree height distribution (Feroz et al. 2006), as well as the topographical conditions in maintaining the habitat heterogeneity of the forest (Enoki 2003 ; Kubota et al. 2004). Aforementioned studies were mostly carried out by ground survey and sampling in the permanent forest plots of the Yona Experimental Forest and the adjacent areas.

Study on forest monitoring using GIS and remote sensing data is very scarce in Yambaru Forest. Takashima et al. (2008) demonstrated that vegetation changes of the Yambaru Forest could be detected and monitored using the collections of aerial photographs along with GIS analysis approach. Another monitoring study was done by Saito (2011) to map the forest age distribution in Kunigami village. These are imperative examples of forest monitoring process using GIS and remote sensing technologies for a real-world solution in a practical and cost-effective methods.

Previous studies mostly focused on the plants, animal, environment and ecosystem of the Yambaru Forest. However, there has been little discussion about the LULC and vegetation structure of the forest through the integration of forest inventory and remote sensing analysis techniques. Precise information of forest assessment and monitoring are crucial for forest planning and management purposes. Therefore, in this chapter, forest vegetation structure – vertically (tree height) and horizontally (crown cover) – as well as LULC attributes were investigated to understand the dynamics of this forest.

2.2 Materials and methods

2.2.1 Vertical vegetation structure

The vertical vegetation structure of Yambaru Forest is assessed from the forest inventory data of twenty sample plots (Figure 2-4a). The survey was carried out in 2011 and 2013 using the National Forest Inventory (NFI) technique. The design of the NFI plot consists of three overlapping circle-shape subplots; namely, small, medium and large with different radii of 5.64 m, 11.28 m and 17.84 m, respectively (Figure 2-4b). In each plot, the topographical condition (slope, aspect, elevation), GPS location of central plot, distance to the nearest forest road and tree characteristics (tree height, dbh, species and condition of the tree) were measured. The minimum tree dbh measured in each subplot was different. For example, in the large plot, only trees with dbh more than 18 cm were measured. For the medium and small circles, the minimum dbh measured were >5 cm and >1 cm, respectively (Hirata et al. 2009).

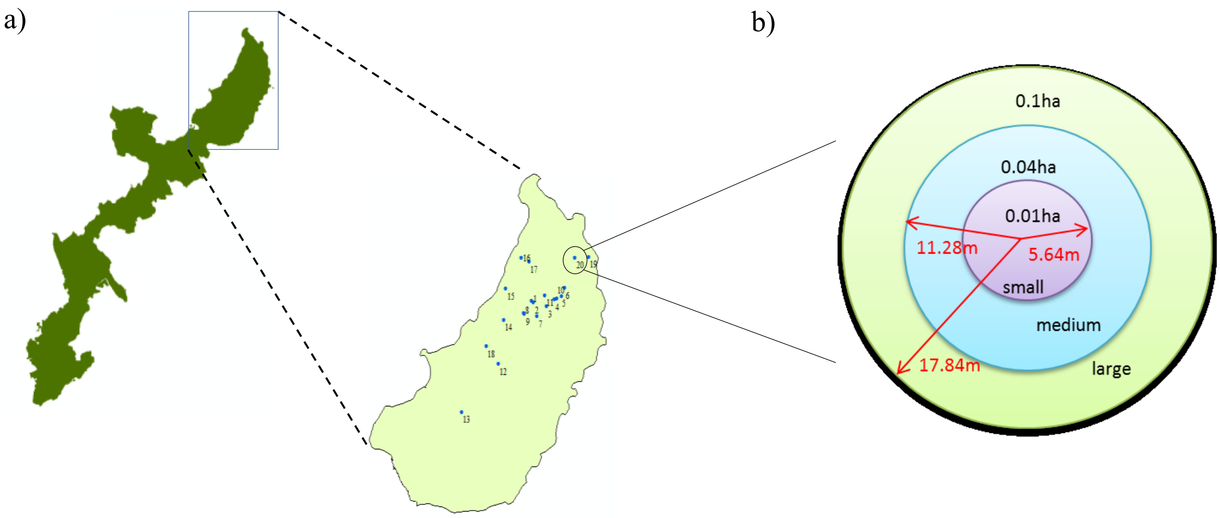

Figure 2-4. a) Twenty sample plots surveyed in the Yambaru Forest area using the NFI technique and b) the circular-pattern of inventory plot with different radii

Data were analysed statistically for vertical vegetation structure, species richness and diversity index (Simpson's, 1-D). Vertical structure or forest layer was examined by dividing tree height into four categories namely low, medium, high and very high. In each category, the diversity index was calculated.

Simpson's diversity index (1-D) was employed in this study to measure the diversity of the vertical forest structure. This index considers the number of species present in a community, as well as the relative abundance of each species (Magurran 2004). Therefore, as species richness and evenness increase, diversity will also increase. The diversity index is calculated as follows:

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

n = the number of individuals in a particular species

N = the total number of individuals

The value of D ranges between 0 and 1. The 0 value represents no diversity and 1 represents infinite diversity. This index was found to be more effective (Lande et al. 2000) than the species accumulation curve, and the utility of Simpson's diversity index was illustrated in a range of contexts including the studies by Ito (1997) and Azuma et al. (1997) in the Okinawa forest settings.

2.2.2 Upper-storey canopy structure

Conventional forest inventory practices require enormous effort, and cost both time- and money. Remote sensing and GIS technologies must be used to reduce such difficulties. A LiDAR for example, is able to capture information concerning the forest characteristics and is well known in estimating forest structure accurately (Fukushi et al. 2008; Pearson et al. 2004). In this study, object-based segmentation and classification techniques applied LiDAR data to delineate the upper-storey canopy in the 0.8 ha area located at Compartment 79 of Yambaru Forest (**Figure 2-5**).

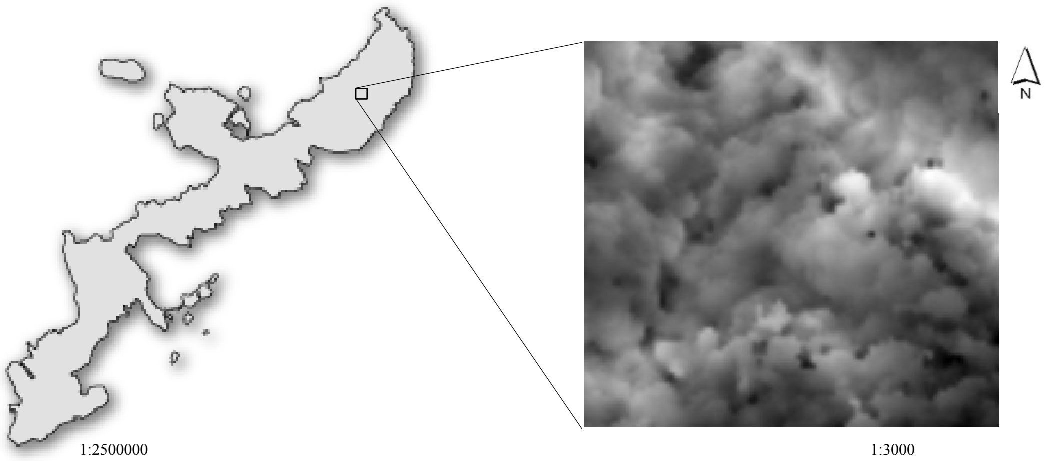

Figure 2-5. The location of study area at Compartment 79 of the Yambaru Forest and its LiDAR image

Raw LiDAR data observed by an Airborne Laser Scanner (ALS) were the primary data of this study. The data were provided in the forms of point clouds data, that contained elevation points with x, y, and z coordinate values, return pulse values, signal strength and intensity as well as GPS time. The data were obtained in April 2011 and flight characteristics are displayed in **Table 2-1**. In addition to LiDAR data, the ortho-photo image captured in October 2011 was also acquired as an additional reference data after the segmentation process. These images have a resolution of 0.5 m on the Japanese Plane Coordinate System and image projection referring to JGD 2000 Zone 15.

Table 2-1. Flight characteristics of the LiDAR data used in this study

Acquisition	25th April 2011
Instrument	ALTM 3100
Flight altitude	1100m
Wavelength	1064nm
Scan frequency	39Hz
Scan angle	±20º
X and Y accuracy	55cm
Z accuracy	15cm

Field survey was also carried out for ten 20m x 20m plots within the same compartment. The plots were located in various topographical conditions, with an elevations and slopes up to 323 m and 75 degrees, respectively. The measurements taken in each plot were tree dbh (> 4cm, at 1.3 m) using a dbh tape, tree height (m) using a measuring pole and the central position of each plot using a handheld GPS device model GARMIN 60CSx. The field data collection was undertaken between October 2011 and November 2012.

From the LiDAR data, the Digital Surface Model (DSM) and Digital Terrain Model (DTM) were derived by interpolation of the point clouds information. The DSM contains elevation information for all the natural terrain features, including vegetation and manmade features, such as buildings and roads. Whereas the DTM contains elevations information for land surfaces only. DSM was created from the pulse of the first return, while DTM was generated by interpolation of the TIN (Triangulated Irregular Network) data produced from the last return pulse of the ALS. Both types of elevation data were resampled to 0.5m mesh products and preprocessed by filtering and smoothing to remove noises. The Digital Canopy Height Model (DCHM), which indicates the height of ground structures and trees, was computed by subtracting DTM from DSM.

Two main steps were adopted to delineate the upper-storey of tree canopy from the LiDAR data: 1) data preparation, and 2) segmentation and classification, as shown in **Figure 2-6**. During the data preparation stage, smoothing and edge detection algorithms were applied prior to the computation of DCHM. It aimed to reduce noise and enhance the pixel edges in the image. This ensured canopy delineation, and the other procedures ran well with less noise influence. Gaussian kernel 3x3 was chosen for image filtering, while Lee sigma edge extraction was performed to allow easy interpretation of tree boundaries and detection of tree canopy edges.

Next, the segmentation process was done to merge the pixels into identical features of the image objects. The multi-resolution segmentation algorithm was used on the DCHM data, and the ortho-photo image was overlaid as a visual reference. In this process, the homogeneous pixels would produce larger objects, while the heterogenic pixels would create small regions of segmented objects based on the scale parameter chosen (Baatz et al. 2001).

In this study, six segmentation cases with different sets of parameters were tested using e-Cognition Developer7 software (**Table 2-2**). A scale parameter refers to an arbitrary value defined by users, whereby a larger value will result in larger image objects and vice versa. Defining the weight of the shape and compactness criterion were crucial parts in probing the best scale parameter for canopy delineation. A greater shape value indicates less influence of image colour (spectral similarity), which will result in less spectral homogeneity in object generation. The user can determine another two sub-criteria, namely, the compactness and smoothness factors under shape criteria. Objects can become fringed (compact) or smooth based on user selection. The values of both criteria range from 0 to 0.9 (Baatz & Schape 2000). It is a trial and error process in defining the best scale parameters to satisfy users and to suit the results to the real world. The coefficient of variation derived from the ratio of standard deviation and mean of segmented features was examined. The low coefficient of variation was selected as it defined that the data have little variability and high stability.

Table 2-2. Settings of the parameters prior to the segmentation process

Case number	Scale parameter	Shape	Color	Smoothness	Compactness
1	20	0.5	0.5	0.5	0.5
2	10	0.5	0.5	0.5	0.5
3	10	0.4	0.6	0.5	0.5
4	5	0.5	0.5	0.5	0.5
5	5	0.6	0.4	0.4	0.6
6	5	0.7	0.3	0.5	0.5

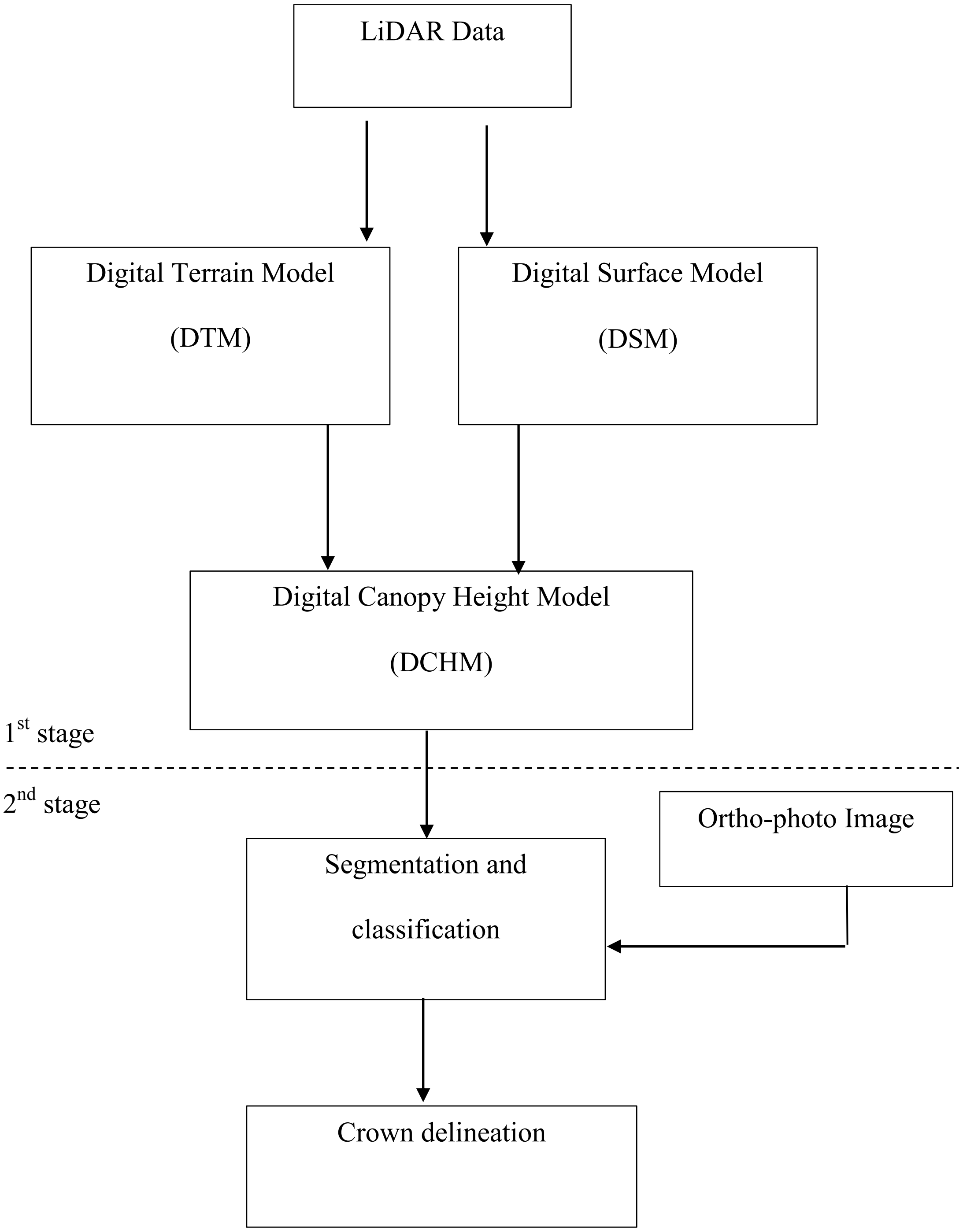

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Figure 2-6. The process of delineating forest canopy structure from the LiDAR data

The segmented image objects were classified into two classes – tree canopy and gaps. Objects with a DCHM value less than the threshold value of 5 m were classified as gaps while other objects were assigned as tree crown. The threshold value was derived from several trial and error steps to eliminate errors produced by the filtering process. After eliminating gaps and unwanted effects, the tree height in each polygon was assigned based on the maximum value using local-maxima algorithm function. Next, each crown was classified into three groups, namely: i) high (height >15m) ii) medium (between 10 and 15m) and ii) low (<10m), to distinguish the distribution of trees based on height. The objects classified as canopy were exported as a shape file (point and polygon) for further analysis in ArcGIS software by ESRI version 9.3. Data management and statistical analysis was performed using statistical package to examine agreement between the estimation of canopy cover by the segmentation process and the forest survey records.

2.2.3 Land use and land cover (LULC) attributes

The land use and land cover of Yambaru Forest were examined by selecting a sample plot located in a logged-over forest in the Kunigami municipality of Yambaru Forest. The total area of the study site was 23 ha, which encompassed a mixture of subtropical forest tree species and forest road networks (**Figure 2-7**). The topography of this area comprises a steep and rugged terrain with elevation ranging to approximately 250 m. The research sites consist of two timber harvesting units with the total harvested area of 5.98 ha, which was logged using the clear-cutting method in winter seasons of 2006 and 2007, respectively. The total harvested area and timber species are listed in **Table 2-3**.

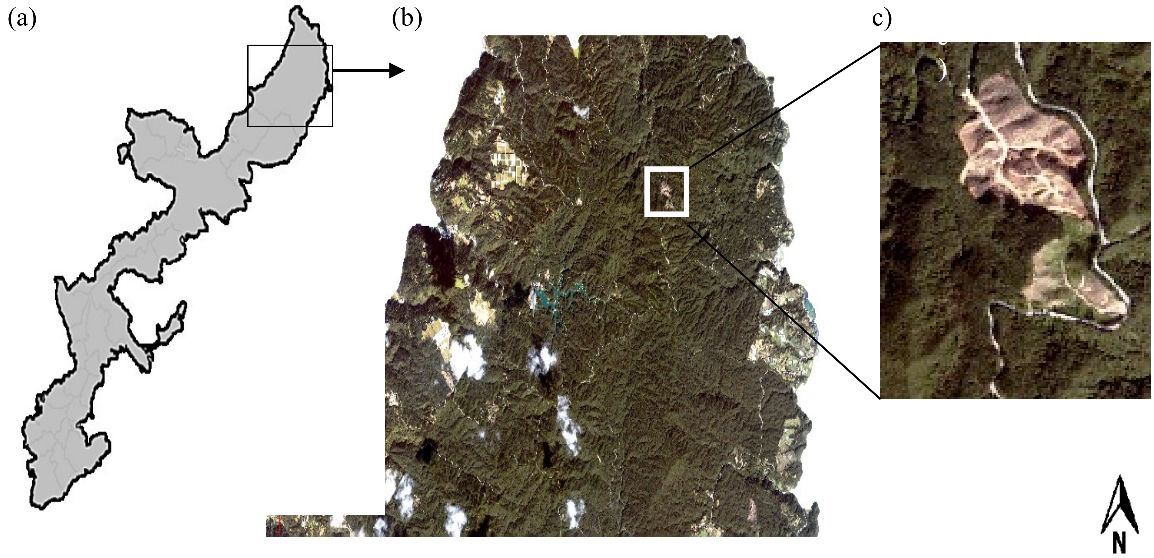


Figure 2-7. (a) Map of Okinawa Main Island showing (b) an IKONOS image of Yambaru Forest and (c) focused to the research site

Table 2-3. Tree species and total area harvested at the study site in 2006 and 2007

Harvested year	Area (ha)				Total harvested area (ha)
	S.wallichii	*D.racemosum*	*M.azedarach*	*C.camphora*	
2006	0	1	0.2	0.19	1.39
2007	2.27	1.2	0.92	0.2	4.59

High-resolution of multispectral IKONOS image was utilized in this study. The image was acquired on the 6th of February 2007 at 2:21 GMT with 1% cloud cover. It was in UTM projection, datum WGS-84 with 4 m resolution. The image was orthorectified by Japan Space Imaging (JSI) and interpolated by the cubic convolution method. Besides satellite data, forest inventory records of vegetation and species distribution, tree height and elevation of the defined area were obtained from the Forestry Department of Okinawa Prefecture. Accuracy assessments of both image classification methods were based on these datasets as well as a combination of independent interpretation of imagery and ground survey, which was conducted in December 2011 and February 2012.

Prior to the image classification, a Normalized Difference Vegetation Index (NDVI) was applied to the image data in order to monitor and measure the vegetation cover of the study area. This is a standard method for comparing the vegetation greenness of satellite imagery. The NDVI index value ranges from -1.0 to 1.0, the negative value indicates a non-vegetated area and higher index value are the indication of healthy vegetation cover. The NDVI is calculated by a ratio of (NIR-RED)/ (NIR+RED) bands (Mas 1999). In this study, the vegetation index of the area ranged from -0.77 to 0.43. The image was analysed using ENVI software package version 4.7 by ITT Visual Information Solution.

Next, the image classification was carried out using both pixel and object-based classification techniques to assess the LULC of the Yambaru Forest. The pixel-based or spectral oriented classification method is a traditional and leading approach provided by a variety of image analysis software. Although it classifies images based on statistical analysis of individual pixels, it is still an acceptable technique for classifying forest area, LULC and vegetation changes. In this study, the supervised classification by maximum-likelihood algorithm was adopted as it was a proven method that often produces the best results (Bhaskaran et al. 2010; Plantier et al. 2006).

The preceding classification method of pixel-based was compared to an object-based approach. This method was first introduced from Germany by Definien Imaging in e-Cognition software (Baatz & Schape 2000). The main concept of this method is to interpret an image by its meaningful object with its mutual relationships. It considers the spectral, form or shape, size, texture and context of an image in the classification process. Segmentation is the first and most important phase in which a homogenous image object is extracted from within the desired resolution at different scale parameters. A hierarchical network of the image object is created in which the upper level image segments represent a small scale object and vice versa. Based on the image objects, the problem of multisource data fusion is tackled by enabling parallel evaluation of image information of an arbitrary source. In this study, four levels of segmentation with different scale parameters were examined (**Table 2-4**). The characteristics of each parameter are described in Chapter II, subchapter 2.2.2 of this study. The segmentation phase is followed by the image classification process using the nearest neighbour algorithm. In recent years, the application and usage of object-based or polygon-oriented classification has increased as several studies have provided better classification accuracy compared to the traditional pixel-based classification method (Bakr et al. 2010). This approach considers both the spectral and spatial information of the texture and form of an image object extracted from segmentation analysis compared to the pixel-based approach that only classifies an image by a solitary pixel.

Table 2-4. Four levels of segmentation with different scale parameters tested in the study

Level	Scale Parameter	Shape and color	Smoothness and Compactness
1	10	0.2	0.5
2	20	0.2	0.5
3	30	0.2	0.5
4	40	0.2	0.5

Finally, the classification accuracy is done to define the agreement between the selected reference material and the classified data. In order to make a direct comparison between both classification methods, the accuracy is assessed in the same environment in which 400 pixels are randomly selected, and their agreement with ground truth are analysed.

2.3 Results and discussion

2.3.1 Vertical vegetation structure

A total of 2,877 trees from 74 species were discovered from the survey. *S.walichii* (local name: Ijyu) was the dominant species and the other subdominant species are presented in **Figure 2-8**. In general, the mean tree height and dbh were at 7.8±3.1 m and 10.4±7.1 cm, respectively. Based on the vertical measure, the trees were divided into four forest layers: i) very high (more than 15 m), ii) high (10 to 15 m) iii) middle (5 to 10m) and iv) low (less than 5 m). The number of individual trees, species and diversity index of each layer are presented in **Table 2-5**.

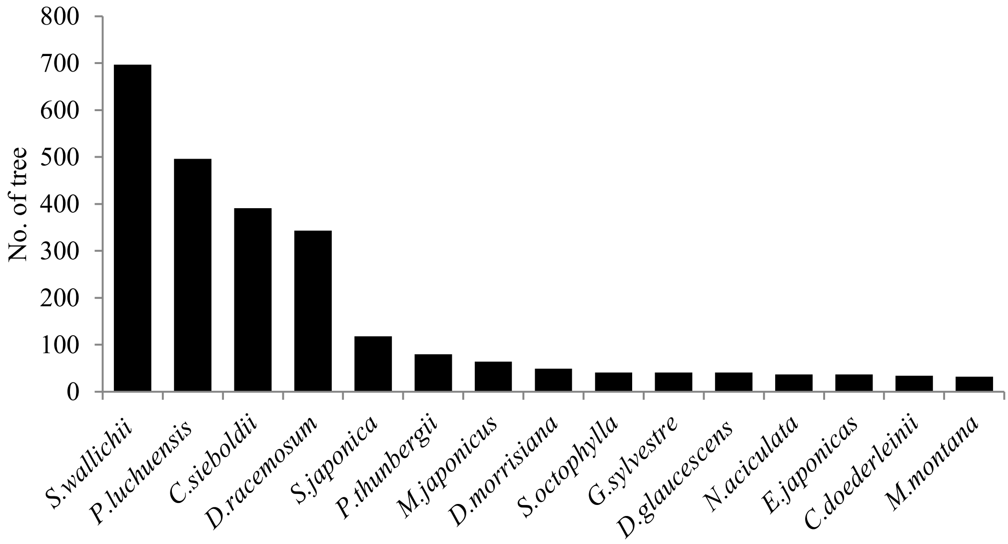


Figure 2-8. The distribution of fifteen main species found in the survey plots

From the analysis, tree density was found to be higher in the middle layer. However, highest diversity was contributed by the trees at the low layer. The results indicate the importance of conserving small trees in the forest because the high diversity of the area depends on the trees that are smaller in height. The high species diversity suggests that the area has high ecological niche availability, various interactions between populations and complex food webs with a favourable environment (Pears 2014).

Table 2-5. Vertical structure characteristics of all plots in the study area

Layer and height range (m)	Very high	High	Middle	Low
	$15.0 \geq TH$	$10.0 \leq TH < 15.0$	$5.0 \leq TH < 10.0$	$5.0 < TH$
No. of species	5	23	54	58
No. of tree	49	571	1711	546
Diversity index	0.2574	0.7072	0.8543	0.8967
Major tree	*P.luchuensis*	*C.sieboldii*	*S.walichii*	*D.racemosum*

The relationship between tree height and distance to the disturbance (forest road) was examined. **Figure 2-9** illustrates that trees grow higher when located farther away from forest roads, but the influence is too small. Additionally, when elevation factors were included, it indicated that at an altitude of 300 m, a stable forest ecosystem was expected as more successful species were found at this altitude (**Figure 2-10**).

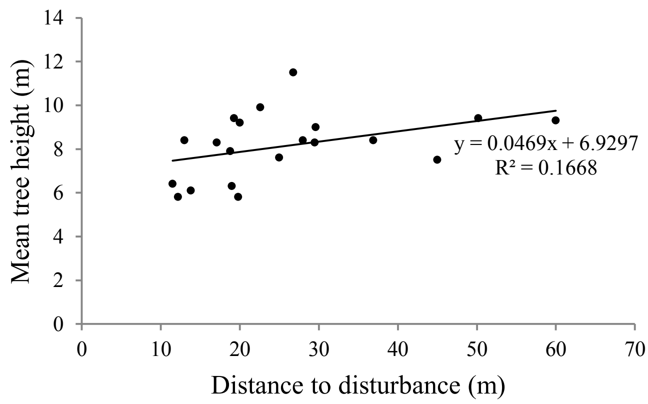


Figure 2-9. Relationship between tree height and distance to the disturbance factor(forest road)

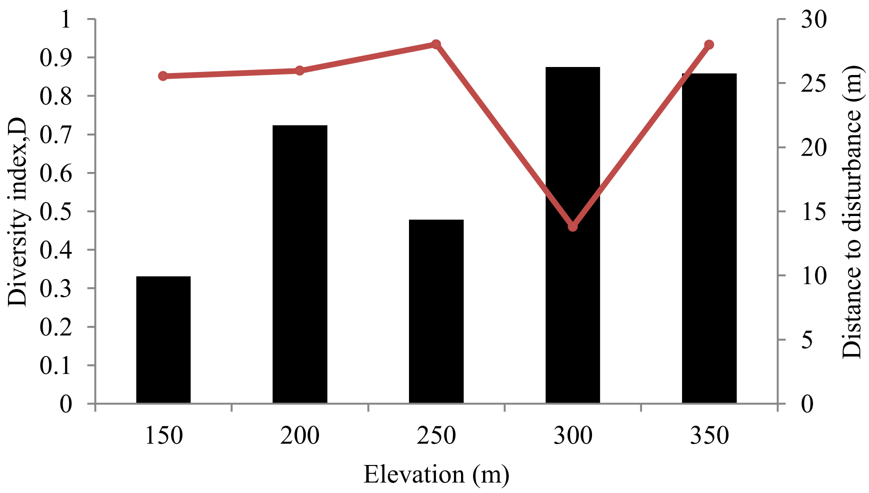


Figure 2-10. Species diversity was found to be higher at higher altitude and at a short distance to the disturbance factor

2.3.2 The upper-storey canopy structure

A total of 1,673 trees from 47 species were found in ten surveyed plots. In general, the tree height and mean dbh were at 7.2 m and 9.0 cm, respectively. The dominant and subdominant tree species are listed in **Table 2-6**. *C.sieboldii* was the main species found in the survey with a mean dbh and tree height of 13.6 cm and 8.2 m, respectively. Based on Shinzato et al. (1986), most of this species were located in the top layer of the forest, and trees at the upper layers mostly ranged from 39 to 41 years old. On the other hand, shrubs mostly occurred on the lower slopes of the forest.

For LiDAR data analysis, all segmentation cases were compared and the case number 6 was selected for further analysis as it yielded a lower coefficient of variation. A total of 1,130 segmented objects were successfully delineated from the LiDAR data with the minimum and maximum tree height of 8.1 m and 21.3 m, and minimum and maximum crown areas at 0.75 m^2 and 39.7m^2, respectively.

Table 2-6. Five main species recorded based on field survey data

Species	No. of tree/ha	Mean dbh (cm)	Mean height (m)
Castanopsis sieboldii	1008	13.6	8.2
Daphniphyllum glaucescens	543	7.8	6.4
Myrsine segunii	475	5.9	6.0
Syzigium buxifolium	335	5.4	5.3
Elaeocarpus japonicas	273	6.5	5.9

Agreement between field data and LiDAR analysis showed that only 33.7% of the upper canopy was successfully delineated. The result was not as expected, since the capability of LiDAR is well recognized to detect individual trees with a greater percentage of accuracy (Persson et al. 2004; Chen et al. 2006 ; Fukushi et al. 2008).

However, the main point of this study is that we would like to highlight the limitations or constraints of utilizing LiDAR data in the very complex topography and vegetation conditions of the subtropical forest in Okinawa Island.

There have been studies that successfully achieved an accuracy level of more than 80% individual tree detection using LiDAR data, particularly in plantation and coniferous forest (Wang et al. 2004; Fukushi et al. 2008). Persson et al. (2004) discovered 71% of real tree numbers of spruce and pine in Sweden, while Chen et al. (2006) achieved 64.1% of absolute accuracy when isolating the tree canopy in an area of savannah.

A high accuracy of canopy delineation in a complex subtropical or tropical forest is unlikely. In the mixed broadleaved forest of Yambaru, species ecology is the main reason for the unsuccessful detection of the canopy cover with high accuracy. *C.sieboldii* is a major broadleaved species dominating Yambaru forest and is characterized by natural sprouting regeneration (Shinzato et al. 2000). As 84% of the species sprouted from the main stumps of trees and developed into multiple branches rather than a single stand (Wu et al. 2001), the multi-stem trees have overlapping canopies, which will be recognized as a single canopy by LiDAR. In addition, tree density is also another factor triggering crown overlap. In this area, vegetation density was considerably high (4500/ha) and trees were found standing close to each other. Therefore, in our analysis, most overlapping canopies were segmented as a single stem with a larger crown area during the segmentation process.

Topography is another issue influencing canopy delineation in Yambaru forest. In the study area, the elevation varied from 115 to 176 m. However, even though it was located in rugged terrain, the elevation did not vary excessively. Neighbouring trees growing at the same slope and elevation compete for light and the same nutrients. The availability of energy has resulted in the coexistence of more tree species, hence increasing species richness and species equitability (Xu et al. 2008). When the competition rate is high in dense vegetation areas, trees may grow about the same height and will again increase the incidence of overlapping canopies, which causes several trees to be grouped into a single stem in the segmentation process.

The subtropical evergreen forest of Yambaru consists of a complex environment, with rich vegetation, rugged terrain, and different soil types; hence, not all the variables can be measured accurately by LiDAR. The agreement between the segmentation and field data was unsuccessful and yielded a lower level of accuracy compared to other studies on plantations or coniferous forests. However, a significant finding from Pitkanen et al. (2004) was reflected in our case study, in that he revealed that even though 70% of dominant trees could be distinguished perfectly, only 40% of individual crown delineation of heterogeneous forest could be detected. Trees with a height of less than 40% to 60% of the dominant species were concealed due to indeterminate tree conditions (Korpela 2004). Bias towards larger trees, underestimation of understorey trees, overestimation of individual canopy and merging of small tree crowns into a single big tree were the main factors in achieving low precision in the canopy detection of heterogeneous forest (Asner et al. 2002).

Laser scanning is the most remarkable technology for automated forest inventory and gives a quite accurate estimation of forest structure, including crown size and tree height (Imai et al. 2004; Nǣsset 2004; Hyyppa et al. 2001). However, in this study further improvement is needed, such as not only utilizing a single LiDAR data, but also integrating other high-resolution data (e.g. IKONOS or QuickBird) to enhance the accuracy level as well as applying improved technical methods for a more reliable outcome.

2.3.3 Land use and land cover (LULC) attribute

Both classification methods detected four land cover types: Forest 1, Forest 2, bare area and forest road (**Figure 2-11**). **Table 2-7** shows the accuracy of the results for both classification methods tested. The pixel-based classification showed a greater accuracy and Kappa Coefficient value compared to the object-based classification technique with 83.7% and 0.79 respectively. The assessment of the ground survey and reference data designated Forest 1 as *C.sieboldeii* forest and Forest 2 was recognized as a mixed broadleaved forest.

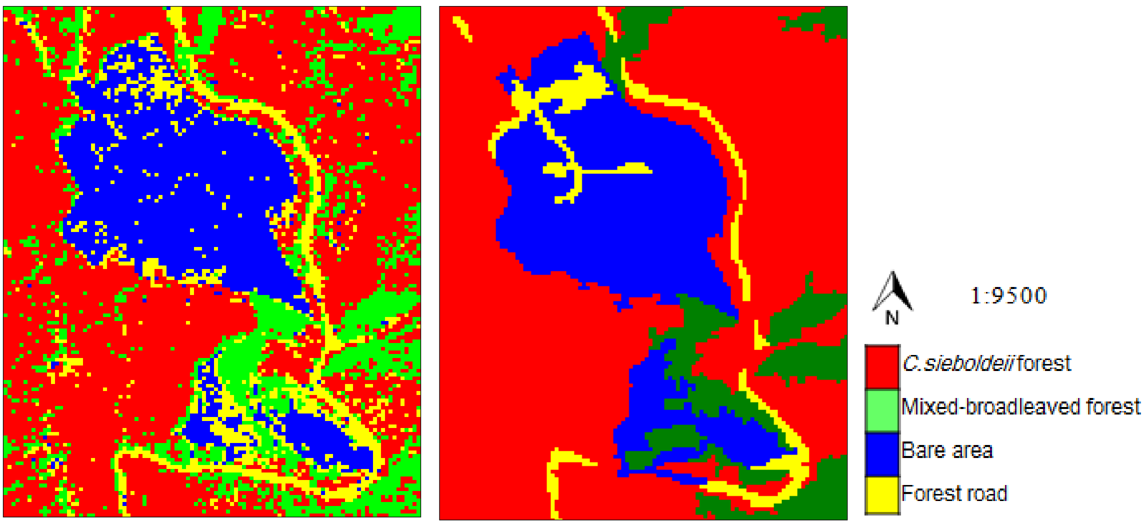


Figure 2-11. Four categories of land cover attributes classified using pixel-based (left) and object-based (right) method

Table 2-7. The accuracy results for pixel-based and object-based classification methods

Classification Method	Pixel-based		Object-based	
Class Type	Producer's Accuracy (%)	User's Accuracy (%)	Producer's Accuracy (%)	User's Accuracy (%)
Forest 1	87.8	83.7	89.2	91.7
Forest 2	80.0	85.9	79.3	92.0
Bare area	82.1	92.0	85.7	68.6
Forest road	84.4	80.2	70.4	76.0
Overall accuracy	83.7		81.3	
Kappa coefficient	0.79		0.76	

Four levels of segmentation were delineated from the defined scale parameters in the object-based classification method (**Figure 2-12**) and details of the statistical output are presented in **Table 2-8**. From the levels tested, level 3 showed the most suitable classification for land cover type detection compared to the other levels. The total overall accuracy and Kappa coefficient using this method were 81.3% and 0.76, respectively.

In general, the pixel-based approach gave a more accurate result as the average vector and covariance matrices were estimated with the highest accuracy. The *C.sieboldeii* forest covered about 51.8% of the total study area while 16.6% was detected as mixed broadleaf forest. Forest roads and the bare area were found to be 11.2% and 20.4% of the total study area, respectively. Compared to the previous data of timber harvesting held in 2006 and 2007, a decline of 21.5% of bare area was found in this study. This condition explains the effect of silviculture treatment by replanting after previous harvesting period in that the planted trees were well nurtured after only 5 to 6 years of replantation.

Both classification techniques showed satisfactory and good accuracy assessment with only small differences in Kappa values. The spectral classification approach by maximum-likelihood algorithm considers each pixel to be classified without any single pixel left behind. It quantitatively evaluates both variance and covariance of the category spectral response pattern when classifying an unknown pixel. Therefore, a salt-and-paper image output was detected, particularly in the forest road classification with some scattered pixels. In addition, within this method, significant information concerning individual patches of vegetation class distribution as well as vegetation density were visibly detected.

The compactness of the image segmentation process is based on a class hierarchy system, which is a key factor influencing the scale parameter in object-based analysis. In addition, the classification characteristics of the segmented object consider both spectral properties and the relationship among the objects. This approach therefore resulted in noticeably segmented objects in the forest road classes where small trails in the middle of the clear-cut area were clearly classified. In the previous harvesting period, these small trails or forest roads were used as a route for logging machinery and to transport timber from the forest towards the main road. The management of forest area relies on detailed information and updated knowledge of their nature and distribution. Therefore, exploration, utilization and application of the latest and novel technologies, such as GIS and remote sensing technique are essential to enhance the forest management system. In Okinawa, the forest inventory data of timber harvesting is frequently updated involving pre (before), post (after) and during the operation period. The monitoring of forest recovery through remote sensing technology, of the problems or pitfalls that occur between these gaps could be solved using good quality image data and suitable analysis methods. Together with a good interpretation of the

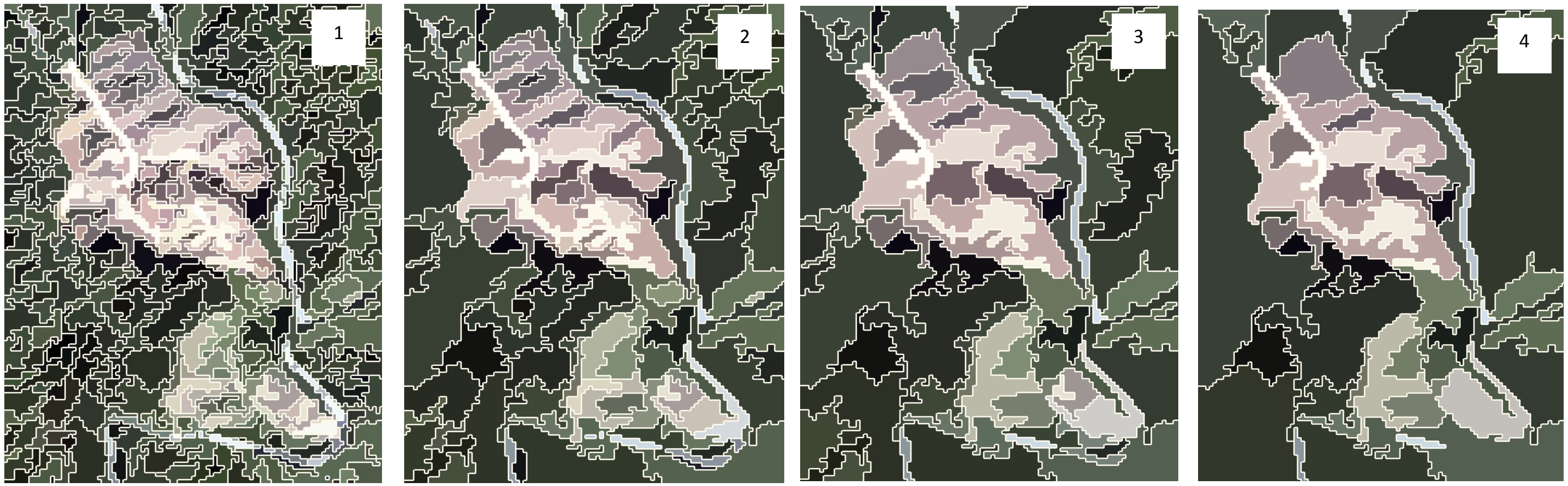


Figure 2-12. Four levels of segmentation results delineated from the defined scale parameters in the object-based classification method

Table 2-8. Statistical output including number of polygons and areas produced from the four levels of segmentation

Level	1	2	3	4
Number of polygons	1377	340	165	109
Min area (m^2)	10.04	20.15	30.59	40.06
Max area (m^2)	102.64	163.45	2087.22	240.33
Mean	23.14	48.17	68.75	83.62
Standard deviation	12.01	23.02	32.04	52.08
Coefficient of variation (%)	51.90	47.80	46.60	62.28

classification results and forestry knowledge, this process helps forest stakeholders to save cost and time for forest monitoring compared to the traditional inventory practices for an efficient and improved forest management system.

Many studies have proven that the output from the image classification method from VHR image data is applicable and practical for use in forestry. Plantier et al. (2006) adopted several classification techniques for IKONOS images to obtain an overview of forest cover characterization in Portugal. In Japan, the investigation of an object-based classification process using VHR images was undertaken by Shiba and Itaya (2011) on forest land use structure to assess the environmental change in the Mie prefecture. Yuan and Bauer (2006) demonstrated the effectiveness of the object-based classification with per pixel maximum likelihood classification using QuickBird images for classification of urban areas in Minnesota. Their study showed that via VHR data, the LULC detected by object based approach in impervious surfaces yield a higher accuracy.

High-resolution data are crucial to assist further works in sample collection, identification and image classification. In this study, the author only applied a 4m resolution of IKONOS image for both classification processes. In future, alternative methods, such as using an automatic image fusion called the pan-sharpened algorithm, which could be derived from a combination of 1m panchromatic and multi-spectral (colour) images, could be used to increase image resolution. A hybrid method integrating pixel-based and polygon-based analysis (Shiba & Itaya 2011) is another prospective approach to enhance the monitoring and management strategy of Yambaru forest area. Hence, the use of LiDAR data and aerial photo image would also help to improve the classification results (Shettigara 1991) as well as the geomorphology data that would be taken into consideration to obtain sound and outstanding output in forthcoming research.

2.4 Conclusion

The subtropical evergreen forest of Yambaru consists of complex vegetation and topographic conditions. The vertical structure of the forest was studied concerning the diversity in different tree height classes. *S.wallichii* was the dominant broadleaved species with a mean tree height and dbh of 7.8m and 10.4cm, respectively. Trees less than 5 m in height strongly influenced forest diversity, whereas major broadleaved trees were found concentrated in the middle layer. The high diversity index showed that the areas comprise of successful species with a stable ecosystem and vice versa. It might be due to the forest gaps that give great chances for regeneration of the pioneer species. In this study, elevation and distance to disturbance has less influence to the distribution of the broadleaved trees.

The upper-storey of broadleaved trees delineated from LiDAR data analysis revealed that only 33.7% of the canopy was successfully detected. In Yambaru, the difficulty in attaining a high accuracy of canopy delineation was due to the differences in tree structures, forest density and topographical conditions of the area. Trees with multiple stems that grow close to each other lead to canopy overlapping. In the segmentation process, these incidents were the main factors that reduced the level of accuracy of canopy delineation by LiDAR data.

Land cover attributes in logged-over forest areas produced by a pixel-based approach yielded higher accuracy than object-based classification methods. Four forest land attributes were detected, namely, *C.sieboldeii* forest, mixed broadleaved forest, bare area and forest road. Post-harvest silvicultural treatment resulted in the declination of bare areas at the study site. Detailed interpretation of the results is important to discover any problems that occur in a specific area and to find the best solution in future. The use of GIS and remote sensing in this study is suggested as an alternative and effective approach to understand the forests condition as well as to improve the monitoring system of Okinawa forest management.

Chapter III

Forest Zonation for Conservation Area

3.1 Introduction

In this chapter, the forest zonal scheme based on elevation gradients is assessed. It focuses on evaluating the Potential Conservation Areas (PCAs) in Yambaru Forest considering factors, such as area availability, forest ownership, water resource areas, forest access roads, forest vegetation, wildlife sanctuary and protected prefectural parks.

Forests for social, environment and economic use are a controversial issue that requires strategic management (Zhang 2005). To satisfy public demand for various environmental values, forest zonation is suggested to be a powerful tool to balance between biological conservation and forest utilization. By dividing the forest area into a number of zones in respect of the priority uses, this management system was effectively reviewed (Zhang 2005 ; MacLean et al. 2008).

Conservation is related to biodiversity. Biodiversity in many studies changes with elevation. In this study, conservation priority areas based on altitude and associated factors was scrutinized. Elevation gradients hold enormous potential to understand the factors underlying the global biodiversity (McCain 2010), as different elevation gradients consist of different environmental characteristics. Among the pioneers who studied how the natural world changes with elevation are Wallace and von Humboldt (Lomolino 2001). Forest composition, functional processes, climate and habitats were structurally changed along elevation gradients (Barry 2008; Romdal & Grtynes 2007). Precipitation and solar radiation increased, conversely air temperature and air pressure decreased with an increase in altitude (Barry 2008). Generally, species richness peaks at mid-elevation depending on the species and study area (McCain 2007) and it rarely increases with elevation (Grytnes & McCain 2007).

In recognition of the importance of elevation for site selection, the parameter was adopted to evaluate the PCAs in Yambaru Forest. **Figure 3-1** shows the general terrain conditions in the Yambaru area. The highest peak is 502 m and consists of complex landform characteristics. Agricultural activities are located on the flat area near to the water resources. Dams were constructed at elevations of less than 200 m and timber harvesting normally takes place at the average elevation range from 150 to 250 m to reduce the impact of logging and to preserve wildlife habitats (Okinawa Development Agency 2003).

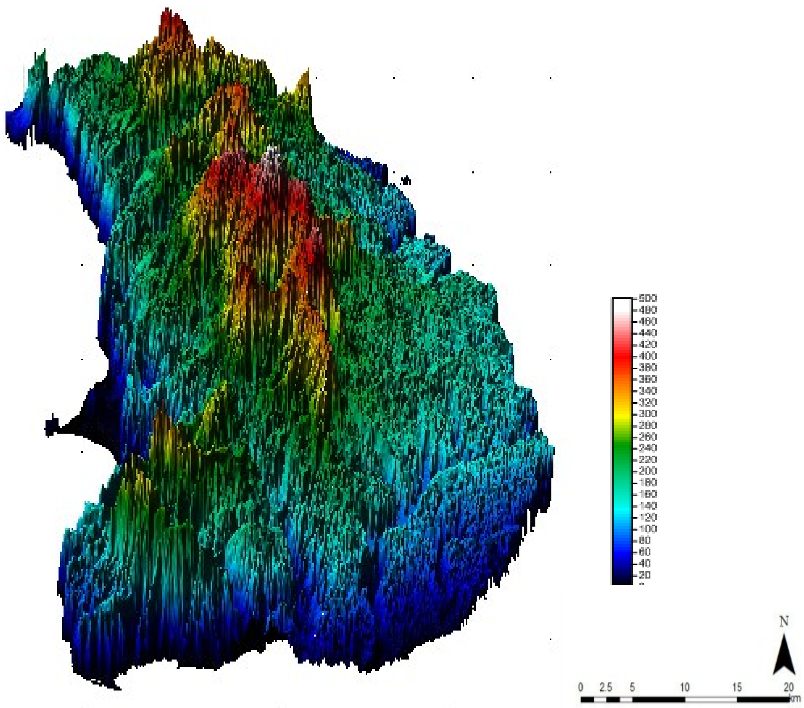


Figure 3-1. The general terrain condition in Yambaru area with the highest peak of 502m

Conserving the whole Yambaru area is impossible due to the multiple forest uses especially for community that utilize the forests for living. Therefore, zoning was suggested as a strategic management plan to balance between forest utilization and protection purposes. However, previous studies in Yambaru paid little attention to the zonation function in the forest management system. Selecting a suitable conservation priority area is a complex and challenging process, particularly in defining practical parameters for site selection. To tackle this issue, the elevation gradient was used to describe the best site selection for conservation priority.

3.2 Materials and methods

3.2.1 Study area

The Yambaru area starting from the Shioya-Taira (S-T) line was selected for the analysis (**Figure 3-2**). The area encompasses of abundant forest with diverse wildlife and subtropical vegetation from natural and artificial forest. *C.sieboildii* and *S.walichii* were the major tree species (Takeshi 2009; Enoki 2003). Topographical condition of the study area was characterized by a rugged terrain with maximum elevation of 502 m, located at the Yonaha Mountain. Precipitation in this area was found to be higher ranging from 1,900 to 4,000 mm $year^{-1}$, compared to the South part of Okinawa Main Island. The mean monthly temperature is 19 to 22ºC and the mean temperature of the coldest month (January) and warmest month (July) are 14.2ºC and 27.3ºC, respectively (Japan Meteorological Agency; retrieved on December 2013). Typhoons are frequently hit the area between July and October, and the prevailing wind direction blow from the northeast in winter and from the southeast in summer. The bedrock is composed of Palaeozoic clay-slate and tertiary sandstone, and red yellow forest soil (Kojima 1980).

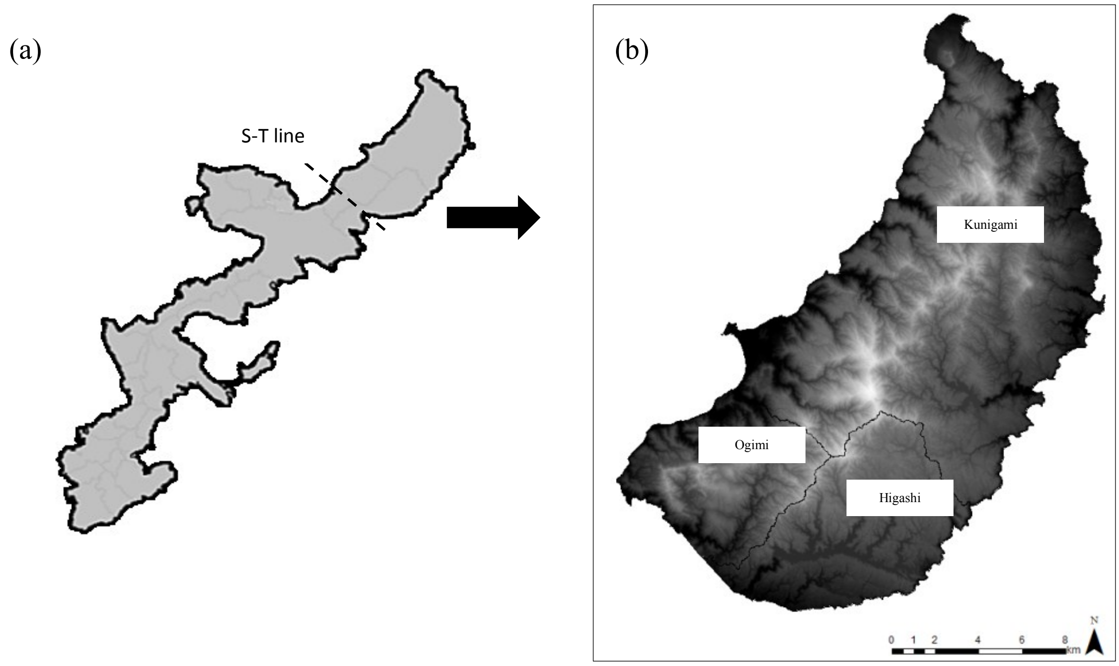


Figure 3-2 (a) The Okinawa Main Island map showing the selected study area (starting from the S-T line) which is located at the northernmost part of the island and (b) the area encompasses of three neighbouring villages named Kunigami, Ogimi and Higashi.

3.2.2 Data processing and analysis

Elevation is the fundamental measurement to create terrain data. The single band raster dataset of Digital Terrain Model (DTM) with 10x10 m resolution supported by the Geospatial Information Authority of Japan was fully utilized in this study. The data contained 2,357 rows and 2,814 columns, covering an approximate area of 30,000 ha.

The pre-processing of the terrain data was done prior to the analysis. Data smoothing by image filtering using a 5x5 low pass filter was applied to the data. The low pass filter replaces a pixel value with the average value of the adjacent pixels. It was applied to reduce the jagged effect that causes problems when identifying topographic features and minimize the noise of the data. Then, the kriging interpolation method was applied to fill holes that represent the no-data pixel of the terrain data (Grohman et al. 2006).

From the digital terrain data, secondary products of contour lines, topographic features, channels and flow directions were produced using spatial analysis and hydrology tools in ArcGIS v10.0. Forest vegetation analysis and tree height were calculated to explain the condition of the sites. This was derived from the subtraction of the DTM from the DSM values using a similar method for the DCHM creation in Chapter II, subsection 2.2.2 of this thesis. Besides the terrain data, supplementary data including the boundary information of forest landowners, maps of protected areas and forest road data collected from various authorities were employed in the study. All maps were in a similar projection format of UTM Zone 52N, datum JGD 2000 for a standard area calculation.

After the pre-processing of the terrain data, contour lines ranging from 50 to 350 m with 50 m intervals were delineated. Using pixel count, the area of each contour gradient was calculated. The elevation gradients were divided into three categories namely; low (50 to 150m), intermediate (200 to 250m) and high (300 to 350m). The boundary data of the neighbouring village, forest ownership, protected parks as well as vegetation and forest networks were overlaid with the contour map and the influence of each factor was examined to choose the ideal elevation category for the PCAs in the Yambaru Forest. **Figure 3-3** briefly showed the flow of the study.

In addition, the PCAs in selected elevation gradients were compared with the forest management and planning map by the DAFF of Okinawa Prefecture. The map was published in 2012 for a 10-year forest planning report which is freely available at the Okinawa Prefecture's website. **Figure 3-4** shows the management map of the northern area which has been classified based on forest functions. The map divided Yambaru area into four main categories: i) production areas (with and without considering environmental factors), ii) water conservation areas, iii) The U.S. military sites, and iv) conservation sites (core and buffer area).

In this study, GIS software of ArcGIS v10.0 (including ArcTool and ArcCatalog) and Surfer10, were utilized as a tool to analyse maps and the DTM data. Data management and statistical analysis was completed using Microsoft Excel and statistical package software.

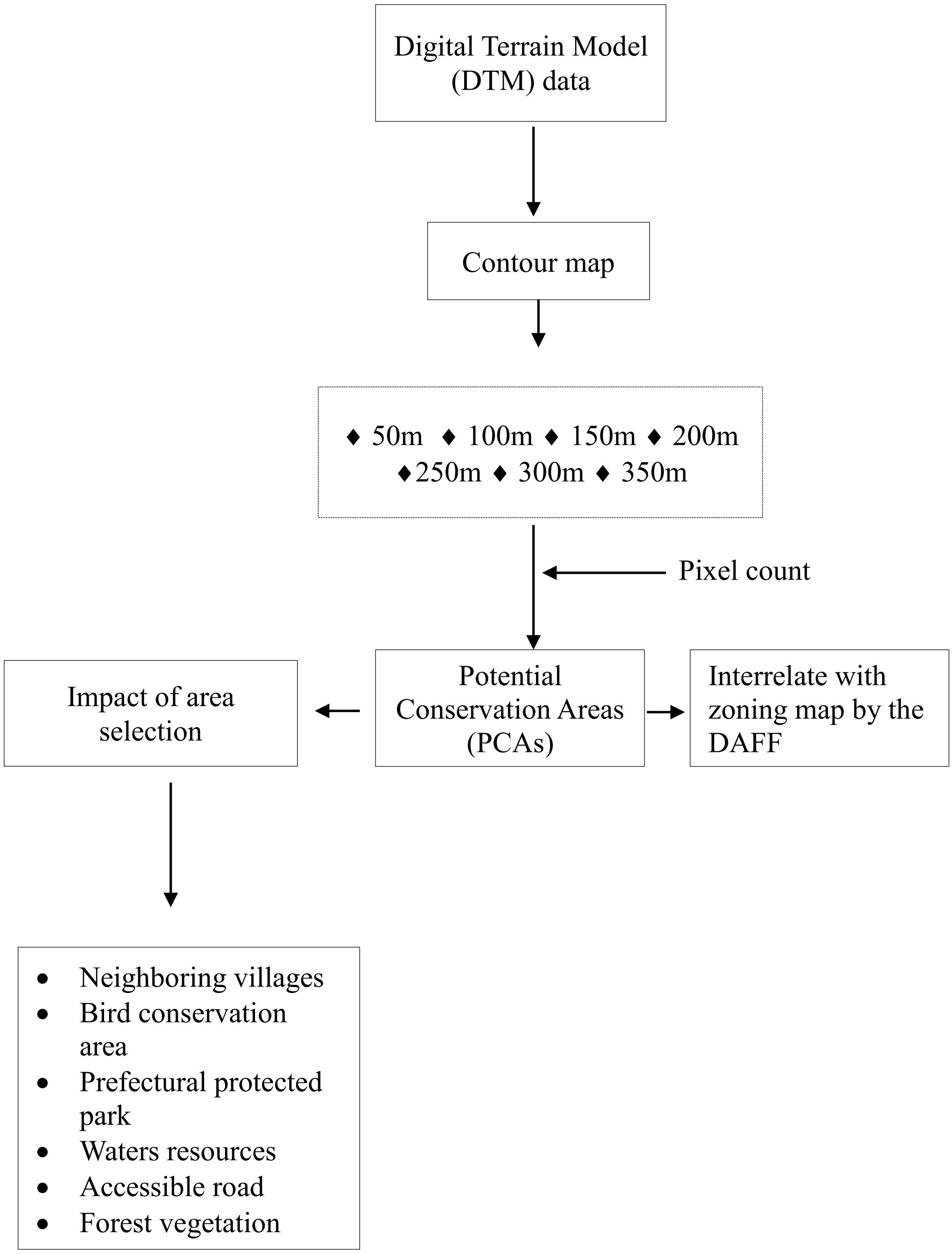


Figure 3-3. The process of delineating Potential Conservation Areas (PCAs) from the DTM data in the study area

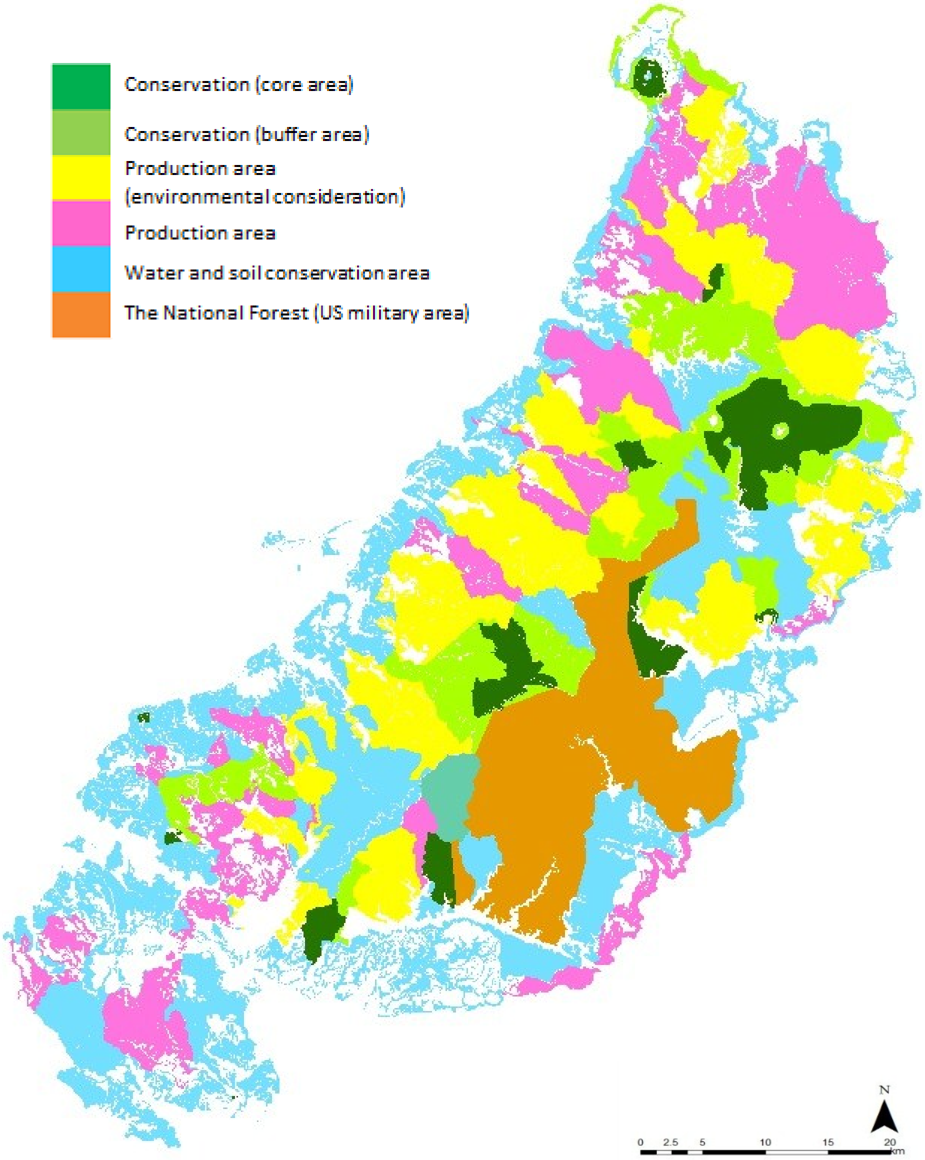


Figure 3-4. The management planning map by the DAFF of Okinawa Prefecture of the entire Yambaru area. The area was zoned for forest conservation (18%), water and soil conservation (32%), timber production (37%) and the U.S training site (13%).

(Source: Okinawa Forest and Forestry Report, published in 2012)

3.3 Results and discussion

3.3.1 The Potential Conservation Areas (PCAs)

The area available for conservation in the Yambaru Forest decreased with an increase in elevation (**Figure 3-5**). The elevation gradients were then divided into three categories, namely i) low (50-150m), ii) intermediate (200-250m) and iii) high elevation (300-350m). **Figure 3-6** shows the proportion of the area in each category. The low category of elevation produced a huge PCAs, which included most of the settlement areas and agricultural lands. Only small PCAs were included within the high elevation category, which appeared to have several patches of separated forest regions. The intermediate elevation category, which ranged from 200 to 250 m contains the optimum PCAs for consideration. The areas are linked as a corridor that connects between the forests in the different villages.

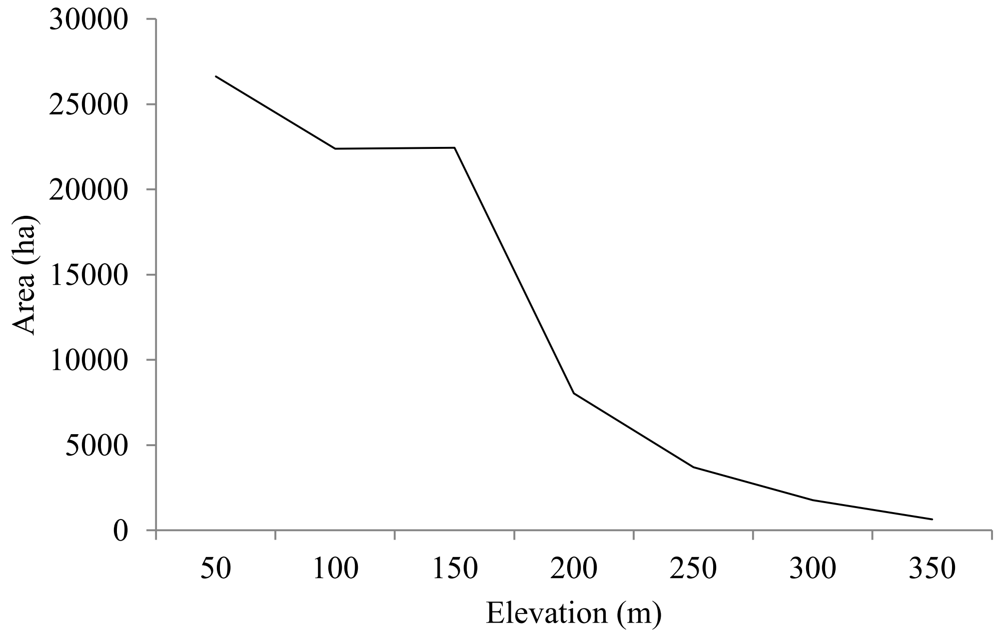


Figure 3-5. Area availability for PCAs at different elevation gradients

Conservation sites require areas that are neither too big nor too small. If the area selected for protection is too big, it may cause a huge obstacle to the community that depends mainly on the forest for a living, e.g. prohibition of timber production restricts the source of income. If the area is too small, it is unsatisfactory in providing habitat for wildlife and vegetation conservation. An intermediate level or middle peak elevation areas provide an optimal condition, which potential area for protection could withstand both natural conservation and timber production. Therefore, in this study focus was given to the intermediate elevation gradient for further inspection.

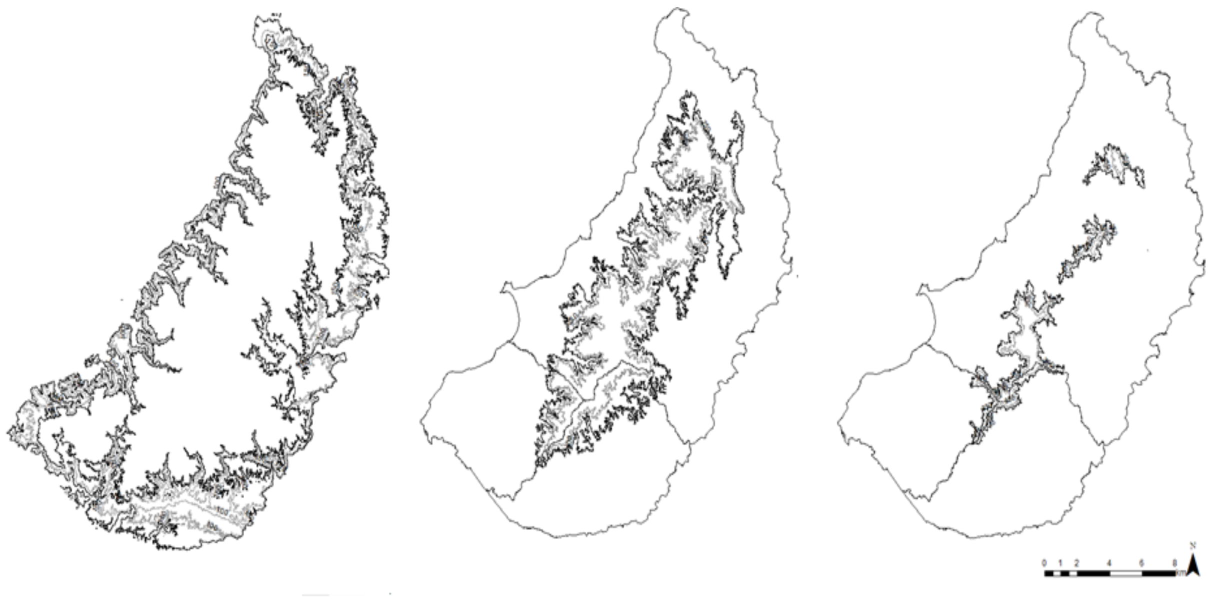
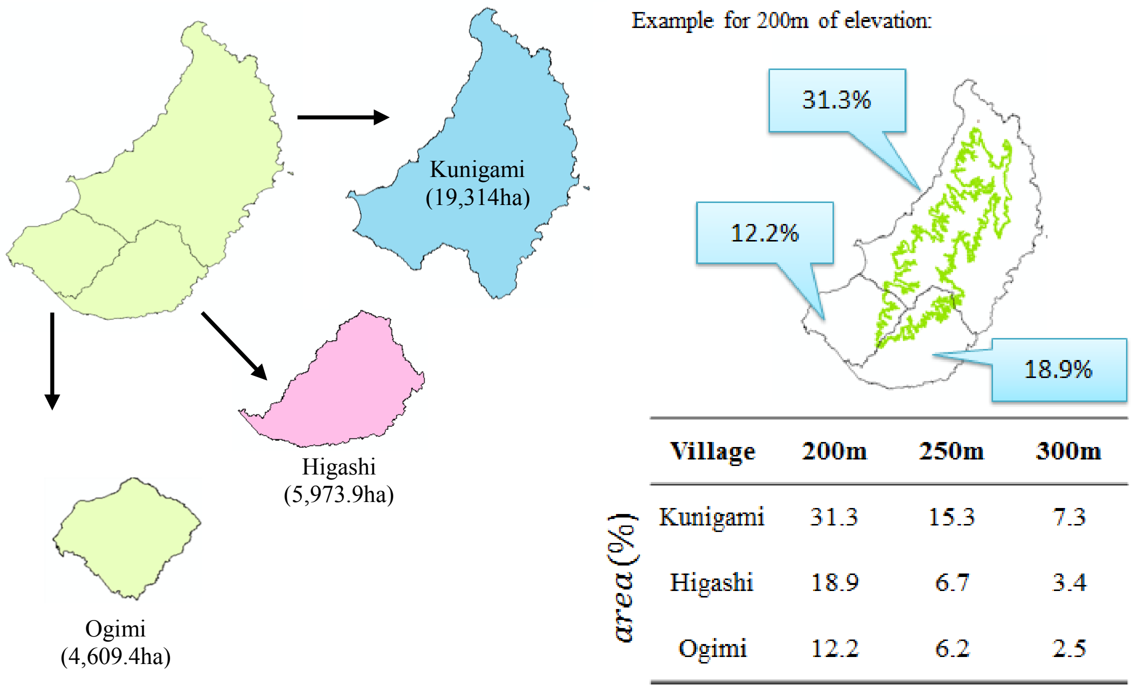


Figure 3-6. The proportion of the PCAs from three categories of elevation level. From left: low (50-150m), intermediate (200-250m) and high (300-350m)

3.3.2 Influence of PCAs on various factors

The site selection for conservation should consider both qualitative and quantitative factors. Quantitative refers to the amount of the available area, while the other one denotes the value of the area. In this study, site quality factors including forest ownership, accessible road, designated protected parks and forest vegetation at the intermediate elevation gradient were analysed.

There are three neighbouring villages located in the study area – Kunigami, Ogimi and Higashi – with an area of 19,314 ha, 4,609.4 ha and 5,973.9 ha, respectively. The higher elevation was mostly located at the Kunigami village. Therefore, Kunigami village would be the biggest contributor for the PCAs compared to the other villages. **Figure 3-7** illustrated the PCAs covered by each village between 200 to 300 m of elevation. For example, at 200 m of elevation, Kunigami village contributed 31% of the village area for a conservation site while Higashi and Ogimi contributed 19% and 12%, respectively.



Village	200m	250m	300m
Kunigami	31.3	15.3	7.3
Higashi	18.9	6.7	3.4
Ogimi	12.2	6.2	2.5

Figure 3-7. Area contributed of each village at different elevation gradients with an example of PCAs at elevation of 200m

Various landowners exist in the study area as illustrated in **Figure 3-8**. At the intermediate elevation level, the village or municipality forests hold the largest area of 13,639.6 ha, followed by the National, individuals and prefectural forests, as presented in **Table 3-1**. Zoning confers an interest in each asset of the landowner to those who control the political power of the locality (Fischel 2000). This factor is highlighted because if the zonation plan for conservation is to be formalized, support from the landowners is a crucial factor that greatly influences the smoothness of the zoning process especially participation from the forests owned by the village and individuals.

Forest managers have their own management goals and hardly attentive on the importance of conservation or protection areas, particularly when timber production is the main management goal. The results from this study provide an indication to the authorities or specific agencies concerning the efforts that are required to inform the forest owner about the new forest landscape management by zoning system and to raise conservation awareness among the community. If ownership transformation is needed, a good negotiation is a prerequisite and compensation payment should be well-planned before transforming the area for conservation sites to avoid problems related to forest ownership in the future.

An increase in elevation changes the availability of wildlife habitat and vegetation structure. In this study, we overlaid the 946 ha of wildlife sanctuary areas and the 249 ha of protected prefectural parks with the PCAs at the intermediate elevation level. The analysis showed that 95% of these parks were intersected with our PCAs output. Non-flying mammals and birds had the highest number of species at mid-elevation (Grinnel et al. 1930). For example, *D.noguchii*, the critically endangered bird species of Okinawa, builds its nest in large *C.sieboldii* trees, which are usually found in the old-growth forest at the middle-peak of the Yambaru forest (Takeshi 2009).

Therefore, it is important to conserve the middle peak region of the Yambaru Forest from habitat fragmentation, particularly by anthropogenic disturbance, which is the main factor contributing to the extinction of wildlife species (Ozaki et al. 2010).

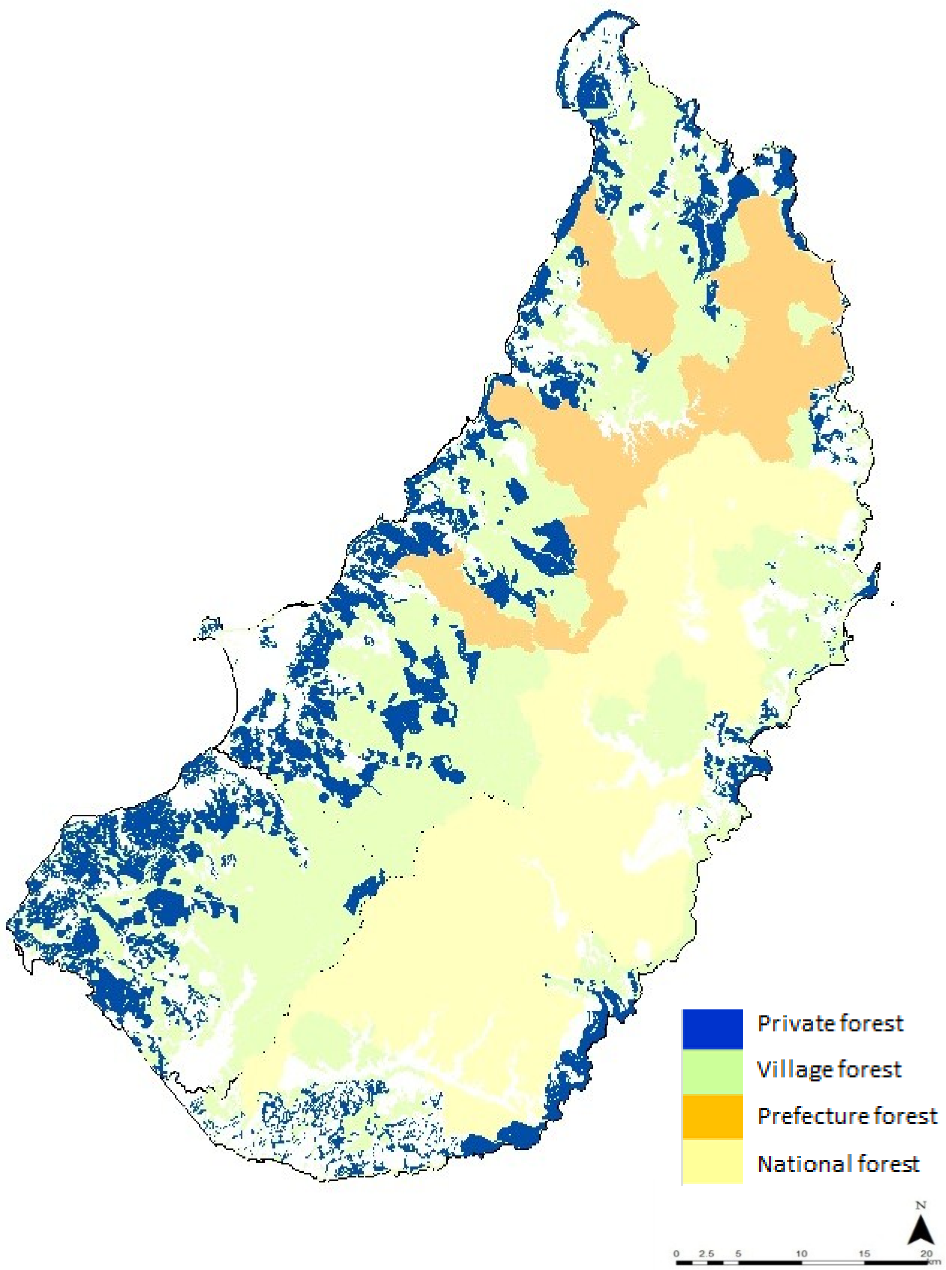


Figure 3-8. The forest ownership map of Yambaru Forest area

Table 3-1. The influence of PCAs (in percentage) at intermediate elevation gradient on forest ownership in the Yambaru Forest

Forest owner	Total area (ha)	200m (%)	250m (%)
Village / municipal	13639.6	28.6	15.8
National	7553.4	28.8	8.8
Individual	4169.0	14.0	9.1
Prefecture	3386.6	49.0	24.5

Forest vegetation was represented by the tree height produced from DCHM analysed by the deduction of DSM to DTM of the LiDAR data. At the 250 m of elevation, average tree height was at 11.6 m, higher compared to 200 m and 300 m with 11.4 m and 10.6 m, respectively. The findings was supported by Rahbek (2005) where he pointed out that vegetation at the mid-elevation peak is characterized by most abundant with optimal tree height. The decreasing number of animals and plant species at a highest elevation was expected and has been verified by many studies (Lomolino 2001; McCain 2005, 2009 & 2010; Rahbek 1997). In this study, the LiDAR data were restricted only for private forest land. Therefore, no vegetation data were available for National Forest area. Since the area is occupied for the north military training sites and no harvesting practice has been conducted, it was predicted that the area consists of large trees and high quality timbers (Shinohara et al. 1996).

The forest road network in Yambaru has been constructed across the forest area. There are two types of forest road, prefectural and village's road. The roads provide corridors for travel and access to recreational and forest educational areas. Forest road information can assist in estimating the number of forest visitors and it is important in measuring forest carrying capacity in term of the ability of the forest area to support number of visitors per time. The main forest road built across the PCAs at the middle elevation gradient was the Ookuni Forest Road, with the total length of 35,537.3 m. The total length of forest network reduced significantly with elevation. Forest roads alter animal behaviour, change their home range (Trombulak & Frissell 2000), and limit habitat area and migration of the flightless bird of *G.okinawae* (Kotaka & Sawashi 2004). Under the Forestry Act, conservation forest is designed not only for public benefit, but also to provide shelter for animals and plants (Forestry Agency 2010). Therefore, at higher elevation with fewer accessible road networks animal mortality particularly associated with the road kill cases could be reduce. The slope stability changes with forest road construction and it is related to the forest hydrological factor. Streams and watershed areas are decisive hydrological linkages that require finest management strategy. In the study, the watershed area was found to cover 80% of the potential conservation area at the middle-peak altitude. Conserving the forest is a way to protect the watershed areas and natural resources. The watershed areas upsurge forest biodiversity by providing an abundant supply of water and nutrients to promote vegetation growth (Kusumoto et al. 2008). Therefore, it is a necessity to protect the areas in order to ensure ample clean water sources for public use. The implications concerning vegetation, accessible forest roads and water resources in the PCAs are summarized in **Table 3-2**.

Next, we compared our PCAs results with the forest management plan proposed by the DAFF of Okinawa Prefecture. **Figure 3-9** illustrates the overlaid PCAs with Okinawa Prefecuture’s planning map and **Table 3-3** summarized the percentage of area attached with the selected elevation gradients for each zone.

Table 3-2. Average tree height, accessible forest road and water resources at the selected PCAs in the Yambaru Forest

Elevation (m)	Average tree height (m)	Total road length (km)	Total stream length (km)	Watershed area (ha)
200	11.4	96.0	60.2	5956.1
250	11.6	65.5	13.8	3091.6
300	10.6	34.1	3.8	1512.1

The total protection areas (combination of core, buffer, water and soil conservation areas) increase with elevation. At 300 m, 55% of PCAs were spatially joined with the zoning plan by the Okinawa Forestry Department, while at 250 and 200 m, the percentage of associated areas were at 51% and 44%, respectively. Forest conservation recommends to restrict commercial timber operations. This is parallel to the results produced by our study where the inclusion of production forest declined with elevation. In addition, the area occupied by the U.S. military was also displayed the same trend. The comparison between the PCAs and the zoning plan of Yambaru area was slightly different, particularly in respect of the allocation of conservation sites. More than 50% of the conservation areas suggested in this study corresponded to the management plan by the Forestry Department of Okinawa Prefecture. Our study proposed to protect the middle elevation area that was characterized by a continuous connection between forest patches and not fragmented by forest functions. In consideration of UNESCO proposal to realize the establishment of the National Park in Yambaru Forest, zoning by elevation showed this advantage. This shows that the elevation gradient is an applicable and practical parameter to describe the best site selection for conservation priority area in the Yambaru Forest.

3.3.3 Study limitations

The study mainly focused at the middle-peak of the Yambaru Forest. Based on characteristics and advantages of middle-peak elevation highlighted by several studies, the other elevation categories were not discussed in detail. The LiDAR data were utilized to describe vegetation structure of the Yambaru Forest. However, in this study the data were spatially limited to the private forest area. Due to data limitation, the National Forest area particularly located at the East side of Yambaru was not included. Since we gained a low precision in detecting the upper-storey canopy cover in Yambaru Forest (Chapter II), the method was not employed to explain vegetation of the study area. Conversely, the tree height parameter was chosen to represent forest vegetation structure in the selected PCAs. In the previous chapter of this study, the potential use of IKONOS was proven in detecting forest vegetation and LULC attributes of Yambaru Forest. However, the imagery data did not cover the important region of our PCAs and therefore the method was not applied in this chapter. Hence, to purchase new imagery data is very expensive, and due to the aforementioned reasons, limitations of this study could be considered for further improvement in future research.

Table 3.3. The percentage of area in each zoning region associated with the PCAs at different elevation levels

Elevation level	Protection area (%)			Production area (%)		National Forest (%)	Unclassified area (%)	Total PCAs (ha)
	core	buffer	water and soil	with environmental considerations	without environmental consideration			
200m	10.8	22.4	11.1	25.9	12.0	13.9	3.8	8043.8
250m	11.0	30.1	9.5	29.9	10.3	7.2	1.9	3702.2
300m	15.3	32.8	6.4	27.2	10.0	5.7	2.5	1774.6

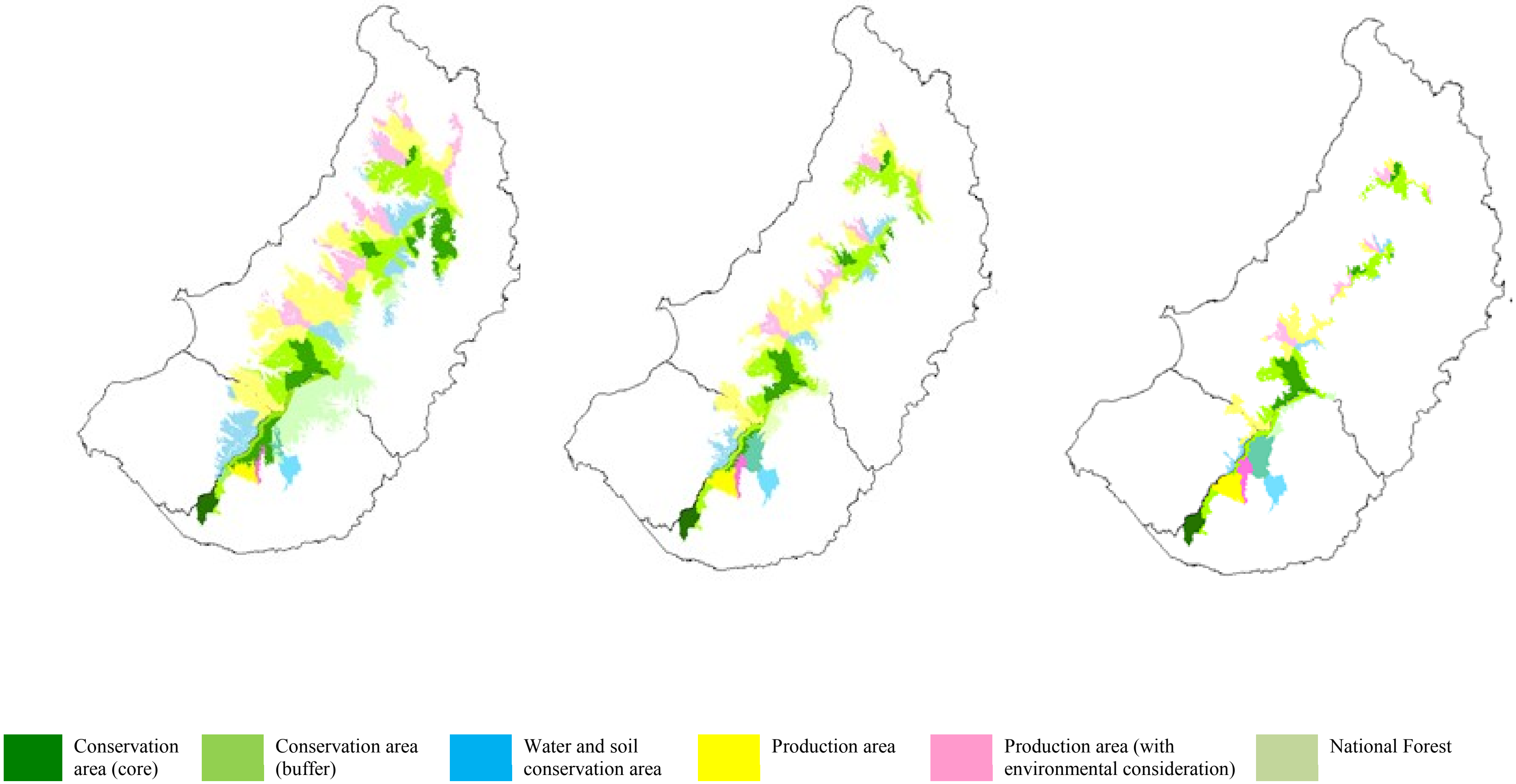


Figure 3-9. The overlaid maps of forest management plan based on forest functions by the DAFF of Okinawa Prefecture with the selected PCAs produced in this study. From the left: at elevations of 200m, 250m and 300m

3.4 Conclusion

The PCAs in the Yambaru Forest derived from the DTM data decreased with elevation. In allowing competing demands for development and other human activities, conservation sites require to be as small as possible with fewer patches and have connections between forest areas. Taking into account the influence of forest ownership, protected parks, watershed areas, vegetation and forest accessibility, it was suggested that a conservation priority site located at the middle-peak elevation of Yambaru Forest, which is range from 200 to 250m exhibit the optimum conditions for conservation site. An increase in the elevation changed the habitat availability and vegetation structure. At the intermediate elevation level, the average tree height was 11.6m, higher compared to other levels. Hence, at this elevation level, fewer accessible roads were detected and major designated protected parks were also included. In the suggested PCAs, various stakeholders hold the land areas with different management goals. Therefore, support from landowners is a crucial factor that greatly influences the smoothness of the zoning process. Half of the suggested PCAs in this study were identical with the zoning plan by the Okinawa prefecture. This showed the significant use of elevation gradients to obtain the best site which should be selected for conservation purposes in the Yambaru Forest.

Elevation gradient is a crucial parameter that corresponds to the UNESCO site selection, particularly in the decision-making process. The practicability of elevation integrated with accessibility, forest vegetation and other data is hoped to provide a better understanding of site selection for conservation and to raise community awareness of the benefits of conserving the forest area. Among the many zonation scheme alternatives, this quantitative method can assist the zoning process with minimum cost, time and effort.

Chapter IV

Alternatives Management for Timber Production

4.1 Introduction

In this chapter, alternative management of timber production forest in Yambaru was evaluated using HARVEST allocation model. Simulation model aimed to provide relevant and cost-effective timber harvesting options for a sustainable timber yield production.

The timber industry in Japan generates an important economic return, but supply of domestic wood has changed in response to the consumption pattern and population growth of the country. In 2011, the total volume of consumption for industrial timber in the world increased to 1.56 billion m^3, which had a huge influence on the Japanese timber industry with an increase in the demand and supply of timber (Forestry Agency 2012). However, the occurrence of issues related to the timber production industry, including the reduction in the forest area due to farmland expansion, the wood price crisis and illegal logging activity (Shinohara 1999), restricting the commercial prospects of timber, forest resource utilization and sustainable timber production.

The total forested area in Okinawa is 106,000 ha, of which 70% is private forests and the rest belongs to the National Forest of Japan, which is occupied by the US military for training areas and bases. The private forests are divided into three categories; namely prefecture forests, individually owned forests and village forests. Forest management that uses a zonation scheme has been introduced by the Forestry Department of Okinawa Prefecture to maintain a balance between forest conservation and utilization. Within this scheme, forests are divided into four main management units; forest conservation area, water conservation area, timber production area and the area for the U.S. military training site.

The forest condition and management system in Okinawa differs from that in other prefectures in Japan. After World War II, there was no stable forest management system, especially for timber harvesting. Forest-related activities including timber harvesting and tree planting are indispensable to support the livelihood of the residents of Yambaru. Individual owners have only small areas of forests, and the aggregate area is not large enough to support a harvesting rotation cycle or to meet timber demand as well as income of local residents. Consequently, the Okinawa government helped to solve the inadequate timber problems by giving tenure to individual forest owners through the forest association to conduct logging activities in a permitted forest area. At this level, the forest association is an important organization in that it distributes the tenured timber areas entrusted by the local government. In addition, the pre-and-post harvest activities were also monitored by the Forestry Department of Okinawa Prefecture through this association. **Figure 4-1** illustrates the management structure of the forest in Okinawa and the role of the forest association in handling the insufficient timber harvest by the communal forest.

The Japan Forest Agency (2012) reported that the annual volume of domestic timber supply was inadequate compared to the volume of timber being imported. Domestic timber is mainly produced from prefecture and village forests with relatively little from communal forests (Shinohara et al. 1996). Timber harvests in Yambaru only focus on small scale activities to provide saw logs, specific manufactured products and pulp. According to the annual report from the DAFF of Okinawa Prefecture (2012), the average patch area per cut from the prefecture forests and village forests was 1.67 ha and 2.21 ha, respectively, and cutting areas do not exceed 5 ha. The annual allowable area for cut of the whole forest is 10 ha, and timber extraction is only scheduled in winter to protect the breeding period of endangered bird species and other wildlife. Stands are chopped down using clear-cutting method using a cable system and tower yarder. This method has been practiced since the 1960s and found to be practical because it allows for natural regeneration, especially from coppice, and promotes growth and seedling restoration. However, this is an extreme harvesting method because it threatens forest wildlife and other biodiversity conservation and has a severe impact on the forest environment (Kubota et al. 2005).

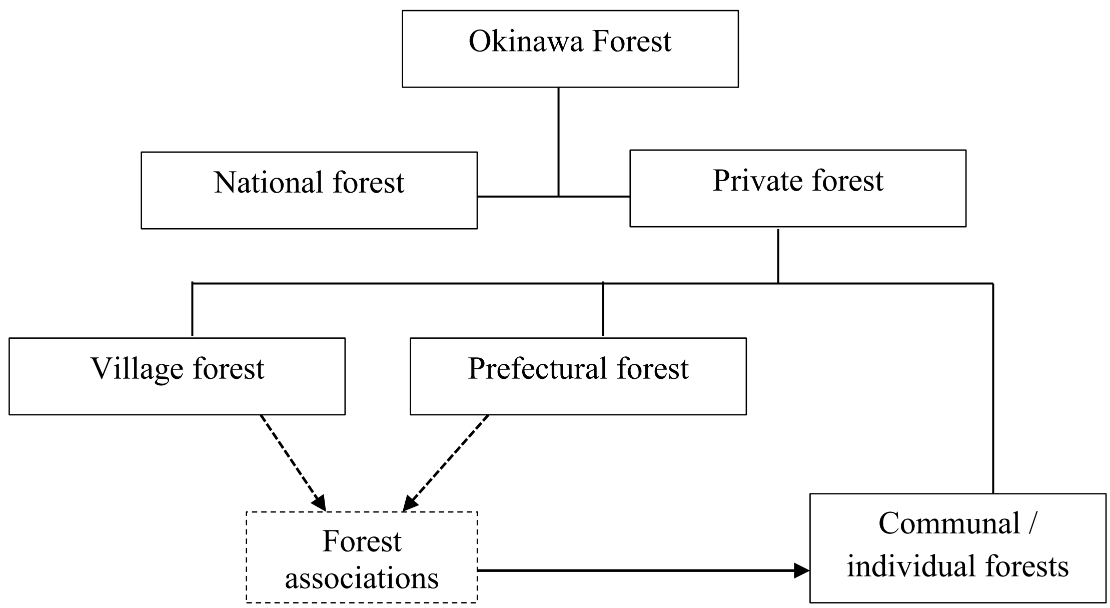


Figure 4-1. The special situation of Okinawa Forest management system

(Note: Forest associations act as leaders to spread harvesting tenure to individual forest owners to ensure adequate timber supply and income for forest workers)

Recently, the reduction of domestic timber production in Okinawa has become a major concern to the country and local people, which compelled the adoption of strategic forest management planning to avoid exploitation, wastage and misuse of the forest resources. Hence, various issues concerning the preeminent harvesting practice have been acknowledged. Consideration of crucial aspects including practical harvesting method, the rotation cycle, species selection, allowable cutting area, minimum tree age to cut and necessary post-harvest silvicultural treatment are important for the implementation of sustainable forest management.

Although extensive research has been carried out in the Yambaru Forest, less are known on the alternative timber management strategies to improve the forest management system. In this study, timber harvest activity in the Yambaru Forest was simulated using HARVEST timber simulation model with the aim of assessing the spatial pattern consequence of strategic forest management options in the subtropical forest of Okinawa Island. HARVEST is a rule-based stochastic model that simulates timber management options by providing visual and quantitative measures to predict spatial patterns of forest openings (Gustafson 1998). It is a strategic research and planning tool based on the raster cell to assess spatial pattern of broad timber management strategies. The model was designed to adopt flexible input rules to allocate timber harvesting based on various forest management goals.

4.2 Materials and methods

4.2.1 Study site

The study was conducted in the 727 ha of the Yambaru timber production zone where evergreen broadleaved trees were prevailing (**Figure 4-2**). The area is characterized by a subtropical climate with an annual precipitation and mean temperature of 2,300 mm and 22ºC, respectively. The study site is located on a hilly and rugged terrain with a maximum elevation of 250 m. The forest is well-known for its high density, and diversity of flora and fauna. Broadleaved trees particularly *C.seiboildii* is the dominant tree species with mean tree height and diameter at breast height (dbh) of 7.2 m and 15.1 cm, respectively (Ito 1997). The oldest stand aged 80 years old. Strong winds with intense rainfall caused by typhoons frequently hit the area between June and October.

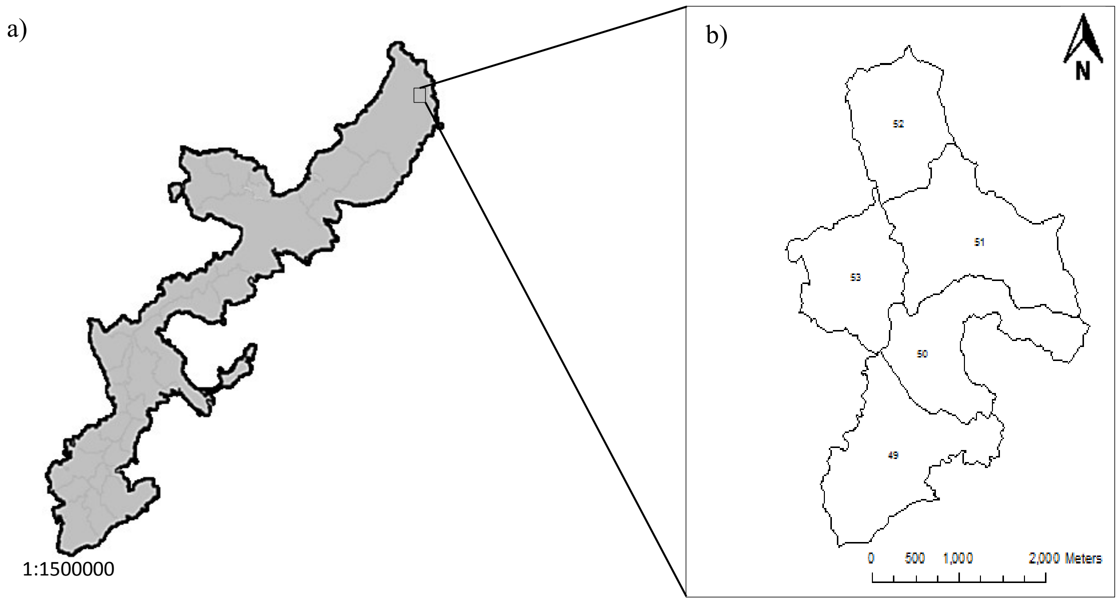


Figure 4-2. a) Study site located at the Northern part of Okinawa Main Island and b) simulation was done on timber production zone consist of five compartments with total of 727 ha of forested areas

4.2.2 Data, parameters and analysis

The data required for the simulation is a set of four maps, including i) forest age map (FA), ii) forest management area map (MA), iii) forest type map (FT), and iv) stand ID map. Maps were generated from the remote sensing image of the IKONOS-2 satellite acquired on February 6, 2007 with UTM projection, datum WGS-84 with 4m resolution. The image was orthorectified by the Japan Space Imaging (JSI) and interpolated using the cubic convolution method. The FA map in this study described the stand age in each cell, and, in this study, the oldest stand was 80 years old. The FT map contains cells that represent the specific forest type and the MA map represents the management unit of each cell. The stand ID map comprises unique ID values, which are used by HARVEST to track the harvest activity in each stand. The IDs remain constant throughout the multiple time period of simulation (Gustafson & Rasmussen 2005). All the input maps were saved in a GIS format and had an equal numbers of rows and columns, cell size and area to ensure that the simulation ran correctly before the control parameters would be set.

Two harvesting methods were tested in this study – clustered and dispersed dispersion methods, which represent small clear-cut and selective cutting, respectively. The maximum patch was set at 5.0 ha and the minimum was 0.01 ha. Since the study site was selected from 15% of the total production forest in Yambaru, the amount of allowable area to harvest was set at 2.1% (15.2ha) from the total study area and the minimum stand age to cut was set at 60 years. Fujii et al. (2010) had proven that a 60-year rotation cycle is an optimal rotation cycle for a sustainable logging regime, which could maintain both the timber yield and tree species diversity. Adjacency constraints were employed in this simulation with 20 years of green-up intervals to prohibit harvest activity held in adjacent stands less than 20 years old. Simulations were run for 8 decades with 10-year time-step with three replications for both harvesting methods. The average total harvested area, number of patches, patch size, edge habitat, forest interior and GIS fragmentation of two different harvesting methods were plotted against time. **Figure 4-3** illustrates the input data, control parameters and outcome of the simulation in this study. Based on the results, potential management and alternative strategies for the timber harvesting activity in the Yambaru Forest were discussed.

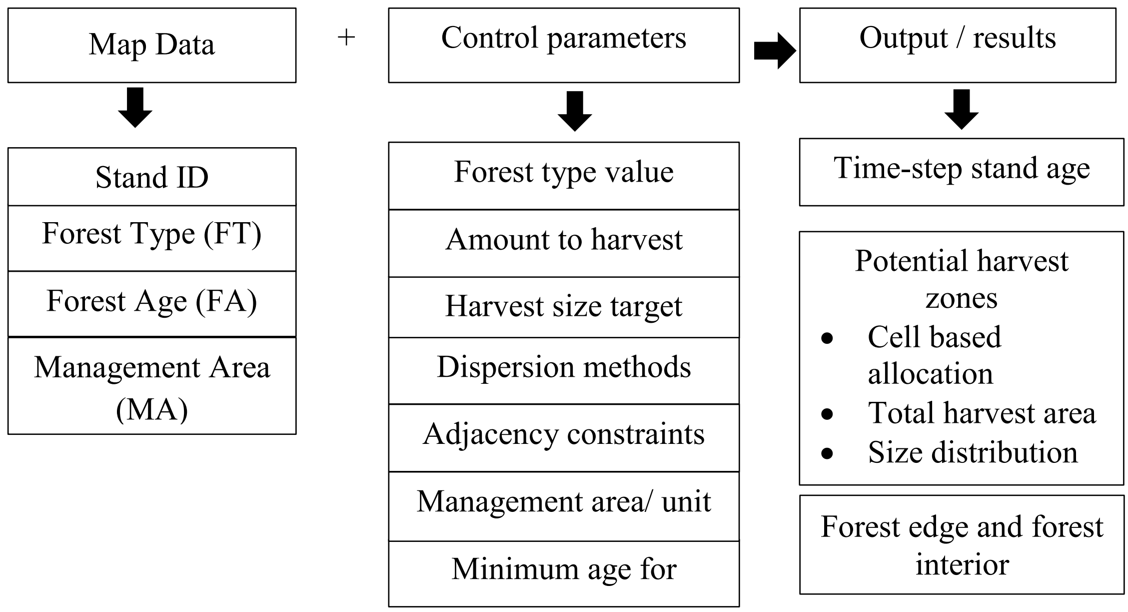


Figure 4-3. Input maps, control parameters utilized in the study and outcome produced by HARVEST simulation model

In this study the simulation was operated by the Timber Harvest Simulation Model (HARVEST) version 6.1 software system developed by Eric Gustafson from the USDA Forest Service (Gustafson & Rasmussen 2005). Data management and statistical analysis was computed using Microsft Excel version 2010.

4.3 Results and discussion

Prior to the simulation process, the initial state of forest area, stand age, average patch size and patch number were calculated (**Table 4-1**). In the initial stage, the average size and number of patches in the study area were 5.02 ha and 24 patches, respectively, with the oldest stand aged 80 years old. The results of the simulation showed that more areas could be harvested per time using the clustered method (**Figure 4-4**). Based on forestry report and a study by Tamashiro et al (2008), the average timber volume of the dominant species at Yambaru Forest is 153 m^3ha^{-1}. Therefore, it was estimated that by using clear-cutting method, it could produce a higher timber volume of 12% compared to the selective-cutting method, with 2,870.9 m^3 and 2,529.7 m^3, respectively. However, the clear-cut method could have long-term ecological impacts by altering the forest ecosystem function and affect species diversity of the forest (Bremer & Farley 2010). A recent study by Jemali (2013) in Yambaru Forest found that albeit post-harvest silviculture treatment was implemented in clear-felling sites, the forest environment would not return to its original condition. The analysis of variance was carried out on the three replications of each dispersion method. The result showed that the size of the patches and areas of edge habitat were the most significant factors related to the timber harvesting methods (Table 4-2). Since the adjacency constraint was enforced in this simulation, it prohibits harvest units from being placed adjacent to the existing openings. It provides ample available areas with optimal stand age in each cutting period to meet the harvesting target in each simulation.

Table 4-1. Distribution of area, size and patches of simulation data at the initial stage

Age (decade)	Area (ha)	Average size (ha)	Number of patches
1	3.27	0.82	4
2	20.79	0.95	22
3	64.11	2.00	32
4	213.94	19.45	11
5	167.01	8.35	20
6	49.15	1.45	34
7	40.18	0.91	44
8	168.53	6.24	27

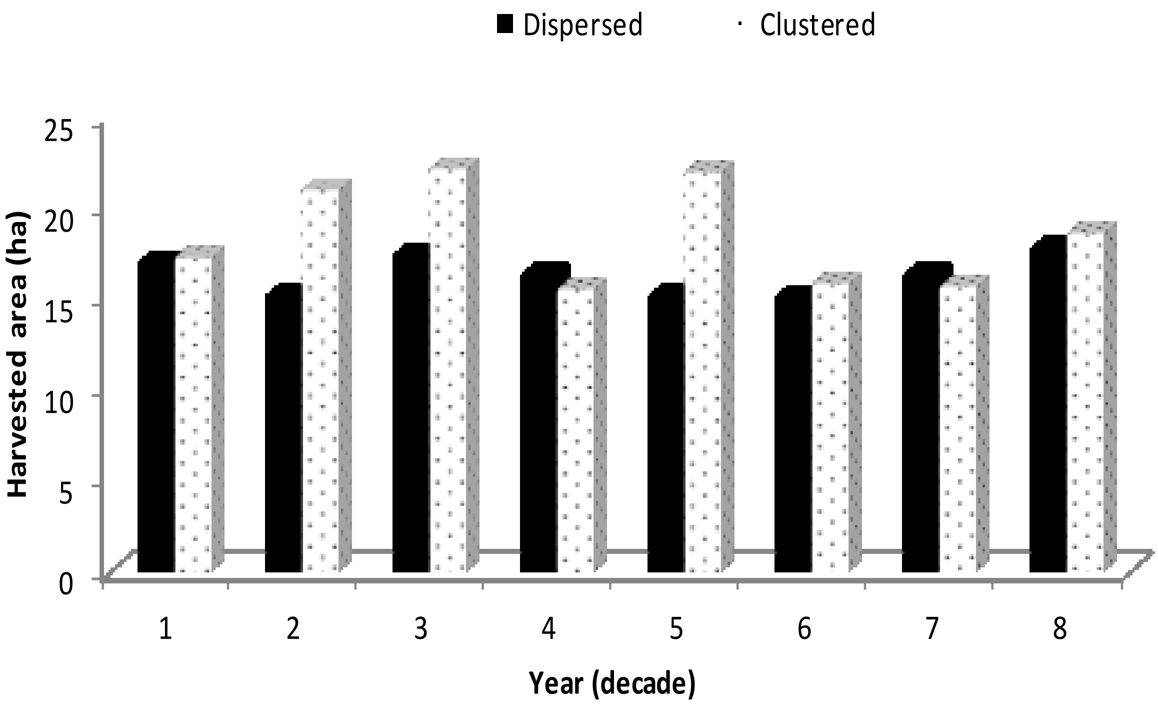


Figure 4-4. Total harvested area (ha) by dispersed and clustered dispersion methods for eight decades of simulation

Table 4-2. Analysis of variance was tested for patch size, edge habitat, total harvested area, forest interior and forest fragmentation in relation to harvesting methods

Analysis of variance	Mean Square	F
Patch size (ha)	25.85	14.81*
Edge habitat (ha)	184.62	8.34*
Harvested area (ha)	19.45	4.19
GIS fragmentation (m)	3.78	0.17
Forest interior (ha)	0.04	0.00

Note: A 5% significant level is adopted (one asterisk)

The selective cutting method mimicked by dispersed dispersion method produced a higher percentage of available cutting area per decade (**Figure 4-5a**). This method is proposed if the forest mangers plan to create many patches with smaller areas in the forest. However, in subtropical and tropical forests, small-scale selective logging has less advantage over the clear-felling logging system in terms of management cost, time and machinery used (Pinendo-Vasquez et al. 2001). The HARVEST simulation attempted to cut a nearby stand, then continued to select a new focal stand. The procedure was repeated until the targeted area was reached. In the clear-felling method, neighboring stands were potentially cut, which created a ring of the harvested area, and removed one stand from the initial stage (Gustafson & Rasmussen 2002). Therefore, in this simulation, larger forest openings were created using this method compared to the dispersed method. Selective cutting method followed a random selection, in which stands were selected independent of each other. In this simulation, the patch size reduced during the first 50 years, and increased gradually as more stands with a minimum age of 60 years old became available and ready to be selected for harvest (**Figure 4-5b**).

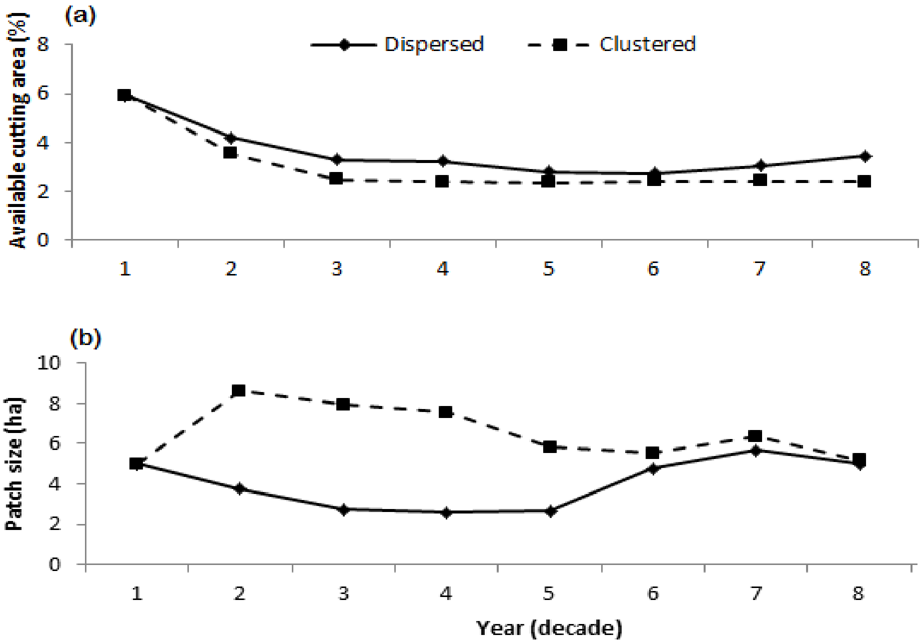


Figure 4-5. (a) Percentage of available cutting area and (b) mean patch size (ha) for different timber harvesting methods (dispersed and clustered) against time

Understanding the interaction of the harvesting area and edge habitat is essential to avoid unintended spatial effects when implementing management strategies (Gustafson & Rasmussen 2002). In this study, forest edge habitat differed significantly across the dispersion methods. Forest edge means forest habitat that is near to forest opening, calculated from the ratio of the perimeter to the area. In this study, area of forest edge was smaller when using clear-felling method compared to the selective-cutting method (**Figure 4-6a**). The larger cutting area characterized by clear-felling had an inverse relationship with the area of the forest edge habitat, which was consistent with other findings (Li et al. 1993; Gustafson 1998). Forest managers could estimate the perception on the habitat quality in different ecological communities using the forest interior parameter. For instance, microclimate edge effects usually extend a few meters into the forest. Some birds or wildlife species avoid residing in areas within close proximity to the forest edge as the area is not safe for shelter, breeding and other particular reasons. This is an important factor to be considered, especially for forest managers who are concerned about the conservation of endangered species, such as *D.noguchii* and *G.okinawae*. Hence, consideration of forest edge is a great tool for conservationists to design protection sites in the Yambaru Forest.

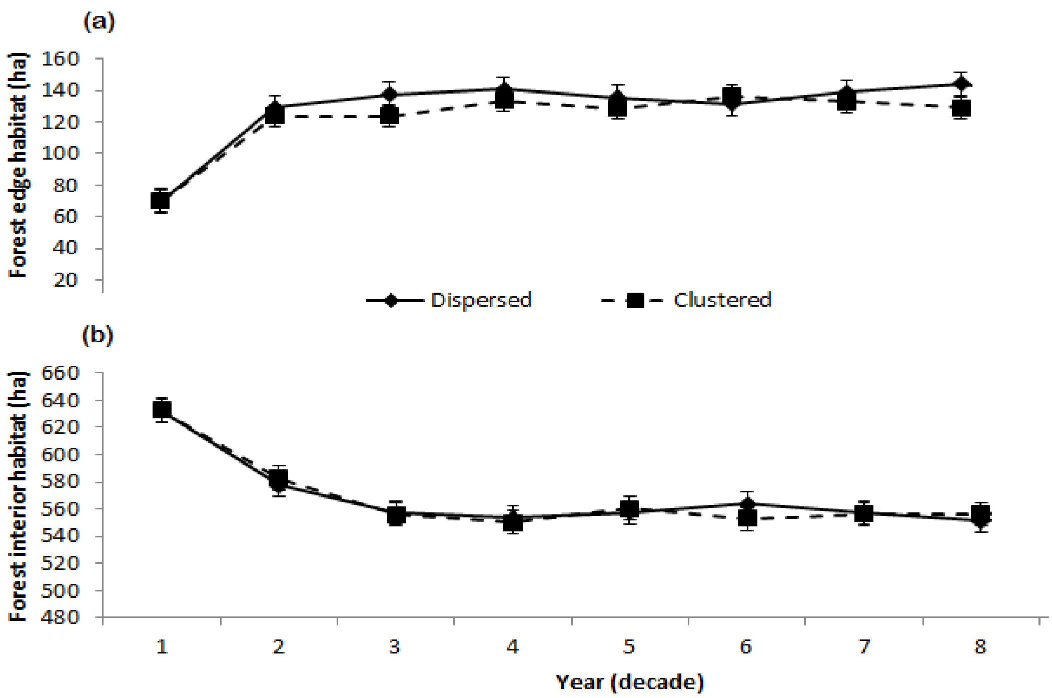


Figure 4-6. (a) Effect of forest edge habitat and (b) forest interior habitat on different timber harvesting methods (dispersed and clustered) against time

Changes in forest interior provide an insight into the dynamics of the zoning strategies for the forest management system. In this study, the forest interior was found to be identical regardless of the logging technique because the simulation was only carried out in the timber production zone (**Figure 4-6b**). Meanwhile, forest fragmentation was calculated using the GISfrag index (Ripple at al. 1991), which is a good index to measure the average distance of the forested cell to the nearest harvesting area without being prone to the patch truncation effect. This parameter is crucial to evaluate the habitat fragmentation effects on wildlife species, biology and environmental impacts (Shifley et al. 2008; Gustafson et al. 2007). Fragmentation could be reduced by increasing the harvest size unit to meet the timber volume objective (Li et al. 1993). In this study, the selective cutting method indicated a small fragmentation area compared to the clear-felling method (**Table 4-3**). Both dispersion methods demonstrated a similar effect for forest fragmentation. However, after 80 years of simulation, the fragmentation area using the clustered method increased; thus, further investigation is needed for clarification.

Table 4-3. Forest fragmentation produced from dispersed and clustered harvesting methods

Year (decade)	Area (m)	
	Dispersed	Clustered
1	86.5	86.5
2	87.7	90.4
3	85.3	88.2
4	85.5	87.5
5	86.9	87.9
6	86.5	77.2
7	78	77.5
8	76.3	86.7

HARVEST is an empirical tool to answer the ‘what-if’ questions related to the timber harvest activity. The model has the capability to produce options for strategic timber management plans as desired by many forest stakeholders. Consistent with its easy, user-friendly and coarse-filter evaluation of management alternatives, the model ignores several forest conditions and constraints. Therefore, several limitations and assumptions were made by the model developer to simplify and reduce the data requirement and simulation time. Factors, such as accessibility, operability and site condition, were not included because the forest age was the only data used for HARVEST as an alternative for merchantability. Stands for harvesting were selected randomly throughout the simulation, and forest succession processes were not simulated. If users are concerned about the changes in the forest composition with alternative management strategies, the LANDIS model is recommended rather than the simulation model by HARVEST. Nevertheless, HARVEST is still a powerful tool for comparing alternative management scenarios. It is able to provide answer to the issues concerning the preeminent harvesting practice, such as harvesting methods, species selection, allowable cutting area, minimum age of tree to cut and the necessary silvicultural treatment, as proven in many studies (Gustafson & Crow 1996; Tang & Gustafson 1997; Gustafson et al. 2002; Leefers et al. 2003).

4.4 Conclusion

Forest-related activities are important for local residents in Okinawa Island. Therefore, integrated management strategies between timber allocation and GIS are required to deal with environmental protection, economic and social needs. The efficiency and flexibility of HARVEST model simulates alternative options for strategic timber management planning by comparing two different dispersion methods in order to estimate the spatial pattern consequence of the timber harvesting activity in the Yambaru Forest. Based on this study, the mean patch size and forest edge habitat displayed the significant factors related to the harvesting methods in the Yambaru

Forest. It was estimated that small-sized clear-cutting would produce a 12% higher volume of timber than selective-cutting. However, the small-sized clear-cutting method would have long-term ecological impacts and could alter the functions of the forest ecosystem and diversity of the species. Selective cutting can reduce the ecological impact in the timber harvesting practice, but the practicability of this method has not been proven to be significant in terms of cost, the total volume of timber production or involvement of high technology machinery.

The results of the simulation indicated that the small clear-cut technique mimicked by the clustered dispersion method is suitable for the timber management strategy for the Yambaru Forest. A comprehensive timber management strategy is indispensable to help forest stakeholders to design alternative strategies with multiple objectives to ensure a sustainable timber yield, especially in the limited region of the subtropical forest of Okinawa Island. HARVEST is a cost effective technique in simulating the dynamics of the forest timber activity. The model could help to mitigate the harvesting effect and avoid unintended spatial effects in the near future for a balanced forest ecosystem. Hence, it is also beneficial in assisting forest stakeholders in the decision-making process to enhance the sustainable forest management system in Okinawa Island.

Chapter V

General Conclusion

5.1 Forest structure and land cover attributes

The Yambaru Forest consists of complex vegetational and topographical conditions. The vertical structure of the Yambaru Forest was studied concerning tree diversity in different height classes. Although major broadleaved trees conquered the middle layer of the forest, trees with smaller in height showed a greater influence on forest diversity. Forest crown cover was evaluated using LiDAR data by the detection of upper-storey canopy structure. Albeit LiDAR was recognized for the accuracy and precision in examine the Earth surfaces, it is not applied in the case of Okinawa forest. The study yielded a low precision of canopy detection in Yambaru Forest due to the complex structure of individual trees, forest density and topographical conditions. The LULC attributes of the logged-over forest in Yambaru was analysed using pixel-based and object-based classification methods. The preceding classification method exhibits the highest precision in detecting land cover attributes derived from IKONOS imagery data. The image classification categorized the study site into four land use type, namely *C. sieboldii* forest, mixed broadleaved forest, forest road and bare land area. A positive impact of post-harvest silvicultural treatment was discovered with an increase of vegetation cover and declination of the bare area in the study site.

5.2 Strategic management for conservation and production areas in Yambaru Forest

A strategic forest management is required to deal with the controversial issues on multiple forest uses for social, economic and environmental demands. Hence, a good management strategy is desired to maintain a balance between conservation and production goals. In this study, forest zoning system using a practical quantitative method based on elevation gradients was introduced as one of the strategic management plan in the Yambaru Forest. It aimed to give an effective and clear zoning region with minimum cost, time and effort. The potential conservation areas decreased with increased of elevation gradients. Taking into account the influence of forest ownership, protected parks, watershed areas, vegetation and forest accessibility, it was suggested that the site with conservation priority locating at the middle-peak (200 to 250m) of Yambaru entailed the optimum conditions for site selection. Since Yambaru Forest is owned by various stakeholders with different management goals, support from the landowners is a crucial factor that greatly influences the smoothness of the zoning process. The practical used of elevation parameter to zoned conservation areas was supported by the identical area detected between the outputs of this study with the forest management plan by the Forestry Department of Okinawa Prefecture.

Two types of potential management for timber production forests were examined using HARVEST allocation model. The simulation model estimated spatial pattern consequences of timber harvest activity in Yambaru Forest. A small-clear cutting mimicked by clustered method was estimated to produce higher timber volume compared to selective cutting that was imitated by dispersed dispersion method. In this study, size of harvested area and forest edge habitat were the main factors related to the harvesting methods. A comprehensive timber management strategy is essential to help forest managers to design alternative strategies to ensure a sustainable timber yield, especially in the limited forest region of Okinawa Island. The timber production model simulation is beneficial in assisting decision-making process for sustainable forest management system in Okinawa Island. Even though there are several limitations of the model, yet it is a practical and cost-effective technique to simulate the dynamic of timber production and to predict the future of the timber industry in Okinawa Island.

5.3 Concluding remarks

For a long-term forest management planning, the strategic management options of zoning system for conservation forest area and alternatives management by simulation models for timber production forest were presented in this study. The proposed methods integrate field data, space-based data of remote sensing as well as technology of GIS to enhance the recent management system. It is a cost-effective and relevant approach to attain sustainable forest management goals. The result is hoped to provide a good scientific knowledge and valuable information that greatly enhance community perception on the sustainable forest management in the Yambaru Forest.

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