IDENTIFYING AND LOCATING TREES OF FRAMEWORK SPECIES USING PHOTOGRAPHY FROM AN UNMANNED AERIAL VEHICLE (UAV)

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MASTER OF SCIENCE
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A THESIS SUBMITTED TO CHIANG MAI UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENVIRONMENTAL SCIENCE

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17 May 2019

This book is dedicated to

my dear beloved son

Jeremy Rai

ACKNOWLEDGEMENTS

I thank the Royal Government of Bhutan (RGOB) and Thailand International Cooperation Agency (TICA) for awarding scholarship to purse post graduate studies at Chiang Mai University, Thailand. In addition, I thank the Forest Restoration Research, Unit, Chiang Mai University (FORRU-CMU) for a small project research grant. I express my heartfelt gratitude to my thesis advisor Dr. Stephen Elliott, FORRU-CMU for his continued and relentless support during the course of my study. Special thanks to FORRU-CMU's staff for their kind support at the field and CMU Herbarium for their support. A special mention to acknowledge and thank Ms. Panipak Saetan and Ms. Nout Kanyapim, who helped in the field for multiple times, despite of their busy schedules. I also thank the University Studies Abroad Consortium (USAC), CMU students for assisting me to validate my thesis results and Mr. Noi from Lucky Car Rent for his excellent transportation services.

Krishna Bahadur Rai

หัวข้อวิทยานิพนธ์ การระบุชนิดและตำแหน่งของต้นไม้ของพรรณไม้โครงสร้างโดยการใช้การถ่ายภาพจากอากาศยานไร้คนขับ

ผู้เขียน นายกฤษณะ บาฮาดูร ไร

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บทคัดย่อ

ความจำเป็นในการระบุตำแหน่งและชนิดของกล้าไม้ให้มีศักยภาพนั้น ได้กลายเป็นสิ่งที่สำคัญเพื่อช่วยในการบรรลุเป้าหมายตามปฏิญญาสหประชาชาติว่าด้วยป่าไม้ ณ เมืองนิวยอร์กปี 2557 โดยมีวัตถุประสงค์เพื่อดำเนินการฟื้นฟูป่าในพื้นที่เสื่อมโทรมขนาด 350 ล้านเฮกแตร์ ภายในปี 2573 ซึ่งอุปสรรคของการจำแนกชนิดของต้นไม้ในป่าเขตร้อนนั้น คือวิสัยทัศน์ของการมองเห็นในระดับภาคพื้นดิน ดังนั้นจึงจำเป็นต้องมีการสำรวจเหนือพื้นดินโดยอาศัยข้อมูลการสำรวจระยะไกลไม่ว่าจะเป็น เครื่องบิน ดาวเทียม หรือเทคโนโลยีภาพถ่าย เช่น ภาพถ่าย hyperspectral และ LiDAR อย่างไรก็ตามเทคนิคการสำรวจโดยวิธีการเหล่านี้มักมีราคาแพงและมีความยากในการเข้าถึง แต่ในช่วงไม่กี่ปีที่ผ่านมาได้มีอุปกรณ์ที่เรียกว่าอากาศยานไร้คนขับ (UAV) ซึ่งประกอบด้วยกล้องที่มีความละเอียดสูงรวมถึงราคาไม่แพงมากนักดังนั้นงานวิจัยนี้จึงศึกษาโดยการใช้ UAV ในการระบุชนิดและตำแหน่งของต้นไม้ทั้ง 9 ชนิด ได้แก่ หาดหนุน (*Artocarpus gomezianus*), ก่อหมูดอย (*Castanopsis calathiformis*), ก่อใบเลื่อม (*Castanopsis tribuloides*), มะกัก (*Choerospondias axillaris*), กร่าง (*Ficus altissima*), มณฑาแดง (*Magnolia garrettii*), สนสามใบ (*Pinus kesiya*), นางพญาเสือโคร่ง (*Prunus cerasoides*) และยมหอม (*Toona ciliata*) ในพื้นที่ศึกษาบ้านแม่สาใหม่ เขตอุทยานแห่งชาติดอยสุเทพ-ปุย ภาคเหนือของประเทศไทย ซึ่งเป็นพื้นที่ป่าไม้ที่ได้รับการฟื้นฟูโดยใช้ไม้พรรณไม้โครงสร้างเมื่อ 20 ปีก่อน โดยหน่วยปฏิบัติการวิจัยการฟื้นฟูป่า (FORRU-CMU) มหาวิทยาลัยเชียงใหม่ ซึ่งมีพื้นที่ขนาด 0.0064 ตร.กม. มีการเก็บข้อมูลทุก ๆ เดือน จำนวน 8 เดือน โดยใช้ DJI Phantom 4 Pro บินเหนือพื้นดินสูง 50 เมตร มีการวางแผนการบินอัตโนมัติแบบเอกสิทธิ์ของซอฟต์แวร์ Litchi

ภาพถ่ายดิจิตอลทางอากาศ (20ล้านพิกเซล) ที่ได้ถูกนำมาใช้ในการพัฒนาคีย์ในแต่ละชนิดของต้นไม้ โดยขึ้นอยู่กับลักษณะของเรือนยอดไม้ ลักษณะของใบและการกรองข้อมูลภาพ จากนั้นทำการทดสอบคีย์เพื่อตรวจสอบความถูกต้องและความน่าเชื่อถือโดยอาสาสมัคร ผลการศึกษาพบว่ามีความแม่นยำในการจำแนกเกิน 50% สำหรับต้นไม้ทั้ง 7 ชนิด และเกิน 70% สำหรับ 4 ชนิด อย่างไรก็ตาม แม้ว่าระบบนี้จะยังไม่สามารถที่จะระบุต้นไม้ได้ทุกชนิดแต่ก็มีประโยชน์สำหรับการระบุตำแหน่งและชนิดของต้นไม้ที่เพียงพอสำหรับการเริ่มต้นของโครงการฟื้นฟูป่า

Thesis Title Identifying and Locating Trees of Framework Species Using Photography from an Unmanned Aerial Vehicle (UAV)

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Degree Master of Science (Environmental Science)

Advisor Dr. Stephen Elliott

ABSTRACT

The need to locate and identify potential seed trees has become crucial, if we are to meet ambitious global reforestation targets of UN New York Declaration on Forests, 2014, which aims to restore forest in 350 million ha of degraded land by the year 2030. Tree species identification in tropical forests is hindered by low visibility from the ground. The possibility of viewing trees from above, using remote sensing platforms (planes and satellites) and imaging technologies such as hyperspectral imagery and lidar are being investigated. However, such technologies are very expensive and not readily accessible. In contrast, Unmanned Aerial Vehicle (UAV), with high-resolution cameras, have become a lot more affordable in recent years. Therefore, the research presented here determined if an off-the-shelf UAV could be used to easily identify nine (9) target tree species in dense regenerating forest from above. The study site was at Ban Mae Sa Mai (BMSM), Doi Suthep-Pui National Park, Northern Thailand, where forest had been restored in two plots (0.0064 km^2 each), by planting framework tree species 20 years previously, by Chiang Mai University's Forest Restoration Research Unit (FORRU-CMU). Digital aerial photographs (20 megapixels) of tree crowns of nine framework tree species (*Artocarpus gomezianus* Wall. Ex Trecul, *Castanoposis calathiformis* (Skan) Rehder & E.H. Wilson, *Castanopsis tribuloides* (Sm.) A.DC., *Choerospondias axillaris* (Roxb.) B.L. Burtt & A.W. Hill, *Ficus altissima* Blume, *Magnolia garrettii* (Craib)V.S. Kumar, *Pinus kesiya* Royle ex Gordon, *Prunus cerasoides* Buch, Ham.ex D. Don, *Toona ciliata* M. Roem) were taken monthly over 8 months, using a DJI Phantom 4 Pro, flown

at 50 m above the ground, along an identical autonomous flight plan using Litchi flight planning software. The photographs were used to develop visual species-identification keys, based on crown and leaf characteristics and image filtering. The keys were then tested for reliability in another similarly aged validation plot, using independent volunteer observers. Identification accuracy exceeded 50% for seven of nine target species and 70% for four of the species. Although, the system cannot be relied upon to locate all trees of target species, it is useful for locating enough seed trees to initiate forest restoration projects.

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LIST OF ABBREVIATIONS

ANR	Assisted Natural Regeneration
BMSM	Ban Mae Sa Mai
CC	Crown Color
CM	Crown Margin
CMOS	Complementary Metal Oxide Semiconductor sensor
CMU	Chiang Mai University
CT	Crown Type
FORRU-CMU	Forest Restoration Research Unit, Chiang Mai University
GPS	Global Positioning System
HCS	Horizontal Crown Shape
HSB	Hue, Saturation and Brightness
ISO	International Standard Organization
LA	Leaf Arrangement
LC	Leaf Color
LT	Leaf Type
macOS	Macintosh Operating System
NIH	National Institutes of Health
RGB	Red, Green, Blue
SGS	Species or Group of Species
UN	United Nations
UAV	Unmanned Aerial Vehicle
VCS	Vertical Crown Shape

GLOSSARY

Alternate	leaf arranged singly at each node on a stem or axis (not opposite or whorled)
Angiosperms	one of the main divisions of flowering plants, containing plants that have ovules enclosed in ovary
Canopy	upper, well-illuminated tree crowns forming roof of the forest
Compound leaf	a leaf divided into leaflets, each of which often has the general appearance of a whole leaf (see pinnate, paripinnate, imparipinnate)
Crown	it refers to the totality of an individual plant's aboveground parts, including stems, leaves, and reproductive structures
Deciduous	shedding leaves annually or periodically; not evergreen
Digital aerial photograph	photographs taken from above with digital camera from unmanned aerial vehicles or aircrafts
Elliptic	refers to leaf shape that is widest in the middle and tapers towards both ends
Evergreen	a plant that retains its leaves throughout the year
Flower	the structure for sexual reproduction in the Angiosperms usually consisting of male organs (comprising the stamens) and female organs (comprising the pistils)
Fruit	the ripened ovary, bearing the seeds
Framework tree species	are indigenous, non-domesticated, forest tree species, which, when planted on deforested sites, rapidly re-establish forest structure and ecological functioning, whilst attracting seed dispersing wildlife

Framework species method	planting indigenous forest tree species, which can rapidly re-establish canopy cover and attract seed-dispersing wildlife, to accelerate forest regeneration and biodiversity recovery
Herbarium	a collect of dried plant specimens for scientific study
Imparipinnate	an odd pinnate, with a terminal leaflet; an unequal number of leaflets
Lanceolate	shaped like the head of the spear or lance, with widest part at the middle
Leaflet	first sub-division of a compound leaf
Oblong	much longer than broad, with sides nearly parallel, widest in the middle
Ovate	with an oval outline broader towards the base than apex, and round ended
Paripinnate	a compound leaf divided into leaf divided into pairs of leaflets, with no terminal leaflet, i.e. an even number
Phenology	the pattern of flowering and fruiting throughout the year
Pinnate	compound leaf with leaflets arranged along each side of a common stalk, usually more or less in the same plane
Simple	a leaf with one blade
Spiral	leaf arranged in spirals
Terminal	at the tip or apex

Chapter 1

Introduction

In most countries, tree seed collection from remnant forest remains essential for forest restoration projects, but current methods are primitive. Collectors walk along forest trails, with binoculars pointed aloft, searching for ripe fruits amongst the minute fraction of the forest canopy that is visible from the ground. Even when a fruiting tree is found, the seeds may not be ripe, necessitating a tedious return trip. So, collectors tend to visit the same trees year after year, which narrows the genetic variety of the planting stock. Clearly, conventional seed collection is inefficient, unpredictable and consequently expensive.

The possibility of approaching trees from above, using remote sensing platforms, is therefore an attractive alternative and various tool are being developed to meet this need (Sutton, 2001). Remote sensing techniques, particularly hyperspectral and high-resolution satellite imaging offer potential alternatives for mapping species distributions. Although remote sensing has become a standard tool for assessing the spatial structure, complexity and dynamics of forests over large areas, especially in the temperate zone (Pouliot *et al.*, 2002; Leckie *et al.*, 2003; Gergel *et al.*, 2007), few studies have successfully used satellite images to map tree species distributions in tropical forests (Clark *et al.*, 2005; Asner *et al.*, 2008). Even when hyperspectral and high-resolution satellite images are used, it is difficult to identify tree species (Read *et al.*, 2003; Clark *et al.*, 2004) and such techniques are very expensive. Therefore, few research institutions, which study tropical forests can afford them (Nagendra & Rocchini, 2008). A potential simple and inexpensive alternative is high resolution digital aerial photographs (Vooren & Offermans, 1985; Herwitz *et al.*, 2000; Trichon & Julien, 2006; Gonzalez-Orozco *et al.*, 2010; Morgan *et al.*, 2010).

Off-the-shelf drones (UAV's) with high-resolution cameras have become a lot more affordable in recent years (Getzin *et al.*, 2012). Furthermore, they can fly very close to tree crowns, revealing details hitherto unobservable from satellites or conventional aircraft. In this study, I acquired digital aerial photographs using a DJI Phantom 4 Pro drone over eight months at Ban Mae Sa Mai (BMSM), Doi Suthep-Pui National Park, Northern Thailand. The photographs were used to develop visual species-identification keys, based on crown and leaf characteristics and image filtering for nine tree species (*Artocarpus gomezianus* Wall. Ex Trecul, *Castanoposis calathiformis* (Skan) Rehder & E.H. Wilson, *Castanopsis tribuloides* (Sm.) A.DC., *Choerospondias axillaris* (Roxb.) B.L. Burtt & A.W. Hill, *Ficus altissima* Blume, *Magnolia garrettii* (Craib)V.S. Kumar, *Pinus kesiya* Royle ex Gordon, *Prunus cerasoides* Buch, Ham.ex D. Don, *Toona ciliata* M. Roem). The keys were then tested for reliability in another similarly aged validation plot, using independent volunteer observers to determine the percent found (tree crowns correctly identified as target species), the errors of commission (missed crowns of the target tree species) and errors of omission (tree crowns misidentified as target species).

1.1. Literature review

Studies on the potential use of aerial photographs for tropical tree identification started in the early 1970's. Sayn-Wittgenstein *et al.* (1978) found that species could be identified with a reasonable degree of success in Surinam. Subsequently, Myers (1982a) explored means of describing upper canopy tree crowns in Northern Queensland rain forests in Australia, developing terminologies based on structural characteristics of internal crown parts, using stereoscopy. These photographs were used to identify crown features by eye. An overall accuracy of 75% was obtained for 24 species and 80 to 100% for important timber species.

Since the 1990's, significant advances in aerial photo survey techniques have been made through use of photographs that have finer resolution and cover large forest areas (Brandtberg & Walter, 1998; Culvernor, 2002; Fenshman *et al.*, 2002; Chubey *et al.*, 2006). Trichon (2001, and Trichon & Jullien, 2006) developed keys for identifying individual tree species from high resolution aerial photographs and assessed the accuracy of these identifications in test locations, focusing on errors of commission, i.e., the percent of crowns incorrectly identified as a target species. In order to map canopy tree densities from aerial photographs, errors of both commission and omission (the percent of canopy trees of the target species missed in the aerial mapping) are both important. The authors developed a typology, with detailed classification criteria, for individual upper crown layers, in French Guyana for 12 tree categories. Photographs were taken along parallel transects, enabling stereoscopic views between photo-pairs. They surveyed the P16 plot in October 1996 from a hot-air airship during the ''Opertion Guyane 96'' scientific mission. They used a FM2 Nikon camera with a 35-mm lens loaded with color slides (Fuji Sensia, 400 ASA). Photographs over the P11 plot were taken in July 1997 from a helicopter, at three altitudes. In each plot, they used mylar balloons filled with helium to serve as spatial landmarks, both during the flight and for further mapping of the canopy. Digital photomosaics were built and inserted in the Paracou GIS. Paper photomosaics were also produced to help locating during field work. Visual interpretation of the photographs was very clear for recognizing some structures within the crown. Trichon & Julien (2006) tested the accuracy of Trichon's (2001) method, obtaining 87% overall tree species identification accuracy, using aerial photography in French Guyana. They used a 5-ha plot for the training set and 16.25 ha for the validation sets. Their terminology was based on crown structural criteria such as shape and texture. The crown criteria to delineate tree species included crown size, status, contour and architecture, foliage cover, texture, color and phenology.

Gonzalez-Orozco et al., 2010 developed an aerial approach to map tree species in Amazonian rainforests. A combination of high-resolution aerial photographs, dichotomous keys and a web-based interface was used for the characterization and identification of tree crowns. Their main objectives were to understand and describe crown properties, suitable for taxonomic identification of 10 taxa; to classify the crown properties in a taxonomical manner, using a dichotomous key, and to determine the accuracy of the keys via a web-based interface. Aerial photography was taken using a Kodak DCS420A digital camera. The camera was mounted vertically in the bottom of the aircraft, level with an open window. Photographs were taken at an elevation of 600 m above the ground, providing images with a pixel size of 21.4 cm and a spatial coverage of 524 m, 348 m. These photographs were used for identification of the crowns and were included in the taxonomic keys. For georeferencing purposes, photographs were also taken at 1200 m above ground. Low-elevation aerial photography, which produces high-resolution data, is not routinely used in the Amazon basin because cloud-free days are rare. Owing to limitations in fuel capacity and high winds which caused unexpected deviation from pre-determined flight routes, it was only possible to cover 80% of the Tiputini Biodiversity Station (TBS) reserve area by airplane. Both high-quality images and distorted imagery was collected. The set of images used for our analysis were those that were not blurred and did not contain irregularities such as shadows and bright illumination. Gyroscopic instrumentation was not used and therefore crowns in these images were geometrically distorted. In order to reduce the motion effect and improve the image quality, a motion compensation frame was used. The camera was calibrated to determine the relationship between the distance of the sensor from the target, the spatial resolution and spatial coverage. Images were also taken from a helium balloon at less than 200 m above the ground. This complementary technique was used to obtain hyper-resolution images of the crowns and establish control points in the observable features of the landscape. The helium balloon images were used as a reference for creating a more robust control point strategy. The combination of the hyper-resolution images (approximately 6 cm pixel size) with the low-elevation airborne imagery was used to improve accuracy in our methodology. The study concluded that crown characteristics, visually identified from aerial photographs, combined with dichotomous keys and a web-based interface, may be a suitable tool for operational purposes, but it should be combined with an automatic classification approach. Identification accuracy averaged 70% for five of the ten taxa studied. Accuracy improved when example images of each tree species were included in the key. The method was well-suited to identify palms and *Cecropia* trees, with an overall accuracy of >70%. Accuracy ranged from 50 to 70% for *Inga* and *Parkia*. Accuracy for the other taxa was <50%. Aerial identification of Amazonian trees using photo-interpretation was less accurate, when the upper layer of the crown had a poorly defined texture e.g. crowns with patterns that contain an irregular surface and low degree of clumping. Taxa that shared common crown properties were the hardest to distinguish. Features that were most indistinguishable were single crowns with foliage textures that vary from mottled to smoky types. *Guarea* and *Pouteria* were the most difficult genera to distinguish using the key.

Garzon-Lopez *et. al*. (2012) evaluated the potential use of canopy tree crown maps, derived from high-resolution aerial digital photographs, as a relatively simple method for measuring large-scale tree distributions. At Barro Colorado Island (BCI), Panama, they used high-resolution aerial digital photographs (~0.129 m/pixel) to identify tree species and map crown distributions of four target tree species. The photographs were taken from a small plane (Cessna 172) that flew parallel transects over BCI. The door of the plane was removed and the photographer took the photographs with a digital camera (12.3-megapixel digital SLR camera -Fuji FinePix S3 Pro- with a 35-mm lens, f-stop 4.5–4.8, shutter speed 1/700–1/1000 s, and ISO speed 400) pointing straight down from the plane while sitting at the entrance and secured with a harness. A constant altitude was maintained. Transects were flown using the directions of a printed flying plan and tracked with a GPS receiver (Garmin 60CSx). Flights were flown in overlapping north-south swaths at an altitude of 400 m in 2005, 700 m in 2006 and 800 and 1000 m in 2007. In 2005, each photograph covered 8.6 ha with a spatial resolution of 0.085 m/pixel. In 2006, coverage and resolution averaged 15.9 ha and 0.114 m/ pixel. The aerial photographs were registered to a geo-referenced March 2004 Quickbird satellite image of BCI (Digital-Globe, Longmont, CO, U.S.A.) using ERDAS IMAGINE v.8.7 software (Leica Geosystems, GA, U.S.A.). They determined crown mapping accuracy by comparing aerial and ground-mapped distributions and tested whether the spatial characteristics of the crown maps reflect those of the ground-mapped trees. Nearly a quarter (22%) of the common canopy species had sufficiently distinctive crowns to be good candidates for reliable mapping. The errors of commission (crowns misidentified as a target species) were relatively low, but the errors of omission (missed canopy trees of the target species) were high. Only 40 percent of canopy individuals were mapped on the air photographs. Despite failing to accurately predict exact abundances of canopy trees, crown distributions accurately reproduced the clumping patterns and spatial autocorrelation features of three of four tree species and predicted areas of high and low abundance. They concluded that visual analysis of high-resolution aerial photography is suitable for the mapping of specific tropical forest canopy tree species across large spatial scales. The method was a relatively low-cost and low-tech alternative to large-scale ground surveys and hyper-spectral remote sensing, with various promising potential applications.

Most researchers in past used photographs taken from customized cameras, mounted on hot-air airships, helicopters, small planes, customized multi-rotor copter drones (Trichon *et al.*, 2006; Morgan *et al.* 2010; Dandois *et al.*, 2013) to develop taxonomical identification systems for tree species, map vegetation mapping or monitor tropical forest dynamics. However, with recent technological advances now allow the use of lightweight unmanned aerial vehicles, flying close to forest canopies, as an alternative to more costly satellite or airborne based imaging systems. UAV’s can cost as little as

USD 300 to a few thousand dollars (Koh and Wich, 2012; Anderson & Gaston, 2013; Getzin *et al.*, 2012).

Paneque-Gálvez *et al.*, 2014, assess a more effective approach using small low cost unmanned aerial vehicle (UAV) to collect data for community-based forest monitoring (CBFM) programs which is a fundamental component of national forest monitoring systems and programs to measure, report and verify REDD+ activities. They discussed about the potential advantages and disadvantages of use of UAV for communities, partner organizations and forest data end-users and to what extent their utilization, coupled with ground surveys and local ecological knowledge, would improve tropical forest monitoring. They reported that the utilization of small drones can enhance CBFM and that this approach is feasible in many locations throughout the tropics if some degree of external assistance and funding is provided to communities.

Zahawi *et al.*, 2015 assessed whether remote sensing measurements from lightweight unmanned aerial vehicles (UAV) are a cost-effective substitute for traditional labor intensive and costly field-based measures for assessing forest recovery and habitat quality. An inexpensive UAV-based remote sensing methodology, ‘‘Ecosynth’’, was applied to measure forest canopy structure across field plots in a 7–9-yr tropical forest restoration study in southern Costa Rica. Ecosynth methods combined aerial images from consumer-grade digital cameras with computer vision software to generate 3D ‘point cloud’ models of vegetation at high spatial resolutions. Ecosynth canopy structure measurements were compared to field-based measures and their ability to predict the abundance of frugivorous birds; key seed dispersers that are sensitive to canopy structure. Ecosynth canopy height measurements were highly correlated with field-based measurements ($R^2 \geq 0.85$), a result comparable in precision to LiDAR-based remote sensing measurements. Ecosynth parameters were also strongly correlated with above-ground biomass ($R^2 \geq 0.81$) and percent canopy openness ($R^2 = 0.82$). Correlations were weaker with proportion-based measures such as canopy roughness ($R^2 = 0.53$). Several Ecosynth metrics (e.g., canopy openness and height) predicted frugivore presence and abundance at levels of accuracy similar to those of field-based measurements. Therefore, they reported that Ecosynth UAV remote sensing provides an effective alternate methodology to traditional field-based measures of evaluating forest structure and complexity across landscapes.

Baena *et al*., 2017 studied if UAVs offer an affordable alternative to satellites in obtaining both color and near infrared imagery to meet the specific requirements of spatial and temporal resolution of a monitoring system. Combining this with their capacity to produce three dimensional models of the environment provides an invaluable tool for species level monitoring. They demonstrated that object-based image analysis of very high-resolution UAV images can identify and quantify keystone tree species and their health across wide heterogeneous landscapes. The analysis exposes the state of the vegetation and serves as a baseline for monitoring and adaptive implementation of community-based conservation and restoration in the area.

Onishi & Ise (2018) developed a machine vision system for the automatic classification of trees using an unmanned aerial vehicles (UAV) and a publicly available package for deep learning. They segmented the UAV image of forest into individual tree crowns and carried out object-based deep learning. As a result, the system was able to classify 7 tree types (deciduous broad-leaved, deciduous coniferous, evergreen broad-leaved, *Chamaecyparis obtuse, Pinus strobus, Pinus elliottii, Pinus taeda*) at 89.0% accuracy. This research was notable, because they only used basic RGB (red green blue) images from a DJI Phantom 4 drone and displayed the potentiality to classify individual tree species in a very cost-effective manner, which can become an important tool for forest researchers and managers.

1.2. Objectives of the study

The objectives of this study were:

1) To develop taxonomic keys to identify tree species from digital aerial photographs taken by an on-the-shelf UAV, based on:
    a) crown morphology (type, shape, texture);
    b) leaf characteristics (shape, arrangement);
    c) phenology (leaf fall/flush, flowering, fruiting, etc.);
    d) image filtering (hue, saturation, brightness) using Image-J.
2) To test the reliability and efficacy of such keys to locate tree species in unknown forest.

Chapter 2

Materials and Methodology

1. Study Area

The study area was located at Ban Mae Sa Mai (BMSM) (18◦51′29.38″N 98◦50′53.60″E), Doi Suthep-Pui National Park in Northern Thailand (1,360 m above sea level) (Figure 2.1), which is about 30 km away from Chiang Mai city. The research was carried out in two restored forest plots namely; 98.2 (Training plot) and 98.3 (Validation plot) each with a total area of 0.0064 km2. The forest in both of these plots had been restored by Forest Restoration Research Unit, Chiang Mai University (FORRU-CMU), in collaboration with local communities using the framework species method, in the year 1998. The climate in northern Thailand consists of three seasons; rainy (mid-May to mid-October), winter (mid-October to mid-February) and summer (mid-February to mid-May). The extreme temperature for 2005-2010 in Doi Ang Kang meteorology station, Chiang Mai province, located at similar altitude ranged from 3.9°C (winter) to 32.1°C (summer). The average annual rainfall (2005-2015) at Doi Ang Kang meteorology station, Chiang Mai province located at similar altitude was 1897.6 mm (Thailand Meteorological Department).

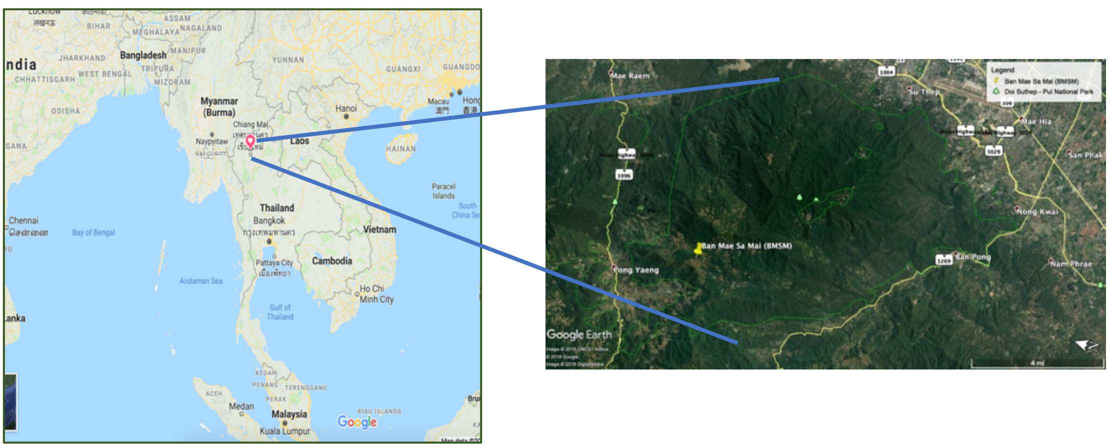


Figure 2.1 Location of study area at Doi Suthep-Pui National Park, Northern Thailand

2. The Framework Species Method

The forest in the study site had been restored using the framework species method of forest restoration as follows. The framework species method involves planting the minimum number of tree species required to re-instate the natural processes of forest regeneration and recover biodiversity. It combines the planting of 20-30 key tree species with various assisted natural regeneration (ANR) techniques to enhance natural regeneration, creating a self-sustained forest ecosystem from a single planting event. Originally conceived in Northern Queensland, to repair damaged tropical rainforest (Goosem & Tucker, 1995), the framework species method has been successfully modified to restore seasonally dry tropical forests to deforested sites in northern Thailand's conservation areas (Elliott *et al.*, 2003).

Framework trees are indigenous, non-domesticated, forest tree species, which, when planted on deforested sites, rapidly re-establish forest structure and ecological functioning, whilst attracting seed dispersing wildlife. Thus, framework tree species promote dispersal of seeds from nearby forest and create conditions conducive to their germination, resulting in recruitment of tree species in planted plots (Figure 2.2). The essential ecological characteristics of framework tree species are therefore:

a) High survival when planted out in deforested sites;
b) Rapid growth;
c) Dense, spreading crowns that shade out herbaceous weeds;
d) Flowering and fruiting, or provision of other resources, at a young age, which attract seed-dispersing wildlife.
e) Easy to propagate

In the seasonally dry tropics, where wild fires in the dry season are an annual hazard, an additional essential characteristic of framework species is resilience after burning. When fire prevention measures fail, the success of forest restoration plantings can depend on the ability of the planted trees to re-sprout from their rootstock after fire has burnt their shoot systems (i.e. coppicing).

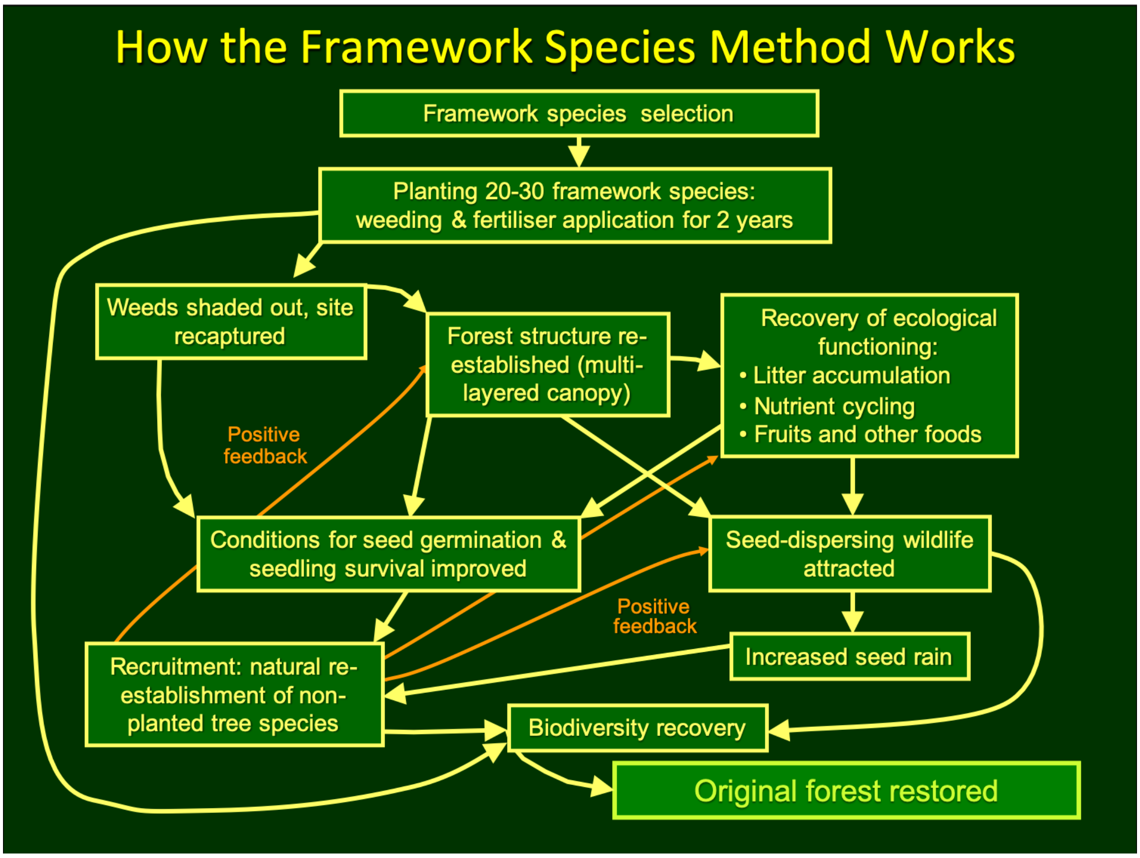


Figure 2.2 How Framework species method works

3. Methodological Strategy

3.1. Mapping and Ground truthing of selected species

Digital aerial photographs were obtained over the training plot (98.2) using a DJI Phantom 4 Pro at an altitude of 100 m above ground in June 2018. The aerial photographs were taken at 50-70 % overlap which was adjusted manually while photographs were taken (Figure 2.3).

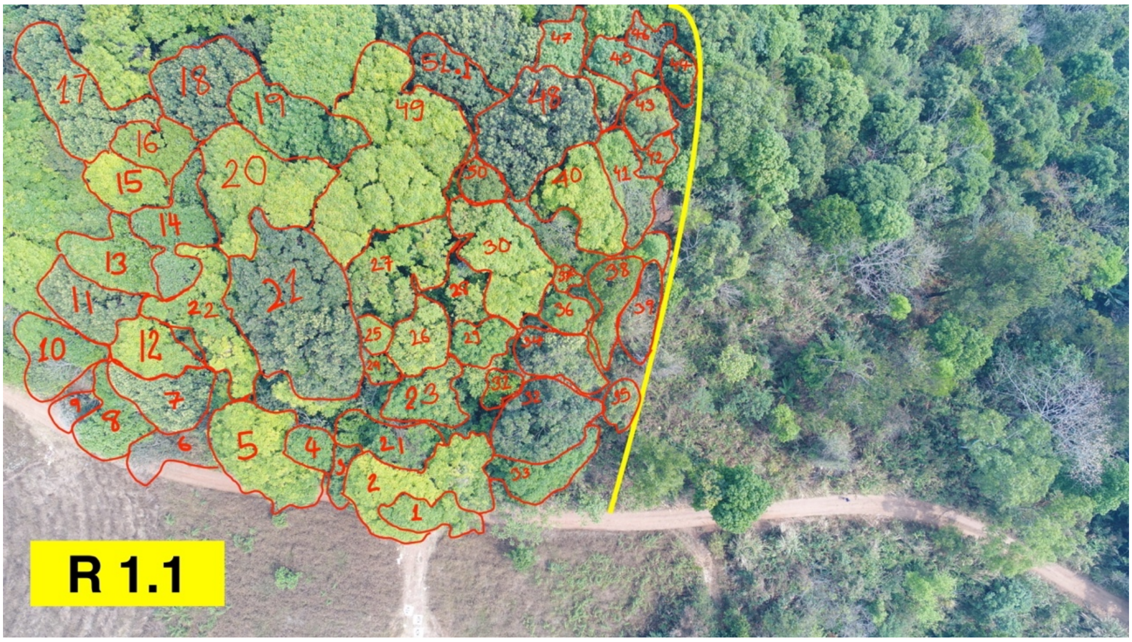


Figure 2.3 Snapshot of marked crowns in macOS Preview App

The digital aerial photographs were then analyzed by eye. All visible crowns were marked and numbered using a freehand marker in the Preview App (MacOS) (as shown in Figure 2.3). Ground truthing was then carried out, to locate and match tree crowns at ground with those in the images. The selection of tree species for the study was based on minimum number of crowns which we were able to locate and match at the field. The minimum threshold for number of crowns for a species to be selected was set at 3 crowns per species in order to study variation within species (Table 2.2).

The tree species were identified by locating identification tags attached to the trees by a previous FORRU-CMU study. For trees without such tags, leaf samples were voucher specimens were collected and compared with named specimens in the CMU Herbarium.

A total of 48 tree crowns of nine tree species were identified and used to develop keys in the training plot (98.2) (Table 2.2). The selected tree species for the study are listed in Table 2.1.

Table 2.1 List of selected tree species for study

SN	Family	Species	
1	Moraceae	*Artocarpus gomezianus* Wall. Ex Trecul	Evergreen
2	Fagaceae	*Castanoposis calathiformis* (Skan) Rehder & E.H. Wilson	Evergreen
3	Fagaceae	*Castanopsis tribuloides* (Sm.) A.DC.	Evergreen
4	Anacardiaceae	*Choerospondias axillaris* (Roxb.) B.L. Burtt & A.W. Hill	Deciduous
5	Moraceae	*Ficus altissima* Blume	Evergreen
6	Magnoliaceae	*Magnolia garrettii* (Craib)V.S. Kumar	Deciduous
7	Pinaceae	*Pinus kesiya* Royle ex Gordon	Evergreen
8	Rosaceae	*Prunus cerasoides* Buch, Ham.ex D. Don	Deciduous
9	Meliaceae	*Toona ciliata* M. Roem	Deciduous

Table 2.2 Number of tree crowns of target species used to develop keys (training plot)

SN	Target species	Number of tree crowns used to develop keys
1	*Artocarpus gomezianus*	4
2	*Castanopsis calithiformis*	5
3	*Castanopsis tribuloides*	4
4	*Choerospondias axillaris*	8
5	*Ficus altissima*	6
6	*Magnolia garrettii*	7
7	*Pinus kesiya*	3
8	*Prunus cerasoides*	7
9	*Toona ciliata*	4
Total number of tree crowns		48

4. Digital Aerial Photograph Acquisition

4.1. Materials Used

4.1.1. DJI Phantom 4 Pro

The DJI Phantom 4 Pro is an unmanned aerial vehicle (UAV) equipped with a 20-megapixel camera (1-inch CMOS sensor) on a gimbal. It comes with an “intelligent” battery, which enables flights of up to 30 minutes (Figure 2.4) and it has obstacle sensing in 5 directions (excluding straight up) made up of vision and infrared sensors, so is ideal for flying close to tree crowns without crashing into them.

Figure 2.4 DJI Phantom Pro 4 at BMSM Training plot

4.1.2. LITCHI Application

Litchi is one of the most popular autonomous flight applications used to fly hobbyist drones. Waypoints and points of interest are easily set in advanced, using Google Earth or the application's "flight hub" in a browser on a laptop or directly on the tablet that is used to control the drone's flight. These waypoint "missions" allow the app to provide smooth and slow, pre-programmed flights, which result in accurately and consistently placed photographs, every time the saved missions are flown. Missions are completed autonomously, regardless of whether or not there is a signal between the drone and the controller, because the flight plan is uploaded into the on-board memory of the drone at the start (Figure 2.5).

Figure 2.5 Snapshot of LITCHI application

4.2. Photograph Acquisition Procedure

4.2.1. Digital Aerial Photographs

Aerial digital photographs were acquired from DJI Phantom 4 Pro digital camera at an altitude of 50 meters above ground, over all individual target tree species, once every month for eight months (June 2018 to January 2019). In order to maintain uniformity of the quality of photographs for all months, the ISO camera setting for DJI Phantom Pro 4 was set to automatic (Figure 2.6). In automatic settings, the ISO range (100-3200), Mechanical shutter speed (8-1/2000s) and Electronic shutter speed (8-1/8000s).

Figure 2.6 Snapshot of camera ISO setting

4.2.2. Flight Plans

The GPS coordinates of all the target trees were recorded on the ground use a handheld GPS receiver and then used to program flight plans in the LITCHI application. At first, I prepared three (3) flight plans for training and one (1) for the validation plots. However, I realized that I had included too many waypoints to complete within the charge of the UAV battery. Therefore, the number of flight plans was increased to four (4) for the training plot and one (1) for validation plot (Figure 2.7).

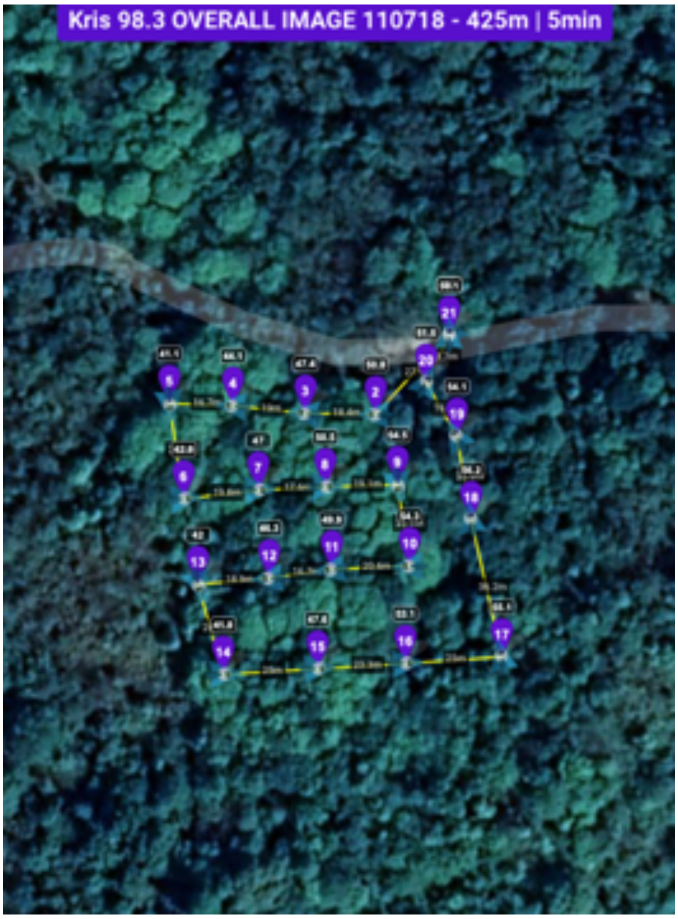


Figure 2.7 Flight plan of validation plot

4.3. Photograph Acquisition

Photography along the fixed flight plans was repeated monthly from June 2018 to January 2019, using the DJI Phantom 4 Pro, flown 50 m above the ground using the Litchi flight planning software. The resolution of the photograph was 5472 x 3078 pixels.

5. Weather during the study period

Northern Thailand experiences incessant rain during months of June to August. In 2018, rain continued until end of October, which proved quite a challenge since the drone cannot be flown in rain. I often had to wait for hours for the weather to clear before the drone could be flown safely. Photographs were mostly acquired between 10:30 to 13:00 h. The sky was usually overcast with some intermittent sunshine during the wet season and mostly clear with plenty of sunshine during dry season (Figure 2.8).

Figure 2.8 Pictures of weather conditions at study area during wet season

6. Development of Dichotomous keys

The digital aerial photographs were analyzed to develop dichotomous keys based on crown and leaf characteristics, phenology and image filtering (Image J).

6.1. Materials used

6.1.1. MacOS (Macintosh Operating System) Preview Application (app)

Preview app is an image and Portable Document Format (PDF) viewer app in MacOS; it enables users to view and print digital images and PDF files (Figure 2.9). Digital aerial photographs from field were stored in a personal computer (PC) in Joint Photographic Experts Group (JPEG) file format. These photographs were then viewed using MacOS Preview App for describing and developing keys based on crown and leaf characteristics and phenological observations and image filtering.

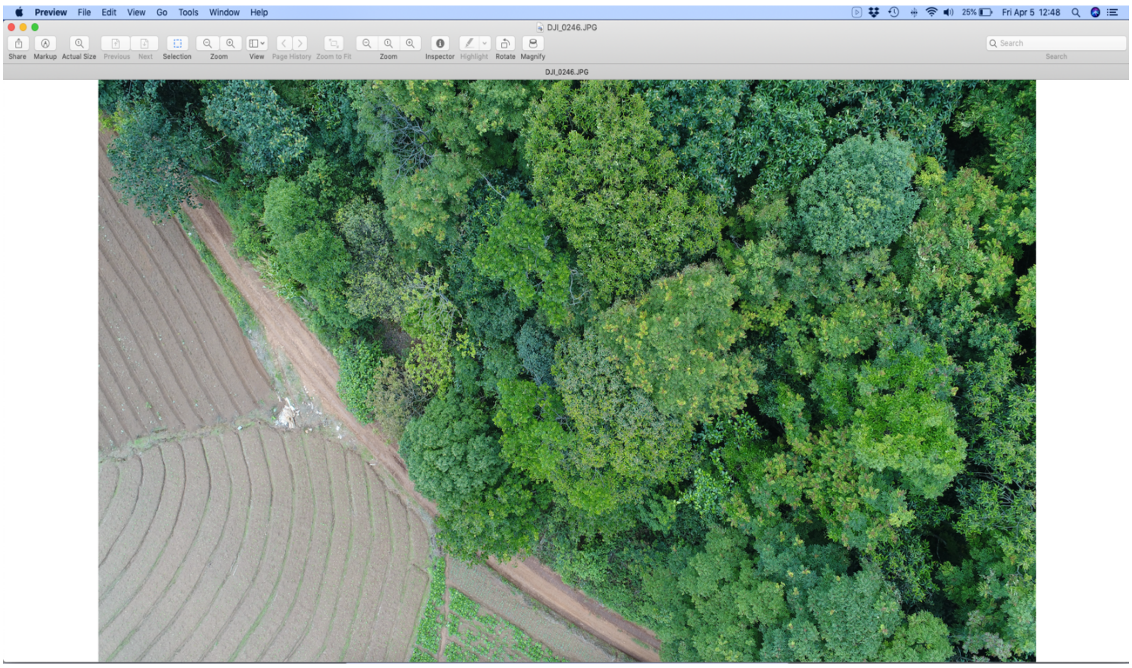


Figure 2.9 Snapshot of macOS Preview app viewer

6.1.2. Image J

Image J is a free, public-domain, Java, image-processing program developed by the National Institute of Health (NIH), United States of America. It runs, either as an online applet or as a downloadable application, on any computer with a Java 1.4 or later virtual machine. It can display, edit, analyze, process, save and print images of various resolutions and formats. It can be used to measure distances and areas on digital photos, by relating numbers of pixel to known measurements, but for this project the main function used was the image filtering tool on RGB (Red, Green, Blue) images using hue, saturation and brightness filters. Hue describes the attribute of pure color, and therefore distinguishes between colors. Saturation (sometimes called "purity" or "vibrancy") characterizes the shade of color, i.e., how much white is added to the pure color. Brightness (also known as Value) describes the overall brightness of the color. The tool colors red any pixels that fall within the range of the hue, saturation and brightness levels that are set by the user. So, for example a tree species with foliage of a more yellowish green than the surrounding trees could be picked out in red, by selecting the yellow end of the spectrum in the hue setting (Figure 2.10). The image J software can be downloaded from publicly available website https://imagej.nih.gov/ij/download.html.

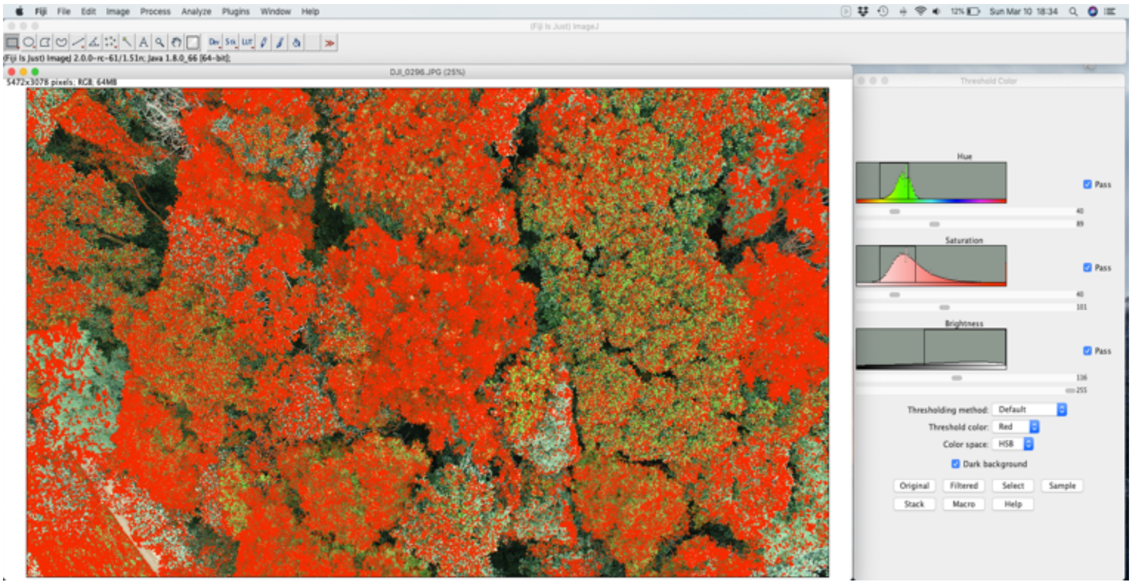


Figure 2.10 Snapshot of Image J software

6.2. Methodology

6.2.1. Crown, leaf, Image filtering and phenological keys

Tree crown and leaf keys were developed observing the digital aerial photographs obtained from the field using MacOS preview app (Figure 2.9). All visible characteristics in photographs were reviewed and selected as description properties. The details are presented in following paragraphs.

6.2.2. Description of Crown Keys

Trichon & Julien (2006) and Gonzalez-Orozco *et al*., 2010 crown criteria were modified and adapted to match the crown types of the tree species selected for this study. Several descriptors of each of 7 crown properties were developed as presented in Table 2.3.

Table 2.3 Properties used for describing tree crowns. Adapted and modified Trichon & Julien (2006) and Gonzalez-Orozco et. al. (2010)

SN	Crown properties	Descriptor/class	Description
1	Crown Type (CT)	Single	Crown entire without sub-division
		Multiple	A crown that has two or more sub-divisions within with each component resembling an individual crown
2	Vertical Crown Shape (VCS)	Slightly rounded, more rounded, hemispherical, pointed	Described based on intensity of curvature at the highest point of crown surface. Pointed > hemispherical > more rounded > slightly rounded
		Flat	Crown surface appears to be more or less horizontal

Table 2.3 (Continued)

SN	Crown properties	Descriptor/class	Description
3	Horizontal Crown Shape (HCS)	Round, oval, elongated, star shaped, irregular	Described based on ratio of crown length: crown breadth: if 1:1 = round; if 1.5:1 = oval; if 2:1 = elongated; if crown shape does not follow above patterns, it is described as "irregular".
4	Crown Margin (CM)	Entire, crenulated, lobed	Entire - if the crown margin is more or less smooth without marked indentations; crenulated - if crown margin has indentations penetrating less than 25% towards to Centre; lobed - crown with deep indentations (>25%). towards its center
5	Foliage Texture (FT)	Smooth	Branches or any other lower elements concealed by dense compact foliage
		Rough	Branches or any other lower elements are distinguishable through the foliage
6	Crown Color (CC)	Green, yellow, red, brown, white, pink, blue	Shades of color or mixture of colors
7	Phenology	Leaf flush, Leaf fall* (described as crown density of 0, 3/4, 1/2, 1/4, 1), flowering, fruiting	Phenological phenomenon at the crown level

*To describe the extent of leaf fall, the concept of crown density developed by Koelmeyer (1947) was used. A tree with full crown of mature leaf was considered to have a crown density of 1 while one which had shed all its leaf was considered to have a crown density of 0. Intermediate degrees of leaf shed were recorded by fractions of 3/4, 1/2, 1/4. The minimum crown density thus, determines the maximum extent of leaf shed.

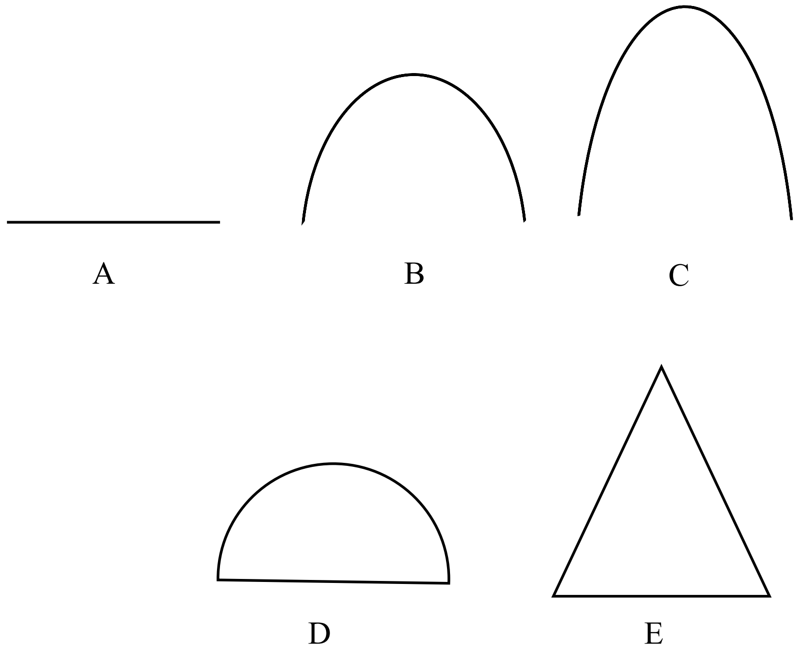


Figure 2.11 Graphical representation of vertical tree crown shape properties (A) flat, (B) slightly rounded, (C) more rounded, (D) hemispherical and (E) pointed.

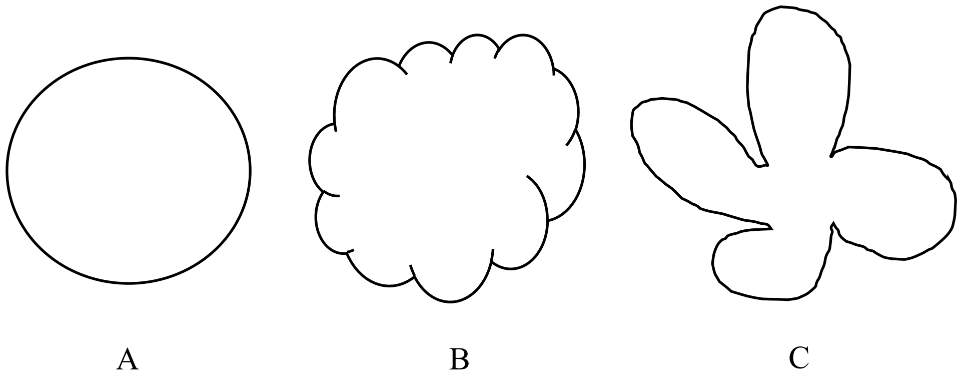


Figure 2.12 Graphical representation of tree crown margin properties (A) entire (B) crenulated and (C) lobed

6.2.3. Description of Leaf keys

Since the UAV was flown close to the tree crowns (<30 m) and was equipped with a high-resolution camera, leaf characteristics, hitherto unobservable from conventional remote sensing platforms, could be recorded. Accordingly, leaf properties and descriptors were developed, based on conventional leaf taxonomy. I selected four of the most distinctive leaf properties to distinguish among the target tree species (Table 2.4).

Table 2.4 Properties used for describing leaves and their descriptors. Adapted & modified from Gardner et al. (2007)

SN	Leaf properties	Descriptor
1	Leaf Type (LT)	Simple or compound
2	Leaf Arrangement (LA)	Alternate, opposite, spiral, whorled, bundled, imparipinnate, paripinnate
3	Leaf Shape (LS)	Lanceolate, ovate, elliptic, oblong, needle-like, elliptic
4	Leaf Color (LC)	Green, pink, yellow, red, mixture of colors, shades of color

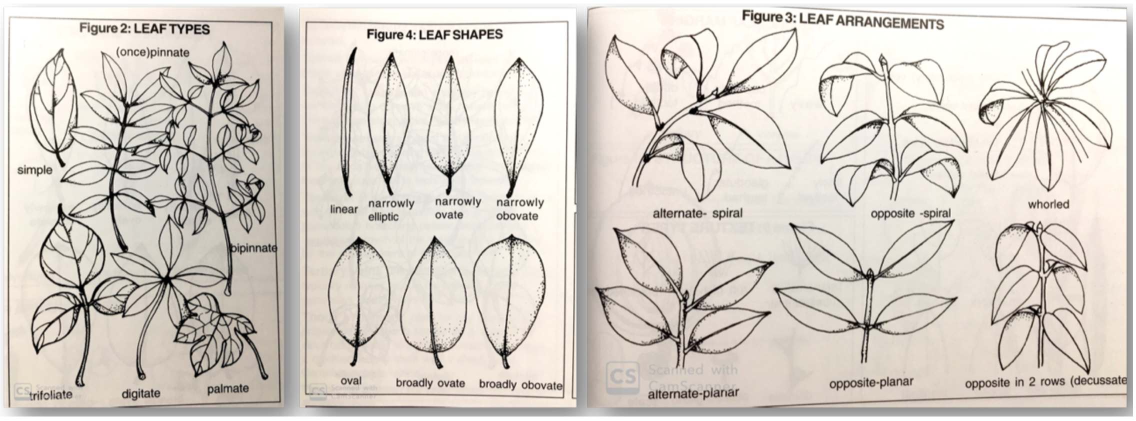


Figure 2.13 Snapshot of graphical representation of properties used to describe leaf (Gardner et al., 2007)

6.2.4. Image filtering keys

Keys, based on quantifiable filtering of image hue, saturation and brightness (HSB) were developed. Hue describes the attribute of pure color; saturation characterizes the shade of color and Brightness describes the overall brightness of the color. Image J software was used to develop these keys. The digital photographs from the field were loaded into Image J software, and the color threshold filter were applied and fiddled the Hue, Saturation & Brightness sliders until all crowns of the target species turned red. The stepwise process of image filtering key development process is demonstrated in Figure 2.14.

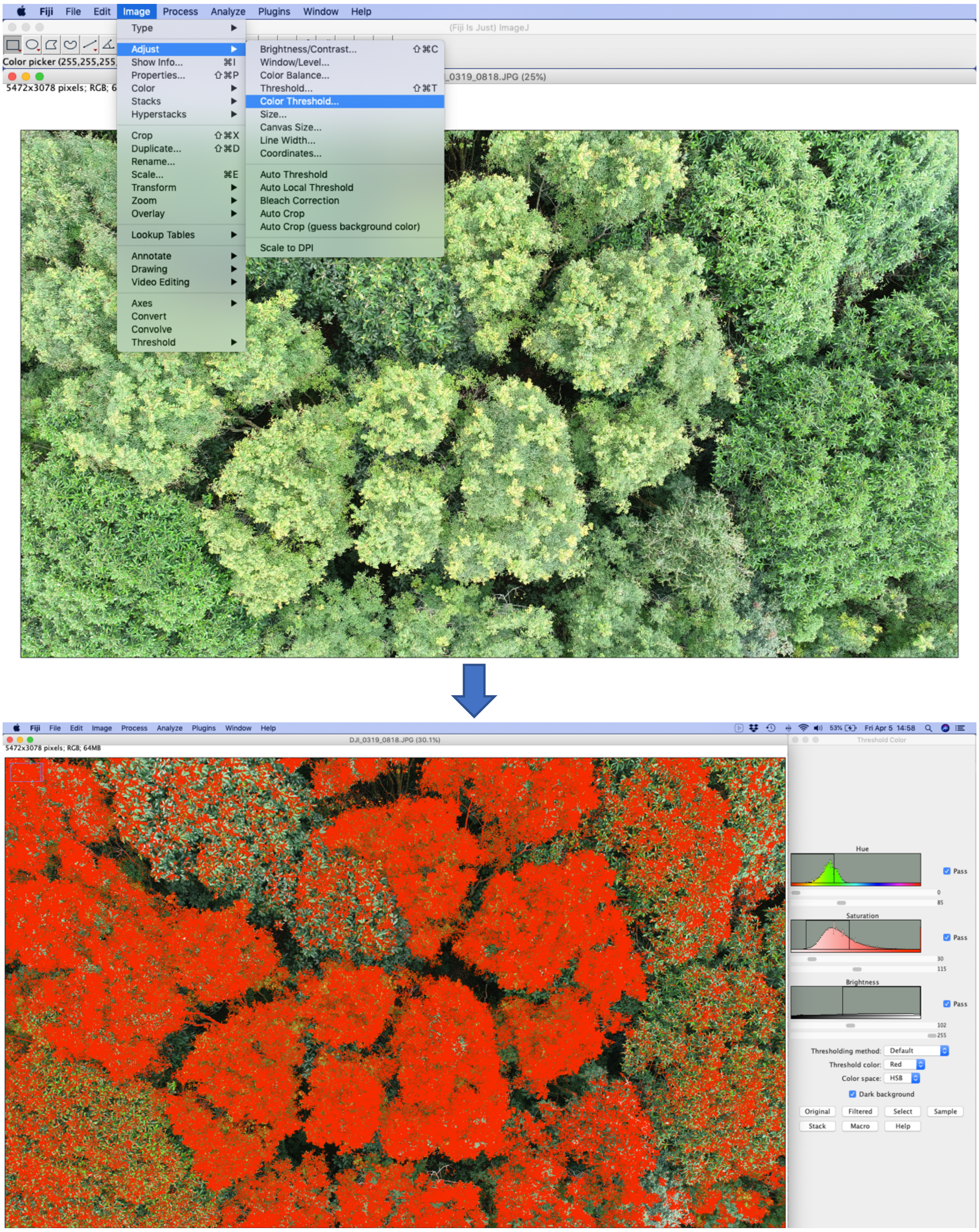


Figure 2.14 Stepwise procedure to develop image filtering keys

Since crown, leaf and Image filtering properties varies with season, separate keys were developed for each month of the study.

6.2.5. Validation of keys

Key validation was carried out by adapting and modifying the methods of Trichon & Julien (2006) and Gonzalez-Orozco (2010).

Eleven (11) volunteer 'photo-interpreters' participated in validation process. It comprised of 3 undergraduate students, 5 postgraduate students and 3 staff from Forest Restoration Research Unit, Chiang Mai University (FORRU-CMU) and came originally from Laos, Liberia, USA and Thailand. The key validation was conducted in three batches over February 12-14, 2019.

6.3. Validation Procedure

6.3.1. Pre-validation activities

The validation activity was carried out in CMU Biology department's computer laboratory. Image J software and a folder consisting of one target crown key and two unidentified photographs for each species were preinstalled in the computers used for the validation process. The photographs for seven months (July 2018 to January 2019) were used for validation activity. The folder provided to each photo-interpreter comprised of photographs of nine species and all seven months, which was randomly mixed. For instance, if photograph for *Artocarpus gomezianus* was of July; then, *Castanopsis calathiformis* was for month of August 2018 and so on. The target species sample size and the number of photo-interpreters involved in each month's key validation are shown in Table 2.5 and Appendix C- Key Validation Results).

For two tree species (*Pinus kesiya* and *Toona ciliata*) that were absent from validation plot (98.3); therefore, I used photographs from the training plot (98.2). I had counted crowns of all the target tree species in each unidentified photograph prior to validation.

6.3.2. Validation Day activities

The photo-interpreters were briefed about the key development process and definition of terminologies used using Microsoft PowerPoint. Each photo-interpreter were provided with printed copies of dichotomous and monthly tree species identification keys and step-wise direction on 'how to use Image J software'. In order to identify tree species, photo-interpreters were directed to open the unidentified photographs in Microsoft Paint software. The photo-interpreters then drew a circle around each tree they recognized as one of the 9 target species, using paint brush and then save it in same folder An example of crown key and unidentified photographs provided to photo-interpreters is presented in Figure 2.15. All folders were collected and then results were analyzed.

Table 2.5 Target species sample size (no. of trees) and photo-interpreters involved in validation

SN	Target species and photo-interpreters (nos.)	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1	*Artocarpus gomezianus*	11	20	9	8	4	4	5
	Photo-interpreter	2	3	2	1	1	1	1
2	*Castanopsis calathiformis*	4	26	-	27	7	10	3
	Photo-interpreter	1	3	-	3	2	1	1
3	*Castanopsis tribuloides*	3	8	8	6	5	2	4
	Photo-interpreter	1	2	3	2	1	1	1
4	*Choerospondias axillaris*	6	6	6	14	23	21	12
	Photo-interpreter	1	1	1	2	3	2	1
5	*Ficus altissima*	4	2	3	1	3	4	6
	Photo-interpreter	1	1	1	1	1	2	3
6	*Magnolia garrettii*	17	7	9	3	8	17	15
	Photo-interpreter	2	1	1	1	1	2	3
7	*Pinus kesiya*	4	6	7	3	3	2	2
	Photo-interpreter	2	3	2	1	1	1	1
8	*Prunus cerasoides*	2	3	2	1	1	1	1
	Photo-interpreter	2	3	2	1	1	1	1
9	*Toona ciliata*	3	7	9	6	4	3	3
	Photo-interpreter	1	2	3	2	1	1	1

Figure 2.15 Photographs of (A) crown key (*Artocarpus gomezianus*) and the unidentified photograph (B) provided for the key validation to photo-interpreters

6.3.3. Data Analysis

The key validation results were reported as % found (trees correctly identified as target species), % error of omission (missed trees of the target species) and % error of commission (trees misidentified as target species). The formulae to analyze the key validation data was modified and adapted from Gonzalez-Orozco *et al.* (2010).

% Found (F) was calculated as:

Equation 1. 1

$$\mathrm{F} = {n^f}/{T} \times \ 100\%$$

where 'n^f' is total number of crowns correctly identified as target species; 'T' is total number of target crowns per species in the photograph;

% Error of Omission (O) was calculated as:

Equation 1. 2

$$\mathrm{O} = {n^o}/{T} \times \ 100\%$$

where 'n^o' is total number crowns of missed trees of target species; 'T' is total number of target crowns per species in the photograph;

% Error of Commission (C) was calculated as:

Equation 1. 3

$$\mathrm{C} = {n^c}/{T} \times \ 100\%$$

where 'n^c' is total number of crowns incorrectly identified as target species; 'T' is total number of target crowns per species in photograph.

The data analysis was carried out using the formulae as stated above for validation results of all individual photo-interpreters and then the final results were reported as average percentage of all 11 photo-interpreters.

Chi-square test was carried out for the results to test for data's statistical significance. SPSS (Statistical Package for Social Science) and ANOVA (Analysis of variance) was used to test for any co-relationship between % found, % Error of Omission, % Error of Commission with tree species and months.

Chapter 3

Results

1. Crown Dichotomous keys

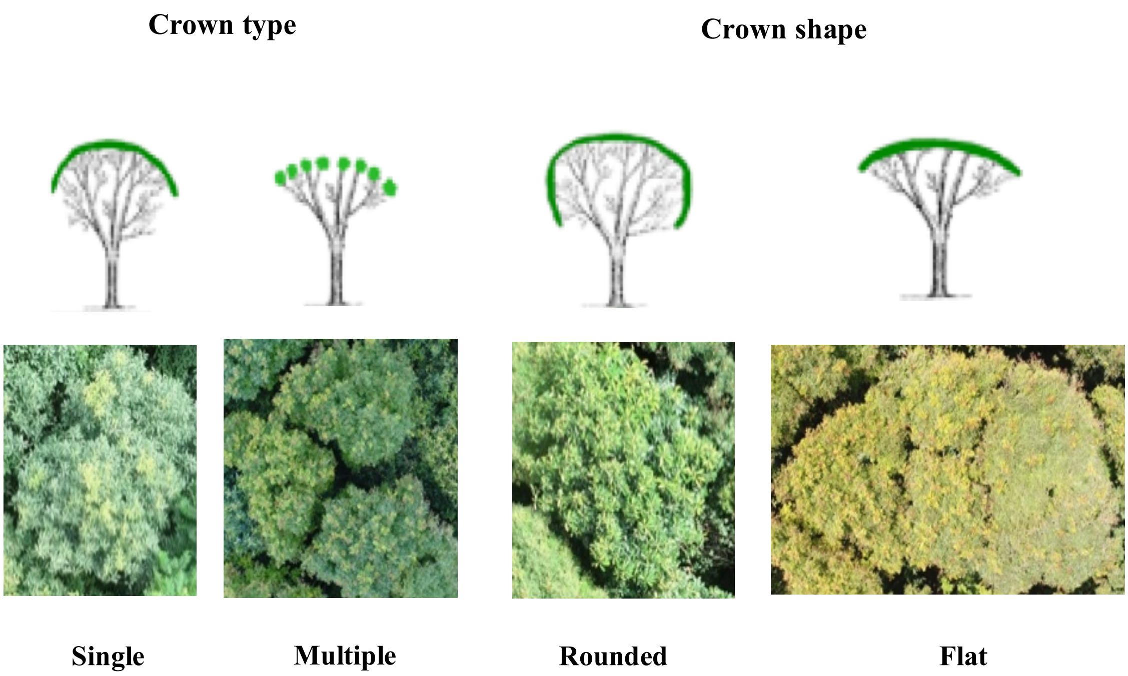
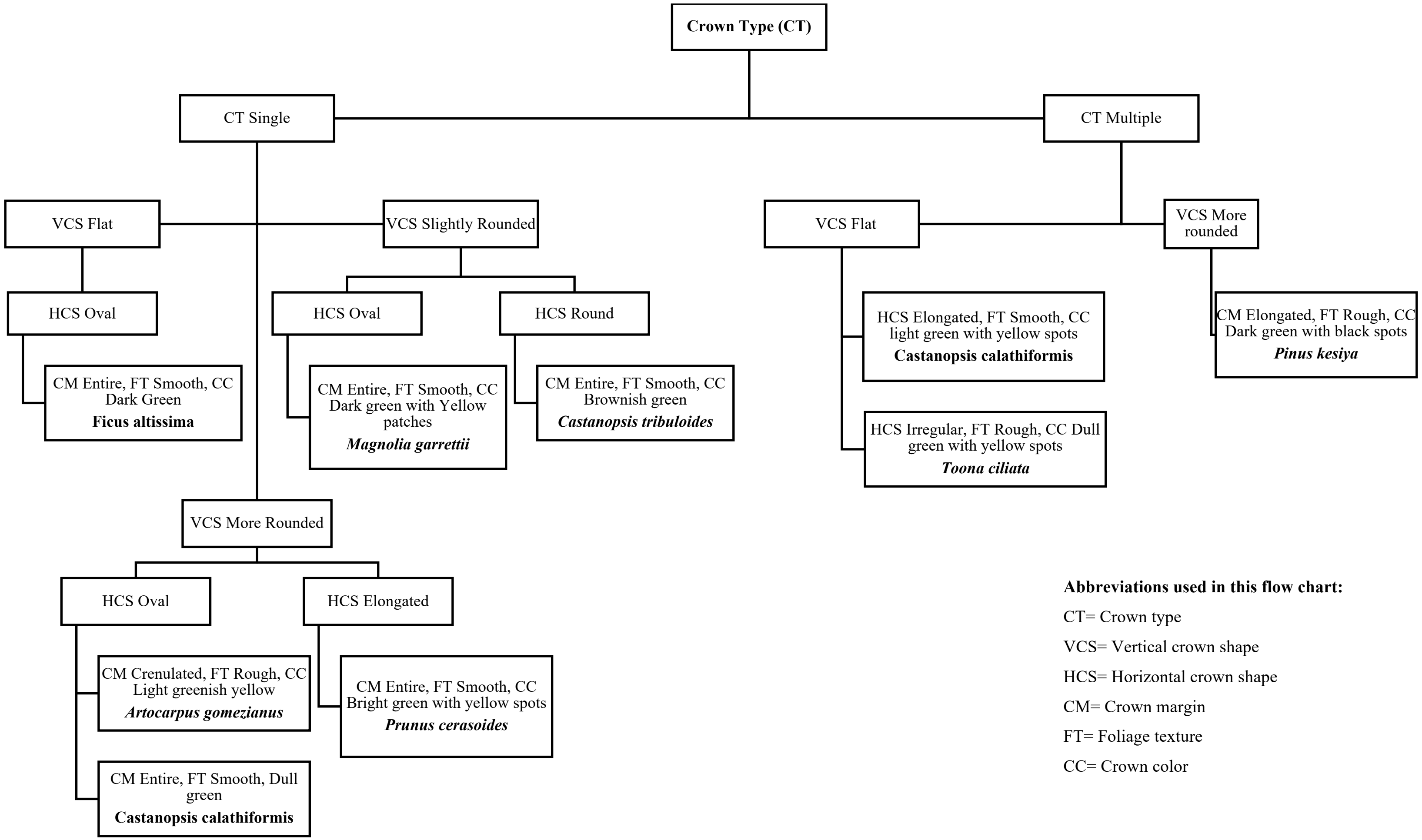


Figure 3.1 Photographs illustrating the most common crown properties in Ban Mae Sa Mai, Doi Suthep-Pui National Park, Northern Thailand

Figure 3.2 Aerial digital photographs of crowns of nine tree species studied in Ban Mae Sa Mai, Doi Suthep-Pui National Park, Northern Thailand. (1) *Artocarpus gomezianus,* (2) *Castanopsis calathiformis,* (3) *Castanopsis tribuloides,* (4) *Choerospondias axillaris,* (5) *Ficus altissima,* (6) *Magnolia garrettii,* (7) *Pinus kesiya,* (8) *Prunus cerasoides,* (9) *Toona ciliata*

Table 3.1 Key A: Crowns (June 2018). For abbreviations see Table 2.3.

A1	Tree crown type single → A2; multiple → A10
A2	VCS flat → A3; slightly rounded → A4; more rounded → A7
A3	HCS oval, CM entire, FT smooth, CC dark green ………......***Ficus altissima***
A4	HCS oval → A5; round → A6
A5	CM entire, FT smooth, CC dark green with yellow patches ………………………………………...………..….***Magnolia garrettii***
A6	CM entire, FT smooth, CC brownish green………...***Castanopsis tribuloides***
A7	HCS oval → A8; elongated → A9
A8	CM crenulated, FT rough, CC light greenish yellow…………………………………………… ***Artocarpus gomezianus***
	CM entire, FT smooth, CC dull green ………...…***Castanopsis calathiformis***
A9	CM entire, FT smooth, CC bright green with yellow spots ……………………………………………………….....***Prunus cerasoides***
A10	VCS flat → A11; more rounded → A12
A11	HCS elongated, FT smooth, CC light green with yellow spots…………………………………………..…***Choerospondias axillaris***
	HCS irregular, FT rough, CC dull green with yellow spots……………………………………………….....……..***Toona ciliata***
A12	CM elongated, FT rough, CC dark green with black spots …………………………………………………......……***Pinus kesiya***



Abbreviations used in this flow chart:

CT= Crown type

VCS= Vertical crown shape

HCS= Horizontal crown shape

CM= Crown margin

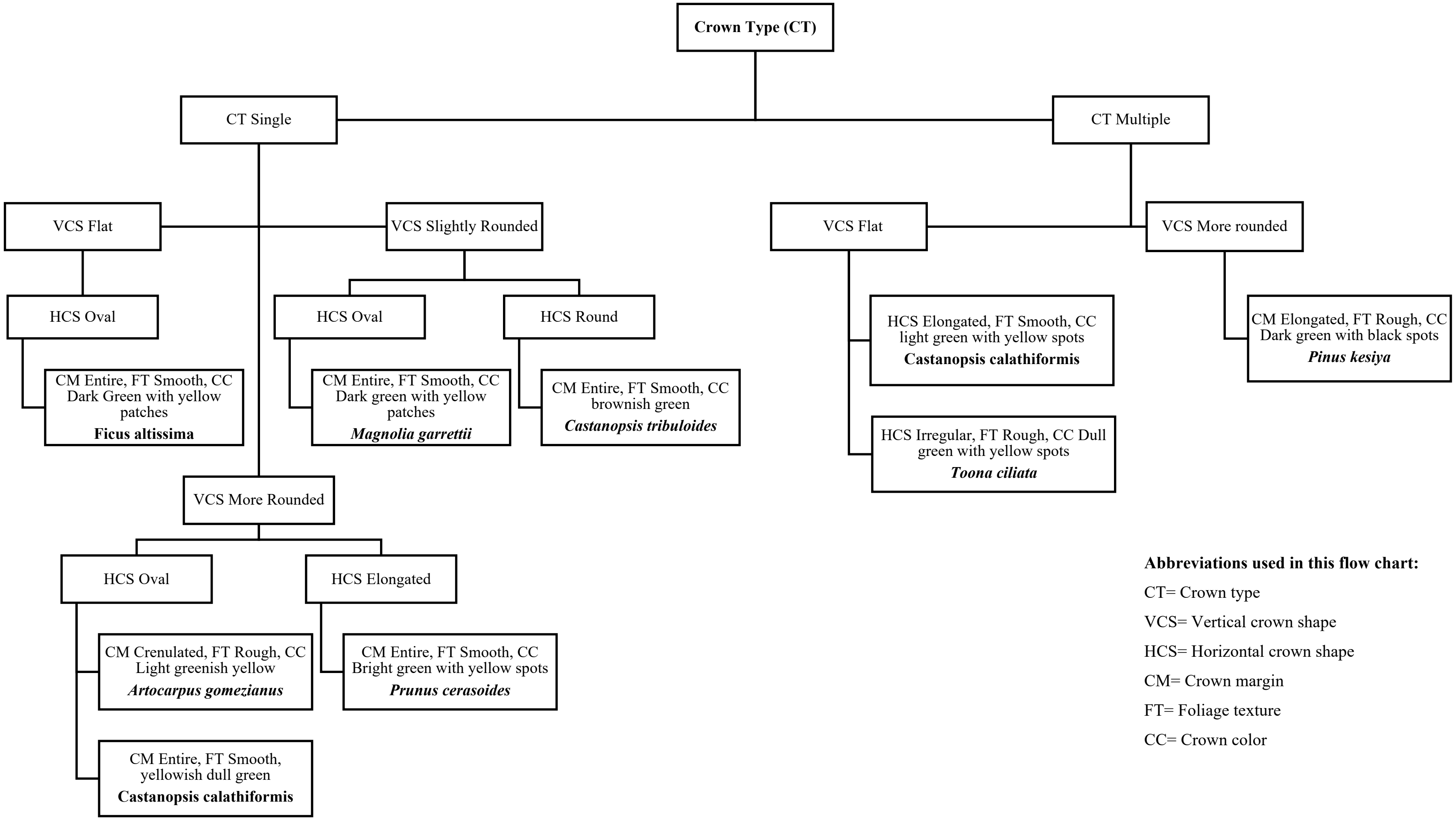
FT= Foliage texture

CC= Crown color

Figure 3.3 Flow chart of tree crown dichotomous keys (June 2018)

Table 3.2 Key A; Crowns (July 2018). For abbreviations see Table 2.3.

A1	Tree crown type single →A2; multiple → A10
A2	VCS flat → A3; slightly rounded → A4; more rounded →A7
A3	HCS oval, CM entire, FT smooth, CC dark green with yellow patches…………………………………………………………***Ficus altissima***
A4	HCS oval → A5; round → A6
A5	CM entire, FT smooth, CC dark green with yellow patches………………………..……………….………..***Magnolia garrettii***
A6	CM entire, FT smooth, CC brownish green……………………………………….............***Castanopsis tribuloides***
A7	HCS oval →A8; elongated → A9
A8	CM crenulated, FT rough, CC light greenish yellow…………………………………………….....***Artocarpus gomezianus***
	CM entire, FT smooth, yellowish dull green………………………………….…………..***Castanopsis calathiformis***
A9	CM entire, FT smooth, CC bright green with yellow spots……………………………………………………….. ***Prunus cerasoides***
A10	VCS flat → A11; more rounded → A12
A11	HCS elongated, FT smooth, CC light green with yellow spots…………………………………………......***Choerospondias axillaris***
	HCS irregular, FT rough, CC dull green with yellow spots
A12	CM elongated, FT rough, CC dark green with black spots…………………………………………………...……..***Pinus kesiya***



Abbreviations used in this flow chart:

CT= Crown type

VCS= Vertical crown shape

HCS= Horizontal crown shape

CM= Crown margin

FT= Foliage texture

CC= Crown color

Figure 3.4 Flow chart of tree crown dichotomous keys (July 2018)

Table 3.3 Key A; Crowns (August 2018). For abbreviations see Table 2.3.

A1	Tree crown type single → A2; multiple → A10
A2	VCS flat → A3; slightly rounded → A4; more rounded → A7
A3	HCS oval, CM entire, FT smooth, CC dark green with yellow patches.…………………………………..………….………***Ficus altissima***
A4	HCS oval → A5; round → A6
A5	CM entire, FT smooth, CC dark green with yellow patches…………………………………..……..................***Magnolia garrettii***
A6	CM entire, FT smooth, CC brownish green…………………………………………….…..***Castanopsis tribuloides***
A7	HCS oval → A8; elongated → A9
A8	CM crenulated, FT rough, CC dark green………..***Artocarpus gomezianus***
	CM entire, FT smooth, brownish green…………………………………….………….…***Castanopsis calathiformis***
A9	CM entire, FT smooth, CC bright green…...……….....…..***Prunus cerasoides***
A10	VCS flat → A11; more rounded → A12
A11	HCS elongated, FT smooth, CC light green with yellow spots……………………………………..................***Choerospondias axillaris***
	HCS is irregular, FT rough, CC dull green…………….............***Toona ciliata***
A12	CM elongated, FT rough, CC dark green with black spots………………………………………………………….……***Pinus kesiya***

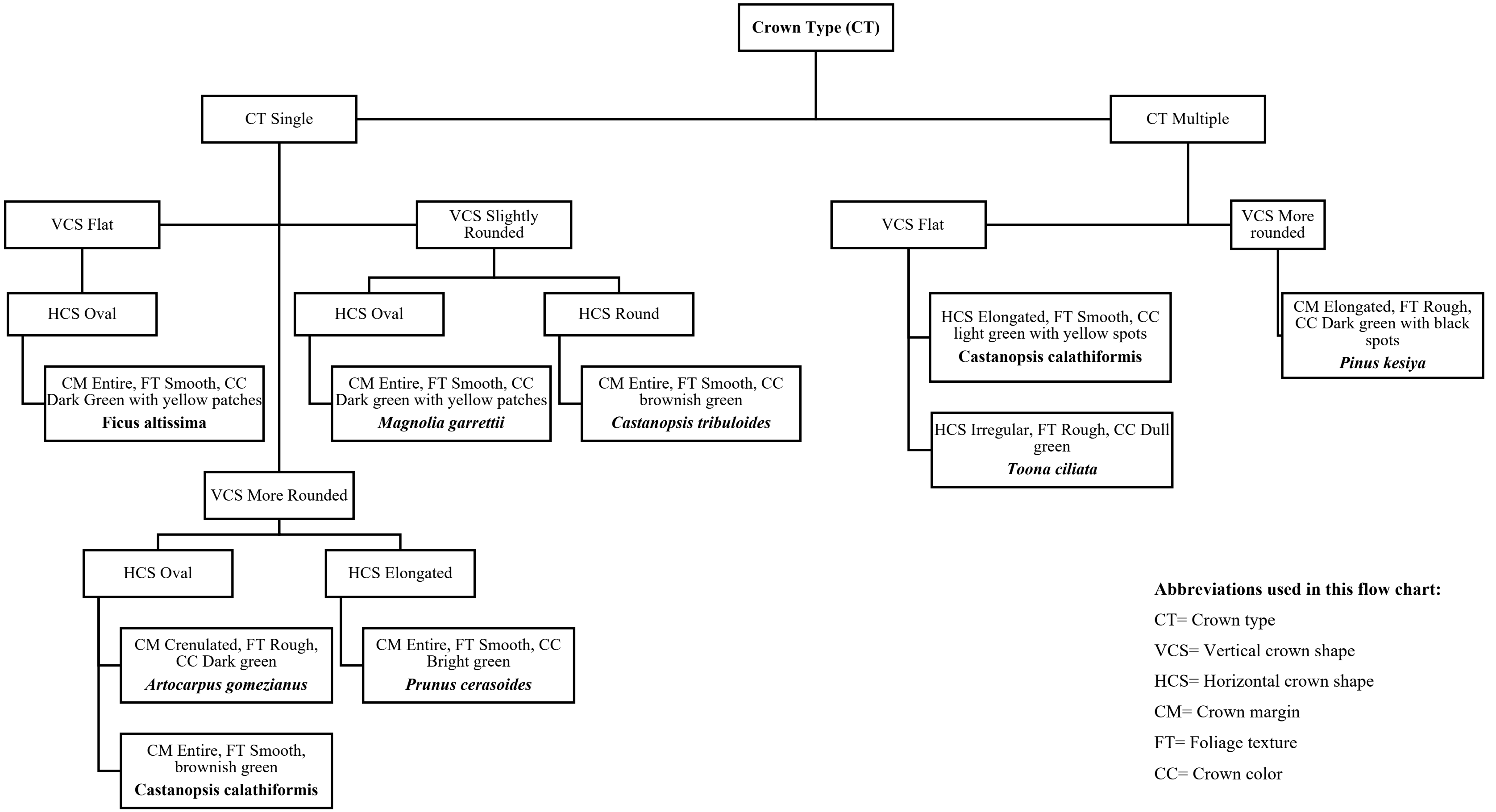


Figure 3.5 Flow chart of tree crown dichotomous keys (August 2018)

Table 3.4 Key A; Crowns (September 2018). For abbreviations see Table 2.3

A1	Tree crown type single → A2; multiple → A10
A2	VCS is flat → A3; slightly rounded → A4; more rounded → A7
A3	HCS oval, CM entire, FT smooth, CC dark green…………..***Ficus altissima***
A4	HCS oval → A5; round → A6
A5	CM entire, FT smooth, CC dark green….…………….…***Magnolia garrettii***
A6	CM entire, FT smooth, CC bright green...................***Castanopsis tribuloides***
A7	HCS oval → A8; elongated → A9
A8	CM crenulated, FT rough, CC dull green………..… ***Artocarpus gomezianus***
	CM entire, FT smooth, dull green……………….***Castanopsis calathiformis***
A9	CM entire, FT smooth, CC bright green……….………...***Prunus cerasoides***
A10	VCS flat → A11; more rounded → A12
A11	HCS elongated, FT smooth, CC light green with yellow spots………………………….……………......***Choerospondias axillaris***
	HCS irregular, FT rough, CC dull green……..…………….…***Toona ciliata***
A12	CM elongated, FT rough, CC dark green with black spots………………………………………………….…***Pinus kesiya***

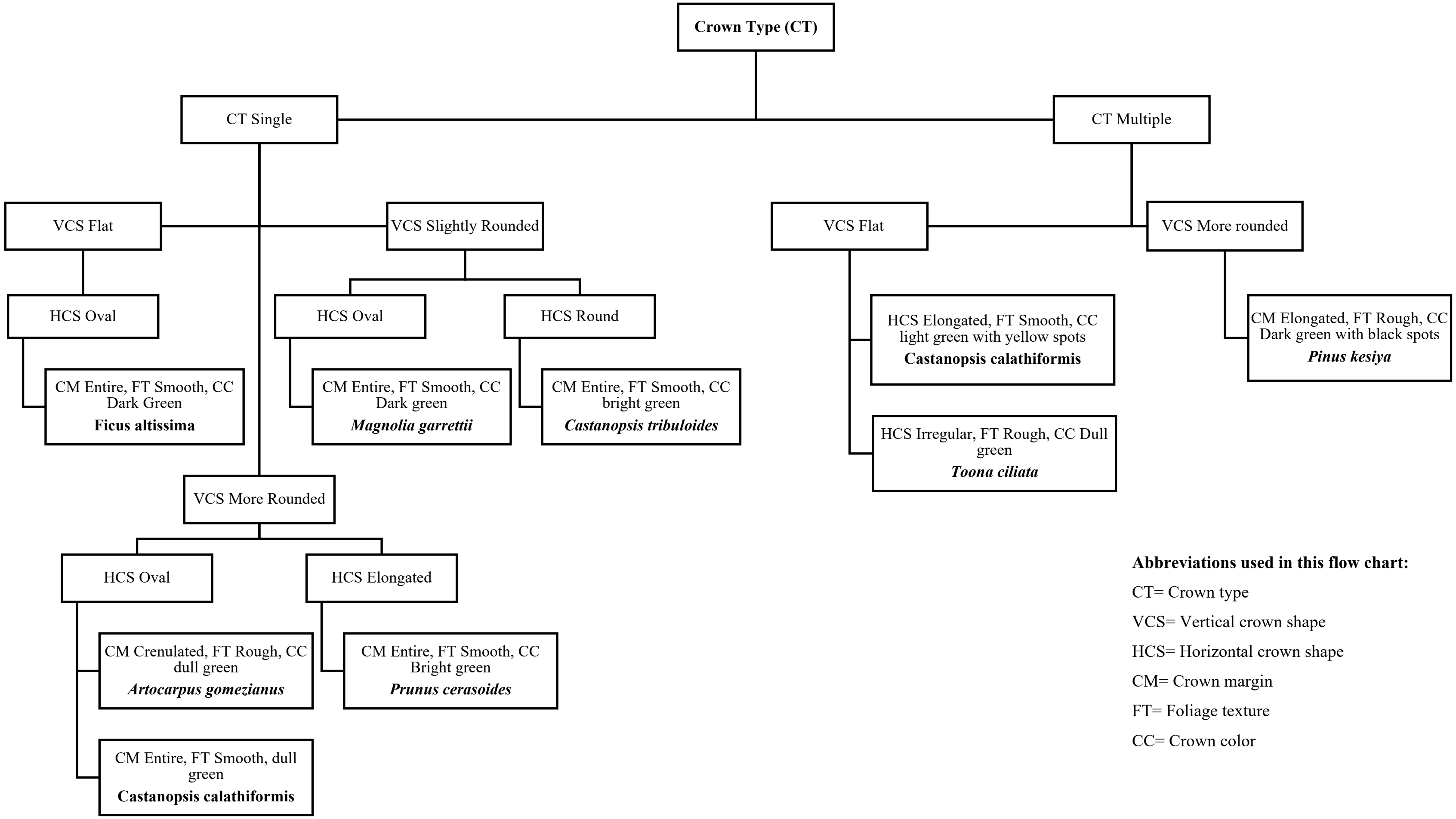
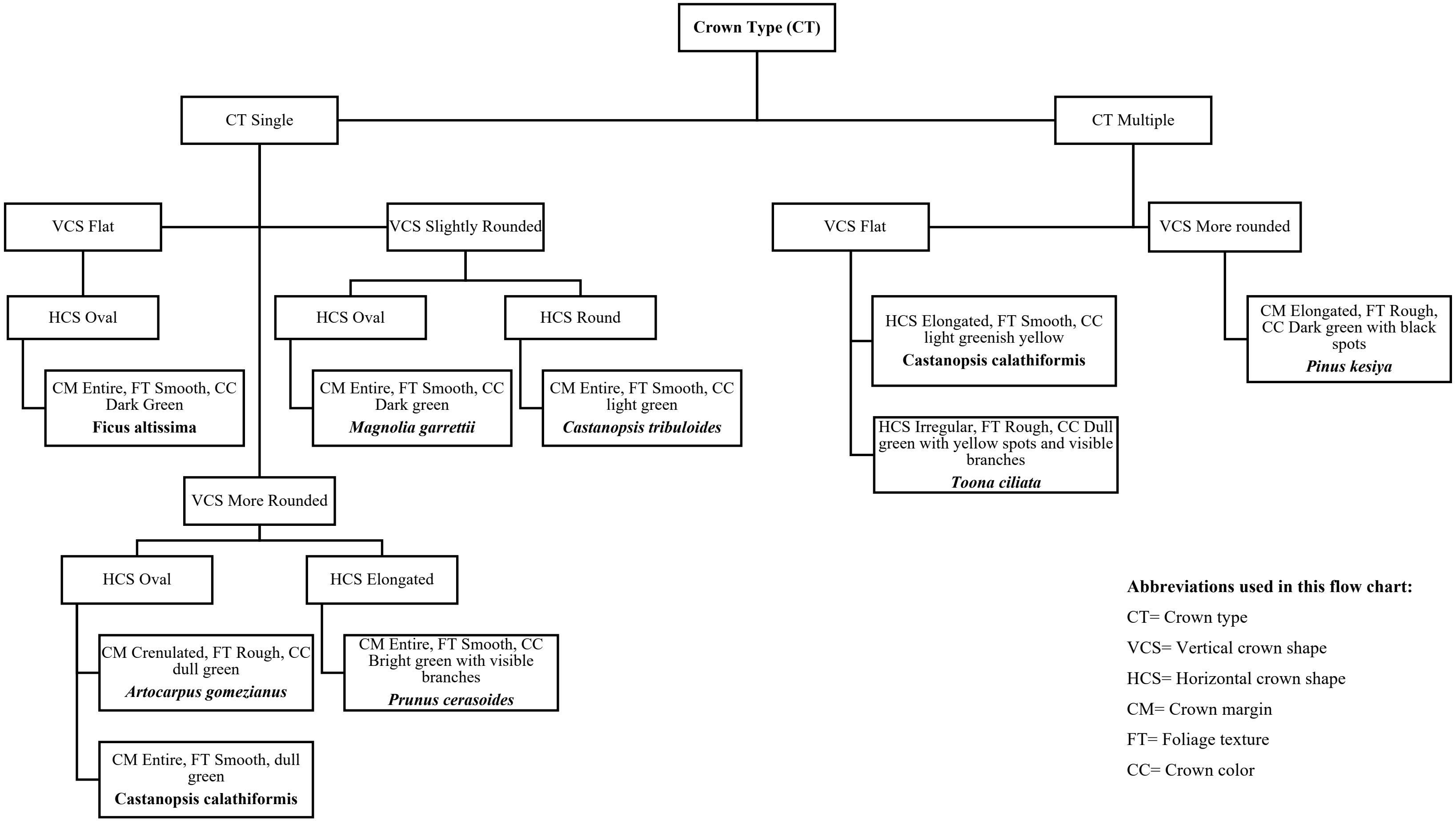


Figure 3.6 Flow chart of tree crown dichotomous keys (September 2018)

Table 3.5 Key A; Crowns (October 2018). For abbreviations see Table 2.3

A1	Tree crown type single → A2; multiple → A10
A2	VCS flat, → A3; slightly rounded → A4; more rounded → A7
A3	HCS oval, CM entire, FT smooth, CC dark green…………...***Ficus altissima***
A4	HCS oval → A5; round → A6
A5	CM entire, FT smooth, CC dark green…………………...***Magnolia garrettii***
A6	CM entire, FT smooth, CC light green……………...***Castanopsis tribuloides***
A7	HCS oval →A8; elongated → A9
A8	CM crenulated, FT rough, CC dull green………….***Artocarpus gomezianus***
	CM entire, FT smooth, dull green……………….***Castanopsis calathiformis***
A9	CM entire, FT smooth, CC bright green with visible branches……………………………………….….…***Prunus cerasoides***
A10	VCS flat → A11; more rounded → A12
A11	HCS elongated, FT smooth, CC light greenish yellow…………………………...……………...***Choerospondias axillaris***
	HCS irregular, FT rough, CC dull green with yellow spots with visible branches……………………………………………….……***Toona ciliata***
A12	CM elongated, FT rough, CC dark green with black spots……………………………………………………...…..***Pinus kesiya***



Abbreviations used in this flow chart:

CT= Crown type

VCS= Vertical crown shape

HCS= Horizontal crown shape

CM= Crown margin

FT= Foliage texture

CC= Crown color

Figure 3.7 Flow chart of tree crown dichotomous keys (October 2018)

Table 3.6 Key A; Crowns (November 2018). For abbreviations see Table 2.3

A1	Tree crown type single → A2; multiple → A10
A2	VCS flat → A3; slightly rounded → A4; more rounded → A7
A3	HCS oval, CM entire, FT smooth, CC dark green…………...***Ficus altissima***
A4	HCS oval → A5; round → A6
A5	CM entire, FT smooth, CC dark green…………………...***Magnolia garrettii***
A6	CM entire, FT smooth, CC light green with yellow spots…………………..…………………………..***Castanopsis tribuloides***
A7	HCS oval → A8; elongated → A9
A8	CM crenulated, FT rough, CC dull green with yellow spots…………………...***Artocarpus gomezianus***
	CM entire, FT smooth, dull green with yellowish patches…..***Castanopsis calathiformis***
A9	CM entire, FT smooth, CC bright green with visible branches……………………………………………….…***Prunus cerasoides***
A10	VCS flat → A11; more rounded → A12
A11	HCS elongated, FT smooth, CC light greenish yellow with visible branches………………………………………….. ***Choerospondias axillaris***
	HCS irregular, FT rough, CC dull green with yellow spots with visible branches……………………………………………………….…***Toona ciliata***
A12	CM elongated, FT rough, CC dark green with black spots……………………….……………………………..…..***Pinus kesiya***

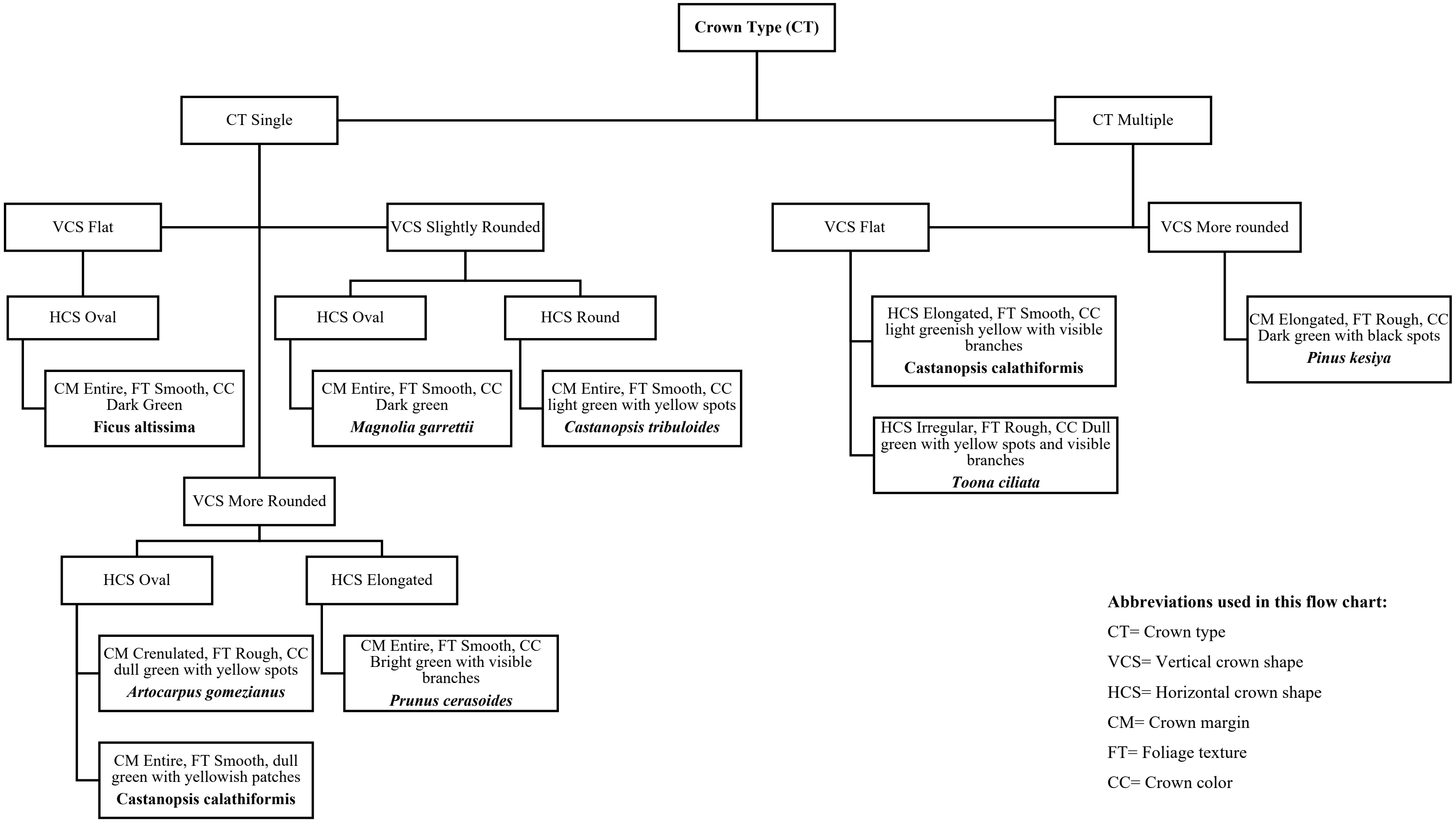


Figure 3.8 Flow chart of tree crown dichotomous keys (November 2018)

Table 3.7 Key A; Crowns (December 2018). For abbreviations see Table 2.3

A1	Tree crown type single → A2; multiple → A10
A2	VCS flat → A3; slightly rounded → A4; more rounded → A7
A3	HCS oval, CM entire, FT smooth, CC bright green……….. ***Ficus altissima***
A4	HCS oval → A5; round → A6
A5	CM entire, FT smooth, CC dark green………..................***Magnolia garrettii***
A6	CM entire, FT smooth, CC bright green..………..…***Castanopsis tribuloides***
A7	HCS oval → A8; elongated → A9
A8	CM crenulated, FT rough, CC dull green………....***Artocarpus gomezianus***
	CM entire, FT smooth, dull green with yellowish patches...***Castanopsis calathiformis***
A9	CM entire, FT smooth, CC only branches visible………..***Prunus cerasoides***
A10	VCS flat → A11; more rounded → A12
A11	HCS elongated, FT smooth, CC light yellow with visible branches………………..…………………………....***Choerospondias axillaris***
	HCS irregular, FT rough, CC dull green with yellow spots with visible branches………………………………………………….………***Toona ciliata***
A12	CM elongated, FT rough, CC dark green with black spots……………………………………….……………..…..…***Pinus kesiya***

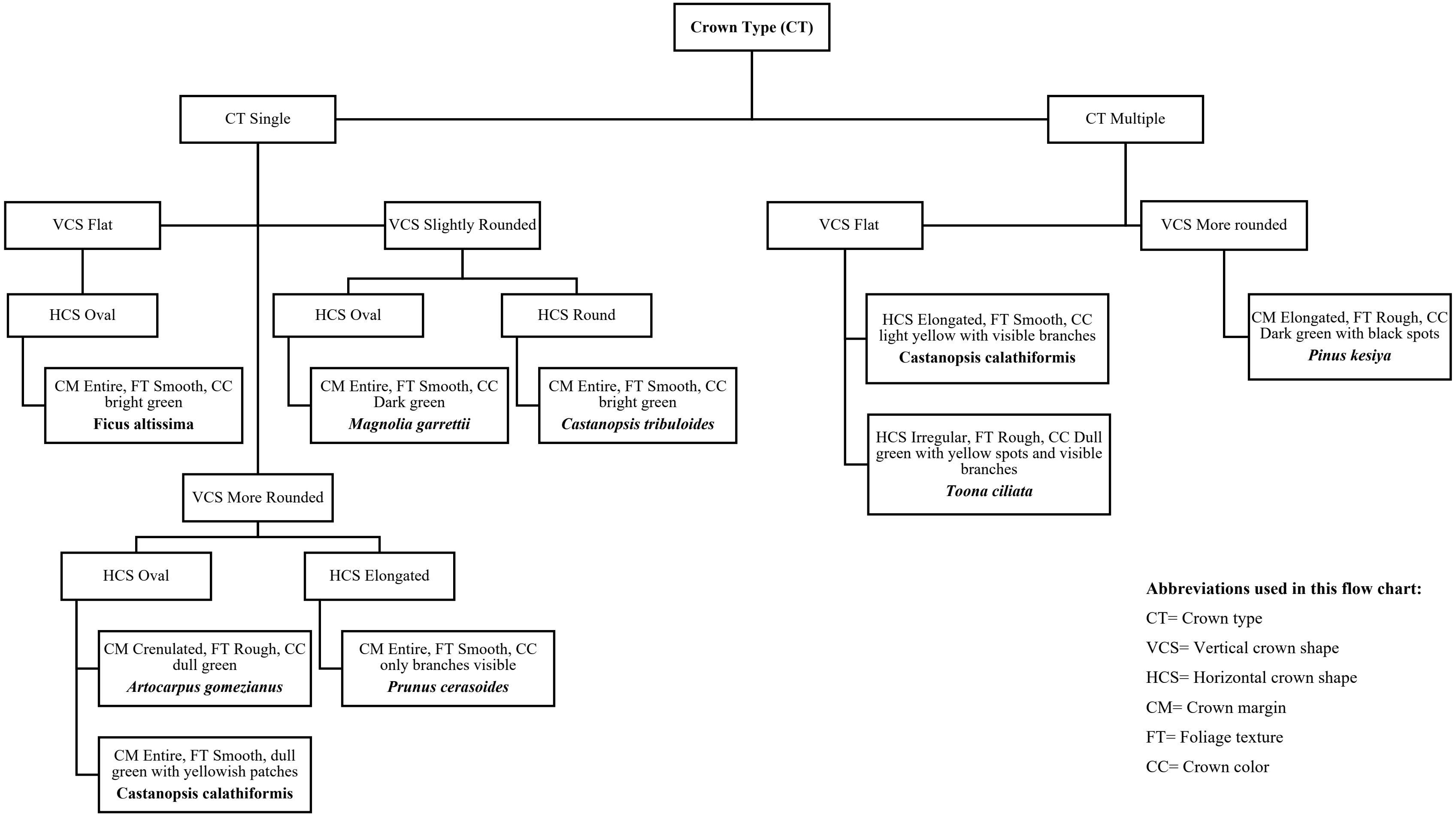


Figure 3.9 Flow chart of tree crown dichotomous keys (December 2018)

Table 3.8 Key A; Crowns (January 2019). For abbreviations see Table 2.3

A1	Tree crown type single → A2; multiple → A10
A2	VCS flat → A3; slightly rounded → A4; more rounded → A7
A3	HCS oval, CM entire, FT smooth, CC bright green…………...***Ficus altissima***
A4	HCS oval →A5; round → A6
A5	CM entire, FT smooth, CC dark green…………………....***Magnolia garrettii***
A6	CM entire, FT smooth, CC bright green..…………...***Castanopsis tribuloides***
A7	HCS oval → A8; elongated → A9
A8	CM crenulated, FT rough, CC dull green..................***Artocarpus gomezianus***
	CM entire, FT smooth, CC dull green with yellowish spots……..***Castanopsis calathiformis***
A9	CM entire, FT smooth, CC only branches visible with pink flowers…………………………………………….....***Prunus cerasoides***
A10	VCS flat → A11; more rounded → A12
A11	HCS elongated, FT smooth, CC light yellow with visible branches………………………………………….. ***Choerospondias axillaris***
	HCS irregular, FT rough, CC dull green with yellow spots with visible branches…………………………………………………..….***Toona ciliata***
A12	CM elongated, FT rough, CC dark green with black spots……………………………….…………………….....***Pinus kesiya***

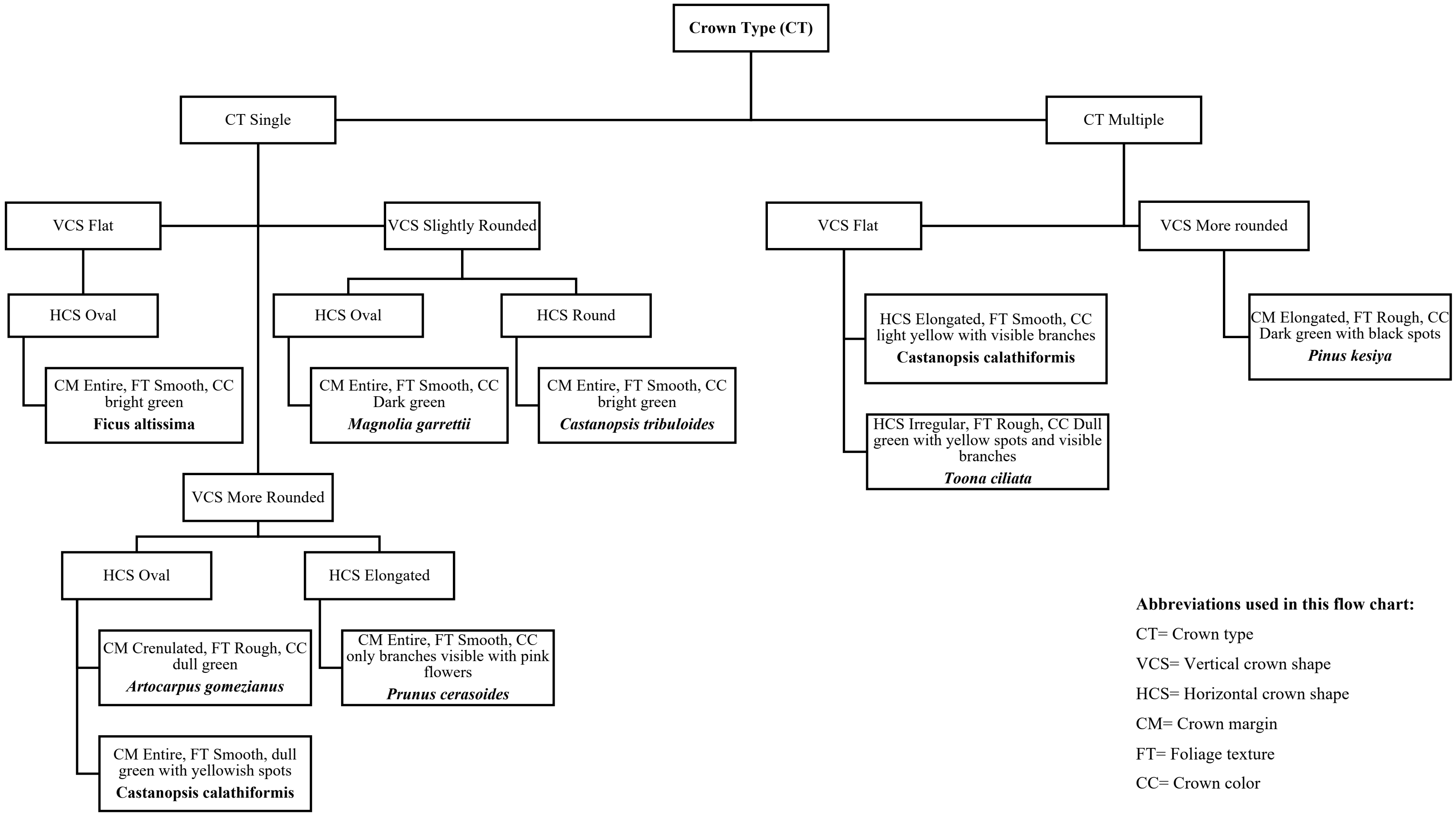


Figure 3.10 Flow chart of tree crown dichotomous keys (January 2019)

2. Leaf Dichotomous keys

Figure 3.11 Aerial digital photographs of leaf of nine tree species studied in Ban Mae Sa Mai, Doi Suthep-Pui National Park, Thailand. (1) *Artocarpus gomezianus,* (2) *Castanopsis calathiformis,* (3) *Castanopsis tribuloides,* (4) *Choerospondias axillaris,* (5) *Ficus altissima,* (6) *Magnolia garrettii,* (7) *Pinus kesiya,* (8) *Prunus cerasoides,* (9) *Toona ciliata*

Table 3.9 Key B: Leaves (June 2018). For abbreviations see Table 2.4

B1	Leaf type is simple → B2; compound → B3
B2	LA is alternate-spiral → B4; bundled → B5
B3	LA paripinnate. LS is lanceolate with tapering end, LC is light greenish yellow………………...…………….………....…....***Choerospondias axillaris***
	LA imparipinnate, LS narrowly ovate with tapering end, LC bright green…………………………………………….……..…. ***Toona ciliata***
B4	LS ovate → B6; LS elliptic → B7; LS lanceolate → B8; LS ovate-oblong, LC bright shiny green………………...………………………..…***Prunus cerasoides***
B5	LS needle-like, LC dark green……………………….……………. ***Pinus kesiya***
B6	LC leathery dark green with prominent midrib…........................***Ficus altissima***
	LC glossy dark green & yellow…………………………***Artocarpus gomezianus***
B7	LC dull green & yellow..***Castanopsis calathiformis***
	LC leathery dark green………………………………………. ***Magnolia garrettii***
B8	LC leathery dark green…………………………….…...…. ***Castanopsis tribuloides***

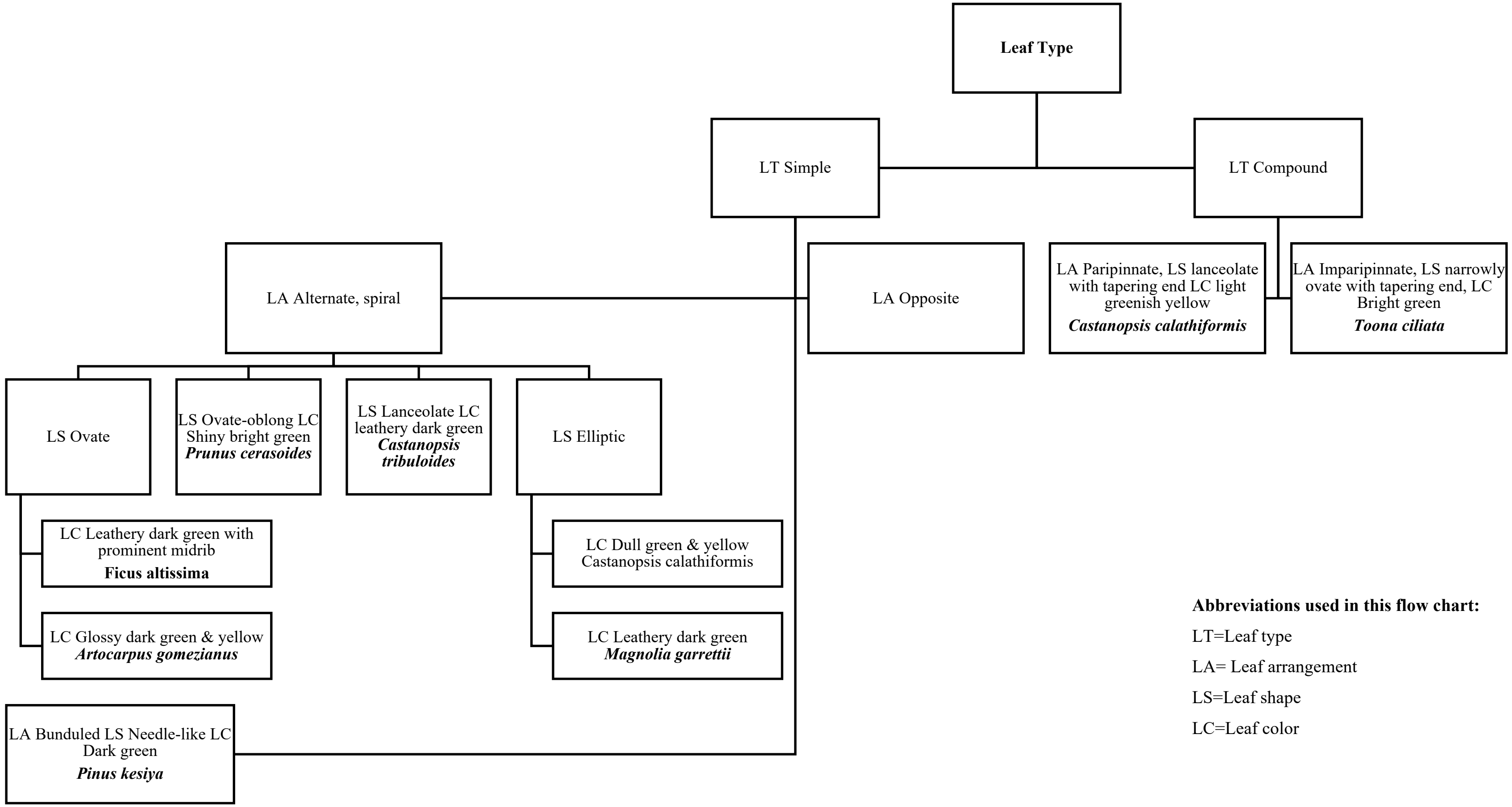
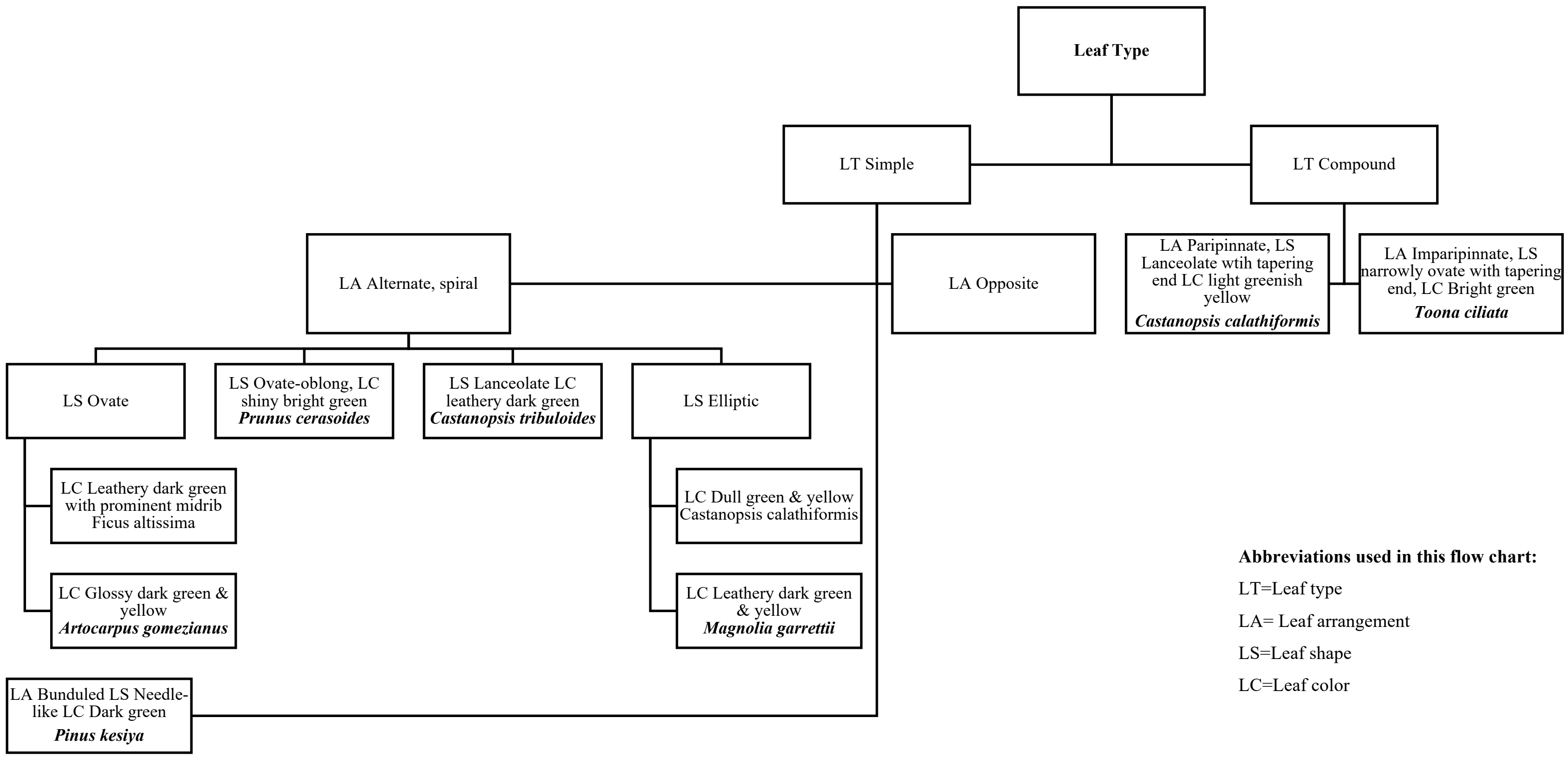


Figure 3.12 Flow chart of leaf dichotomous keys (June 2018)

Table 3.10 Key B; Leaves (July 2018). For abbreviations see Table 2.4e 2.4

B1	If leaf type is simple → B2; compound → B3
B2	LA alternate-spiral → B4; bundled → B5
B3	LA paripinnate, LS lanceolate with tapering end, LC light greenish yellow……………..……………………………..…..***Choerospondias axillaris***
	LA imparipinnate, LS is narrowly ovate and tapering end, LC bright green………………………………………..…………..…..***Toona ciliata***
B4	LS ovate → B6; LS elliptic → B7; LS lanceolate → B8; LS ovate-oblong, LC bright shiny green……………..………………………….. ***Prunus cerasoides***
B5	LS needle-like, LC is dark green……………………… …….. ***Pinus kesiya***
B6	LC leathery dark green with prominent midrib…………. …....***Ficus altissima***
	LC glossy dark green & yellow.…………………... ..***Artocarpus gomezianus***
B7	LC dull green & yellow……….........................***Castanopsis calathiformi***s
	LC leathery dark green & yellow…....................................***Magnolia garrettii***
B8	LC leathery dark green………………………………..***Castanopsis tribuloides***



Abbreviations used in this flow chart:

LT=Leaf type

LA= Leaf arrangement

LS=Leaf shape

LC=Leaf color

Figure 3.13 Flow chart of leaf dichotomous keys (July 2018)

Table 3.11 Key B; Leaves (August 2018). For abbreviations see Table 2.4

B1	Leaf type simple → B2; compound → B3
B2	LA alternate-spiral → B4; bundled → Key B5
B3	LA paripinnate, LS lanceolate with tapering end, LC light greenish yellow………..……………………….……........***Choerospondias axillaris***
	LA imparipinnate, LS narrowly ovate with tapering end, LC dull green……………………………………….……………..…***Toona ciliata***
B4	LS ovate → B6; elliptic → B7; lanceolate → B8; ovate-oblong, LC bright shiny green…………….……………………………………….. ***Prunus cerasoides***
B5	LS needle-like, LC dark green…………………………….………..***Pinus kesiya***
B6	LC leathery dark green with prominent midrib..……………...***Ficus altissima***
	LC glossy dark green……………………………….….***Artocarpus gomezianus***
B7	LC dull green & yellow…………………………...***Castanopsis calathiformis***
	LC leathery dark green & yellow…………………………***Magnolia garrettii***
B8	LC leathery dark green………………………………***Castanopsis tribuloides***

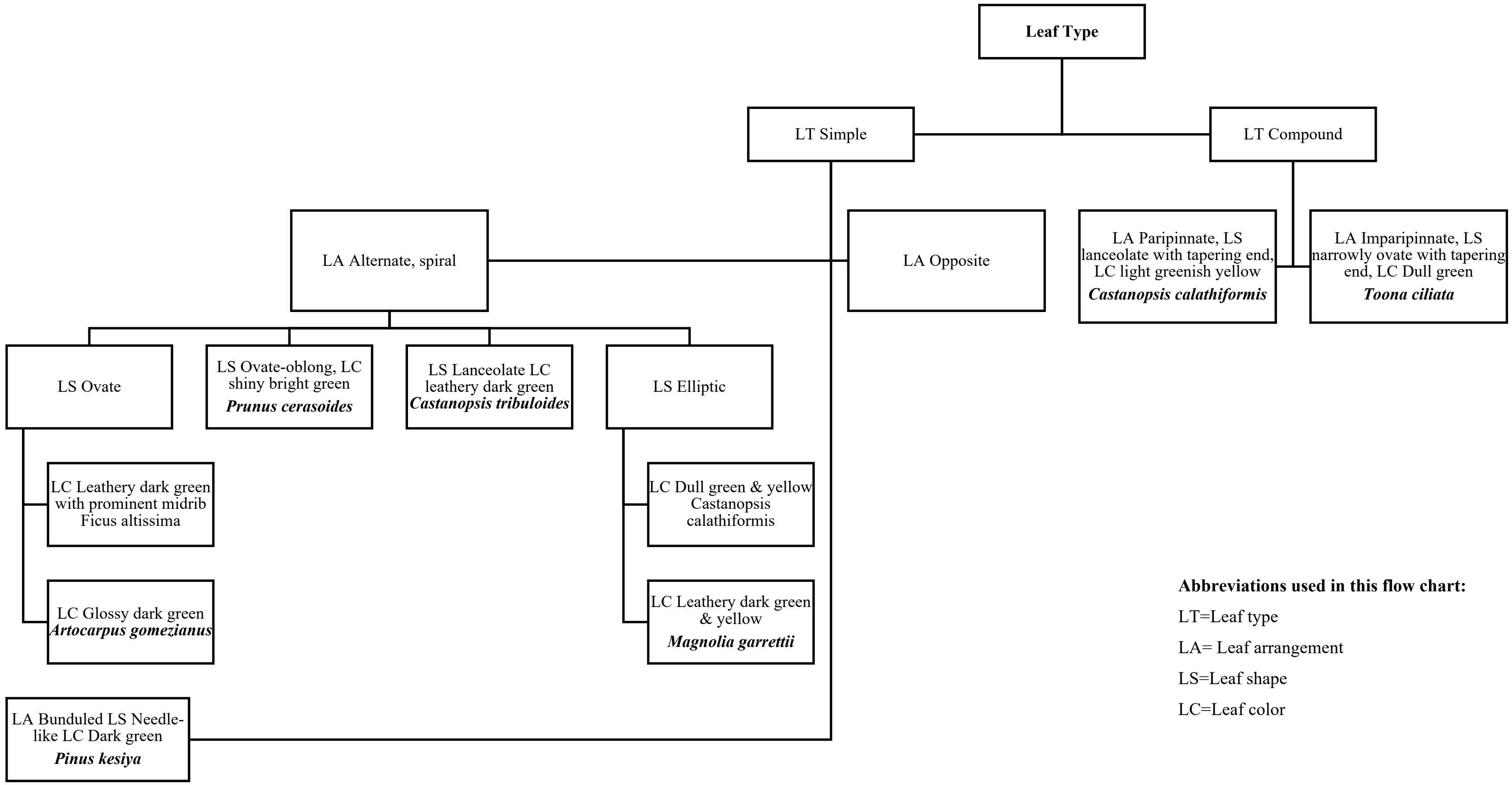


Figure 3.14 Flow chart of leaf dichotomous keys (August 2018)

Table 3.12 Key B; Leaves (September 2018). For abbreviations see Table 2.4

B1	Leaf type is simple → B2; compound → B3
B2	LA alternate-spiral → B4; bundled → B5
B3	LA paripinnate, LS lanceolate with tapering end, LC light greenish yellow…………….…………………………..…… ***Choerospondias axillaris***
	LA imparipinnate, LS narrowly ovate with tapering end, LC is dull green…………………………….……..…………….……..... ***Toona ciliata***
B4	LS ovate → B6; elliptic → B7; lanceolate → B8; ovate-oblong, LC bright green and yellow……..……..…………………………….……...…***Prunus cerasoides***
B5	LS needle-like, LC dark green…………………………..……..…***Pinus kesiya***
B6	LC leathery dark green with prominent midrib………………..***Ficus altissima***
	LC is glossy dark green…………………………..***Artocarpus gomezianus***
B7	LC dull green & yellow…....................................***Castanopsis calathiformis***
	LC leathery dark green & brown……………….……..…..***Magnolia garrettii***
B8	LC leathery dark green………………………………***Castanopsis tribuloides***

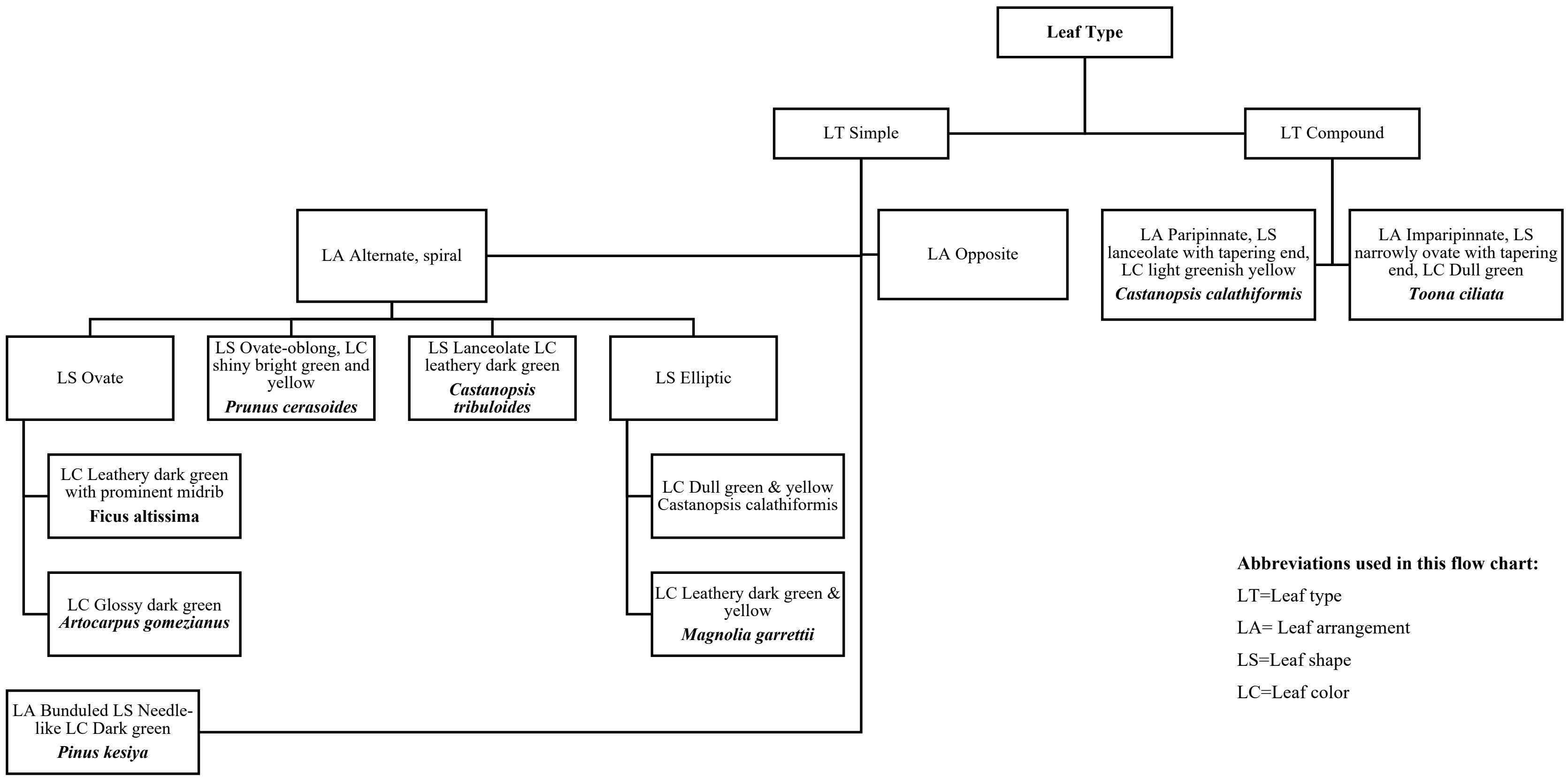


Figure 3.15 Flow chart of leaf dichotomous keys (September 2018)

Table 3.13 Key B; Leaves (October 2018). For abbreviations see Table 2.4

B1	If leaf type is simple → B2; compound → B3
B2	LA alternate-spiral → B4; bundled → B5
B3	LA paripinnate, LS lanceolate with tapering end, LC is light greenish yellow……………………………………………***Choerospondias axillaris***
	LA imparipinnate, LS narrowly ovate with tapering end, LC dull green………………………………………………………… ***Toona ciliata***
B4	LS ovate → B6; elliptic → B7; lanceolate → B8; ovate-oblong, LC green & yellow………...***Prunus cerasoides***
B5	LS needle-like, LC dark green…………………………………………***Pinus kesiya***
B6	LC leathery dark green with prominent midrib………………….***Ficus altissima***
	LC glossy dark green…………………………………...***Artocarpus gomezianus***
B7	LC dull green & yellow……………………………***Castanopsis calathiformis***
	LC leathery dark green & brown……………………………***Magnolia garrettii***
B8	LC leathery dark green…………………………........***Castanopsis tribuloides***

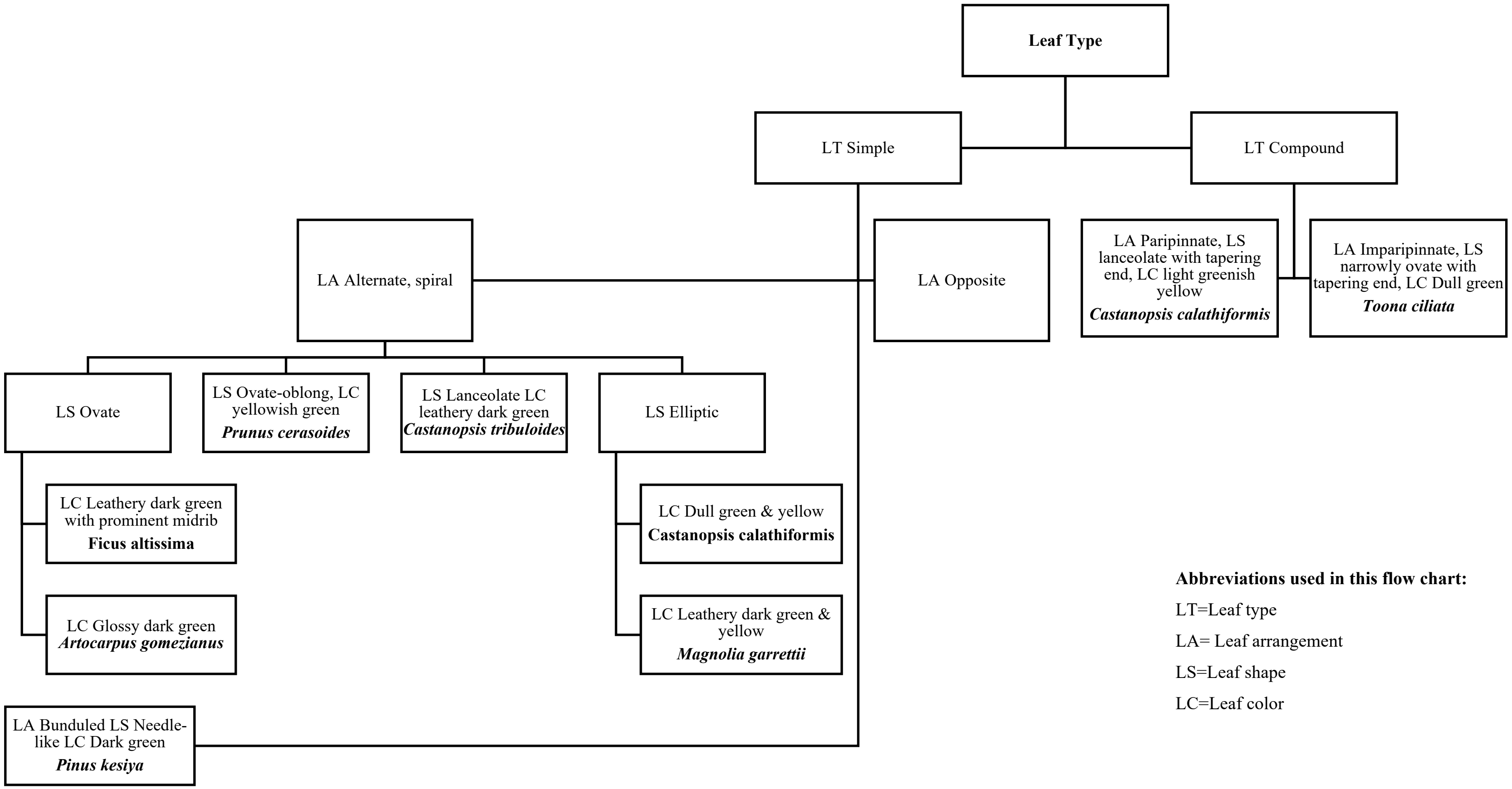


Figure 3.16 Flow chart of leaf dichotomous keys (October 2018)

Table 3.14 Key B; Leaves (November 2018). For abbreviations see Table 2.4

B1	If leaf type is simple → B2; compound → Key B3
B2	LA alternate-spiral → B4; bundled → B5
B3	LA paripinnate, LS lanceolate with tapering end, LC is light green & yellow…………………………..…………………… ***Choerospondias axillaris***
	LA imparipinnate, LS narrowly ovate with tapering end, LC dull green & yellow………………………………………………………… ***Toona ciliata***
B4	LS ovate → B6; elliptic → B7; lanceolate → B8; ovate-oblong, LC green & yellow…………………………………………..……..***Prunus cerasoides***
B5	LS needle-like, LC dark green……………………..…………..***Pinus kesiya***
B6	LC leathery bright green with prominent midrib…………..….***Ficus altissima***
	LC glossy dark green…………………………….…..…***Artocarpus gomezianus***
B7	LC dull green & yellow………..…………………......***Castanopsis calathiformis***
	LC leathery dark green & brown…………………………...***Magnolia garrettii***
B8	LC leathery dark green……………………………….. ***Castanopsis tribuloides***

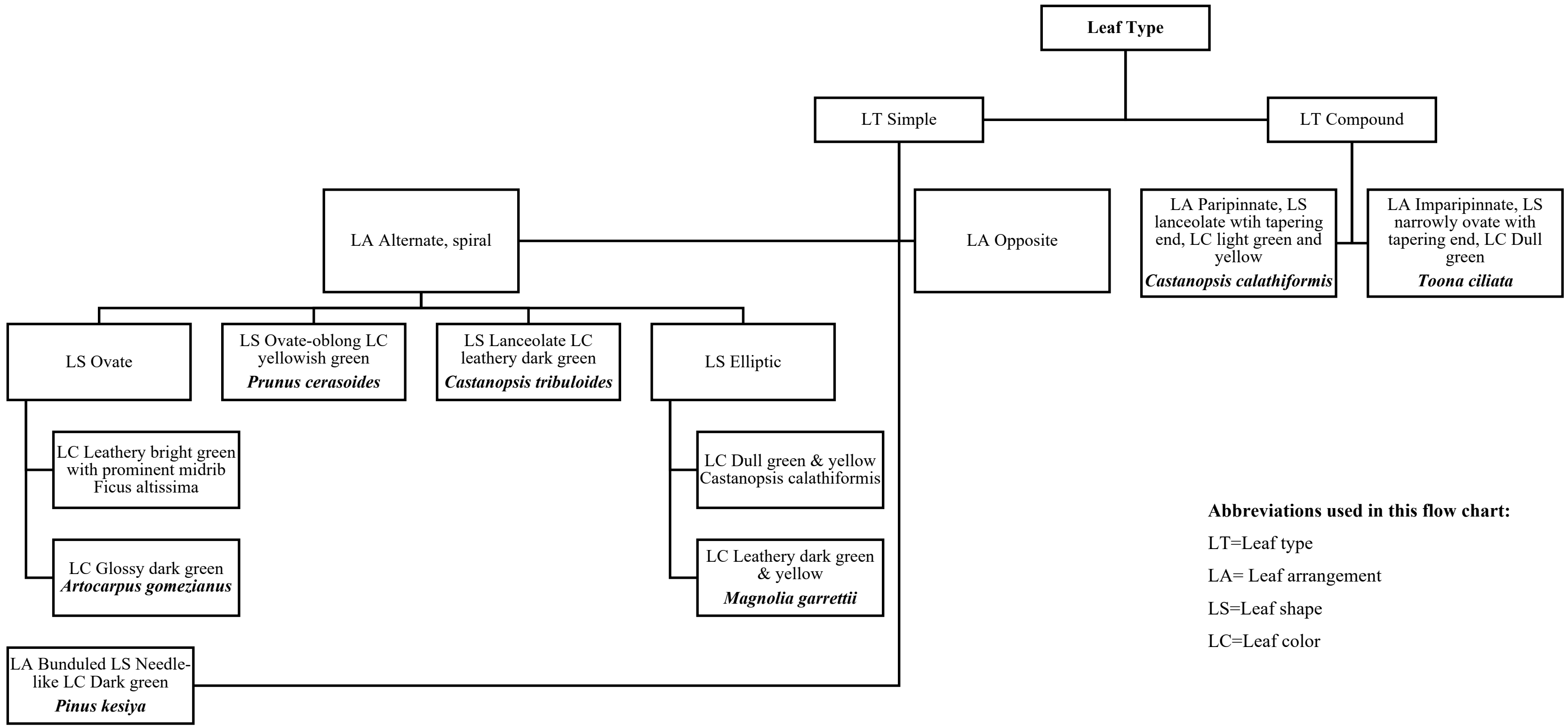


Figure 3.17 Flow chart of leaf dichotomous keys (November 2018)

Table 3.15 Key B; Leaves (December 2018). For abbreviations see Table 2.4

B1	If leaf type is simple → B2; compound → B3
B2	LA alternate-spiral → B4; bundled → B5
B3	LA paripinnate, LS lanceolate with tapering end, LC yellowish green………………...……………………..……..…***Choerospondias axillaris***
	LA imparipinnate, LS narrowly ovate with tapering end, LC dull green & yellow……….…………………………………….……..…..***Toona ciliata***
B4	LS ovate → B6; elliptic → B7; lanceolate → B8; ovate-oblong, LC yellowish green………..………………….…………………………..…***Prunus cerasoides***
B5	LS needle-like, LC dark green………………………………….....***Pinus kesiya***
B6	LC leathery bright green with prominent midrib…………..….***Ficus altissima***
	LC glossy dark green……..…………………………***Artocarpus gomezianus***
B7	LC dull green & yellow….……………………….…..***Castanopsis calathiformis***
	LC leathery dark green & brown.………………………..…***Magnolia garrettii***
B8	LC leathery dark green………..………..……………..***Castanopsis tribuloides***

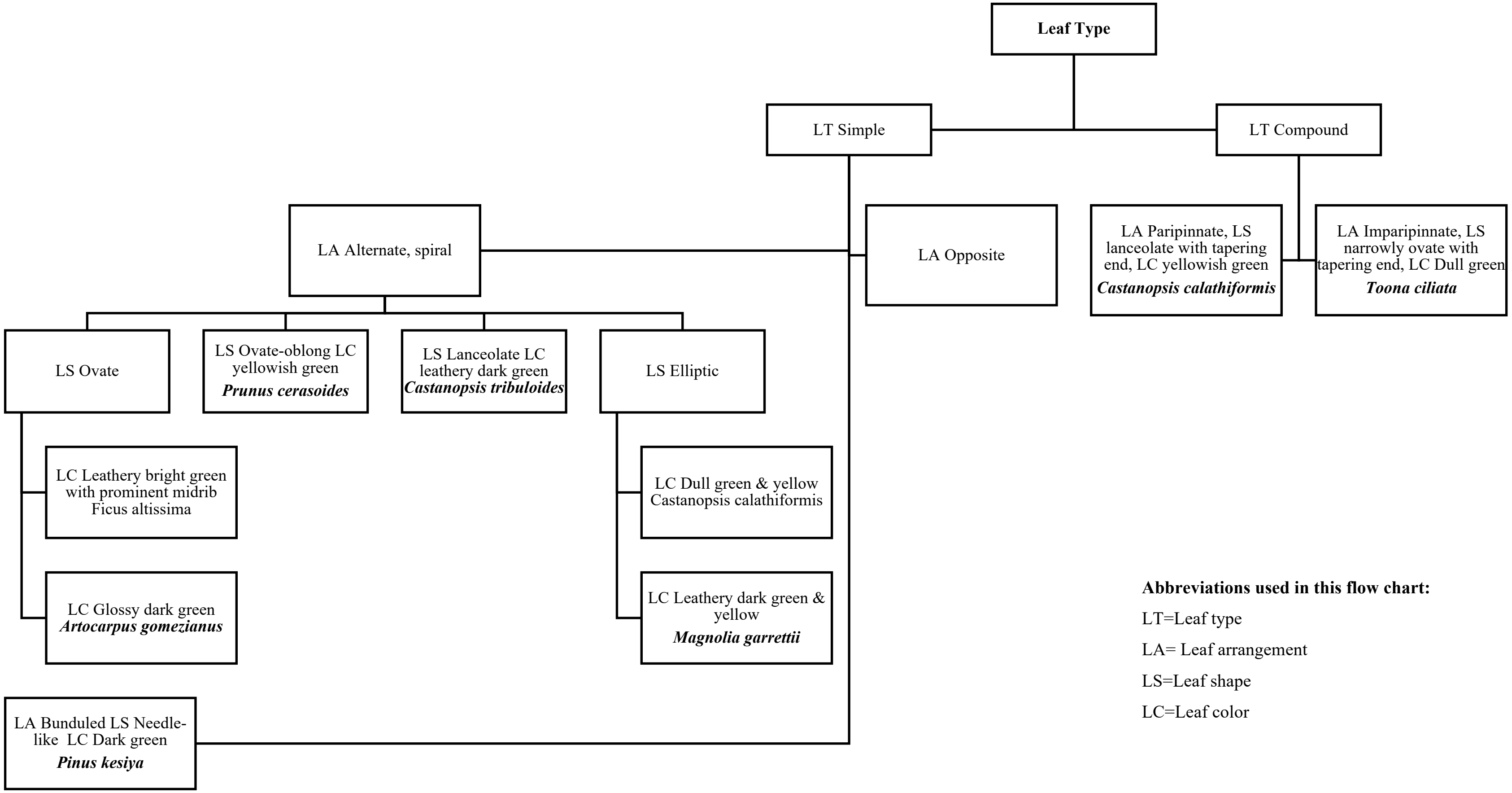
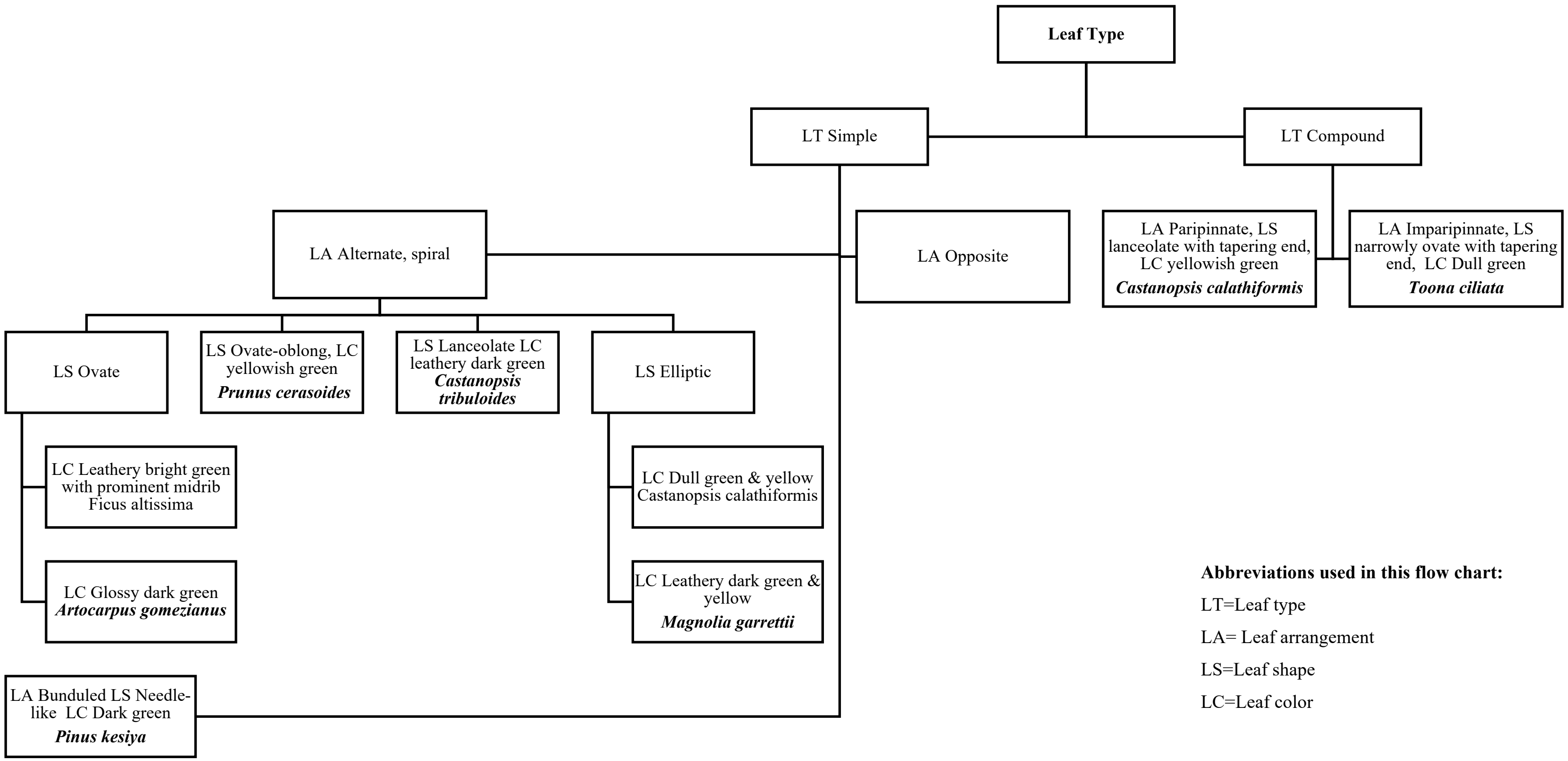


Figure 3.18 Flow chart of leaf dichotomous keys (December 2018)

Table 3.16 Key B; Leaves (January 2019). For abbreviations see Table 2.4

B1	If leaf type simple → B2; compound → B3
B2	LA alternate-spiral → B4; bundled → B5
B3	LA paripinnate, LS lanceolate with tapering end, LC yellowish green……………...……..……………………..… ***Choerospondias axillaris***
	LA imparipinnate, LS narrowly ovate with tapering end, LC dull green & yellow…………………………………..…………………….……***Toona ciliata***
B4	LS ovate → B6; elliptic → B7; lanceolate → B8; ovate-oblong, LC yellowish green……..…………………………………………..….***Prunus cerasoides***
B5	LS needle-like, LC dark green………..…………………………..…***Pinus kesiya***
B6	LC leathery bright green with prominent midrib…………..…. ***Ficus altissim***a
	LC glossy dark green……..……………………….….***Artocarpus gomezianus***
B7	LC dull green & yellow………………..……….***Castanopsis calathiformis***
	LC leathery dark green & brown.………………………….....***Magnolia garrettii***
B8	LC leathery dark green……..……..…………………..***Castanopsis tribuloides***



Abbreviations used in this flow chart:

LT=Leaf type

LA= Leaf arrangement

LS=Leaf shape

LC=Leaf color

Figure 3.19 Flow chart of leaf dichotomous keys (January 2019)

3. Image J filtering keys

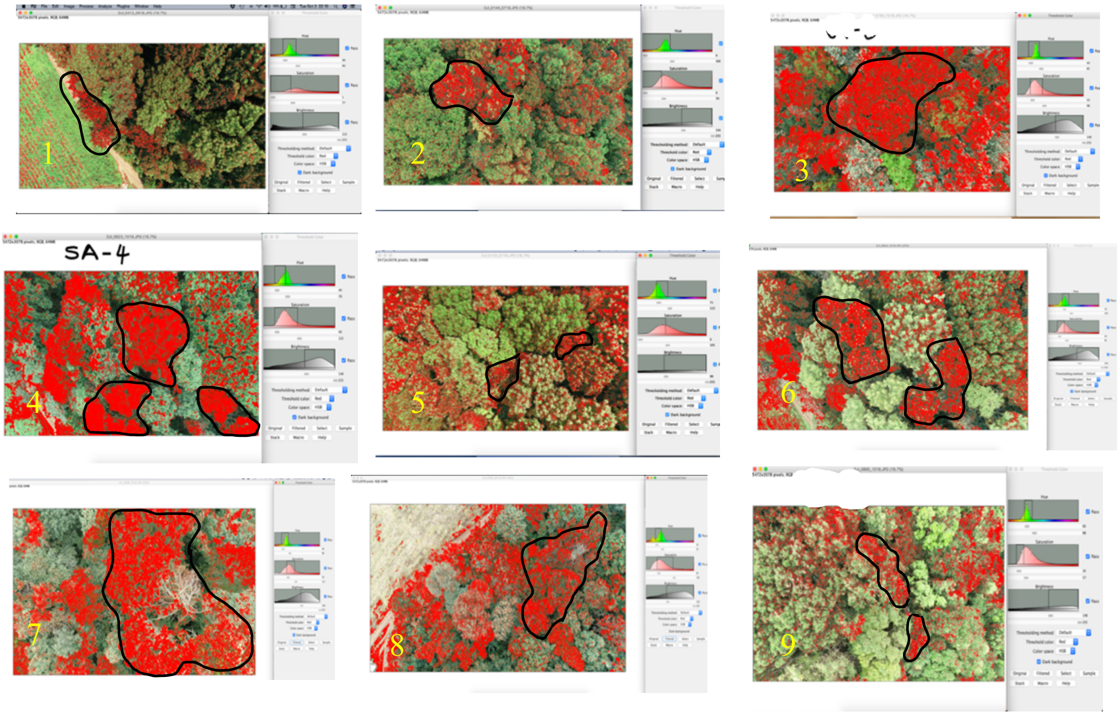


Figure 3.20 Image J filtered images for tree crowns (circled) of nine tree species studied in Ban Mae Sa Mai, Doi Suthep-Pui National Park, Thailand, (1) *Artocarpus gomezianus,* (2) *Castanopsis calathiformis,* (3) *Castanopsis tribuloides,* (4) *Choerospondias axillaris,* (5) *Ficus altissima,* (6) *Magnolia garrettii,* (7) *Pinus kesiya,* (8) *Prunus cerasoides,* (9) *Toona ciliata*

The monthly image filtering keys for nine target species is presented in following paragraphs. The image J filtering keys have two sets of numerical data i.e. upper and lower value for Hue, Saturation and Brightness (HSB). For some of the months, the image filtering keys for species are presented as range. This is because more than one crown was used in order to develop the image filtering keys; therefore, variation in upper and lower values of HSB within species were reported in range.

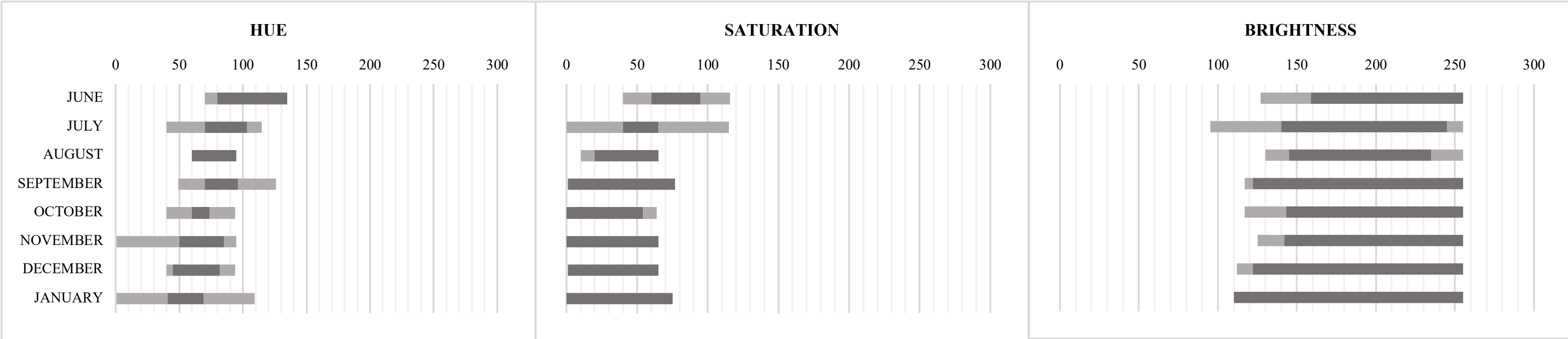


Figure 3.21 *Artocarpus gomezianus* image filtering keys

** Darker bars represent where range of lower and upper values overlap, and lighter bars represents where they do not overlap*

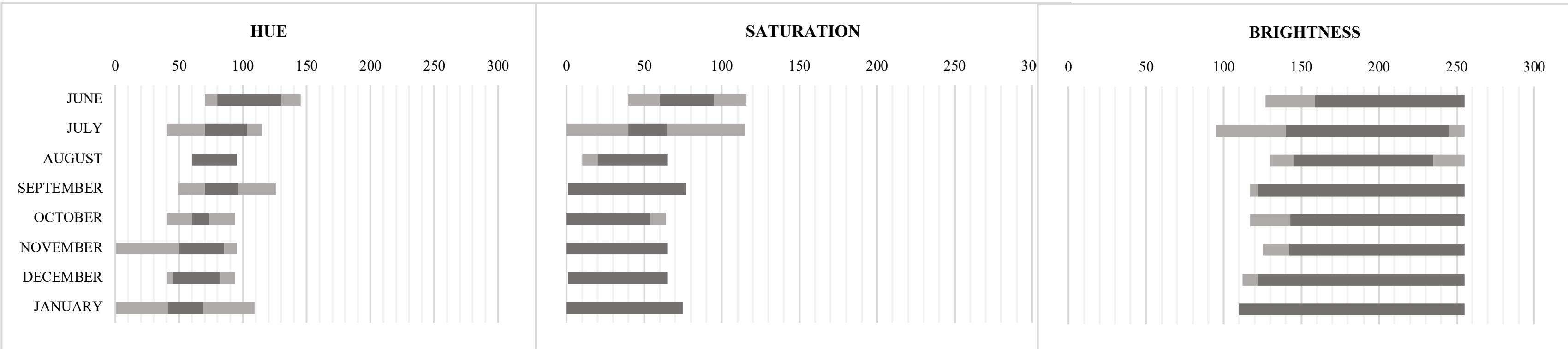


Figure 3.22 *Castanopsis calathiformis* image filtering keys

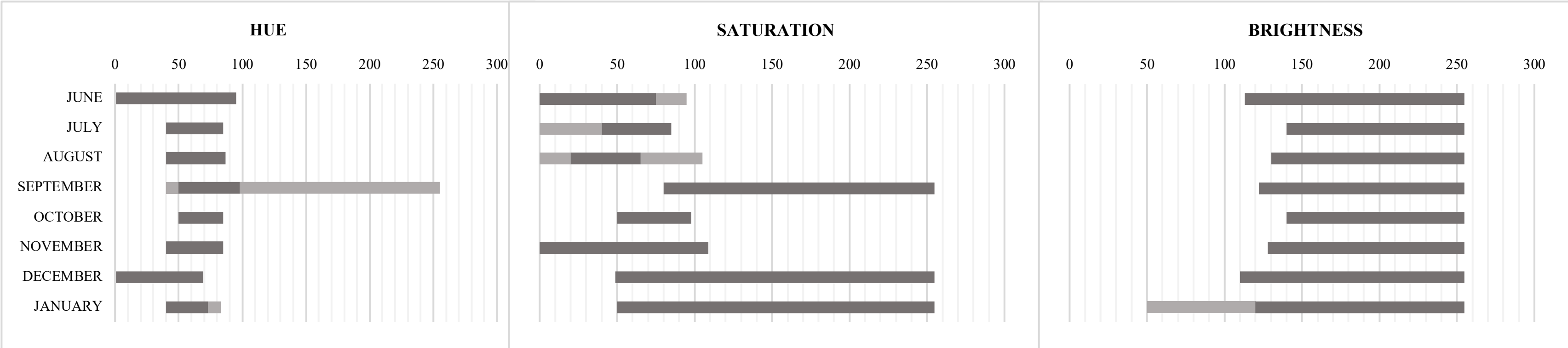


Figure 3.23 *Castanopsis tribuloides* image filtering keys

**Darker bars represent where range of lower and upper values overlap, and lighter bars represents where they do not overlap*

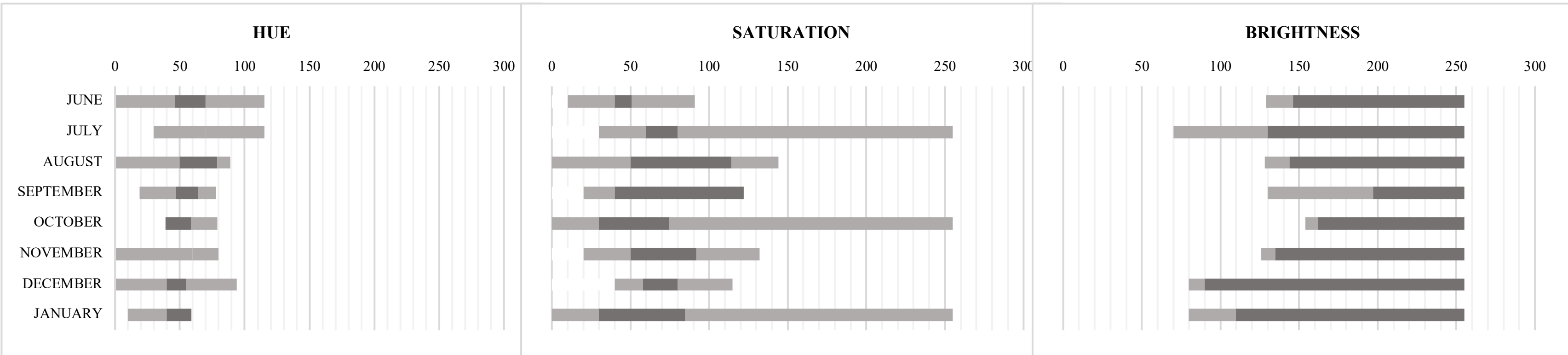


Figure 3.24 *Choerospondias axillaris* image filtering keys

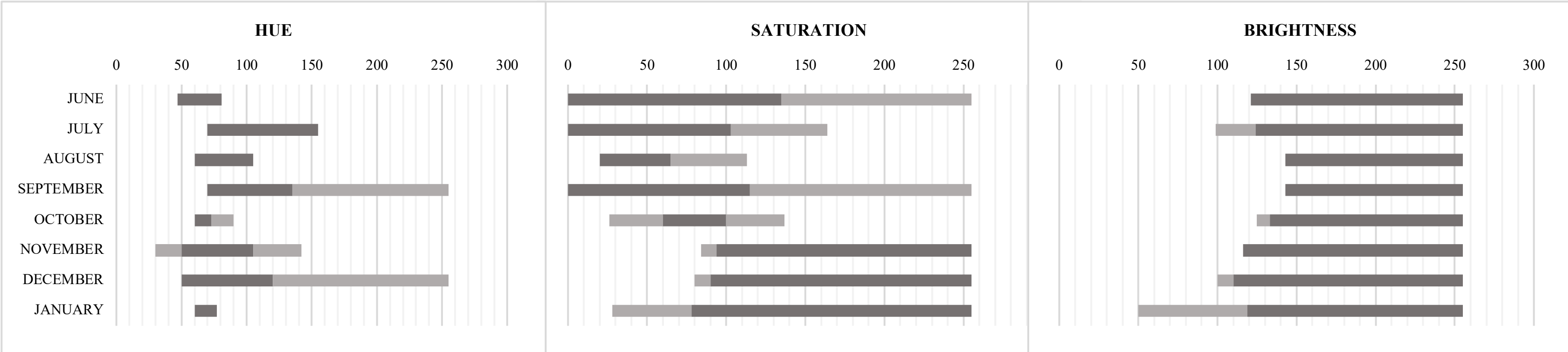


Figure 3.25 *Ficus altissima* image filtering keys

** Darker bars represent where range of lower and upper values overlap, and lighter bars represents where they do not overlap*

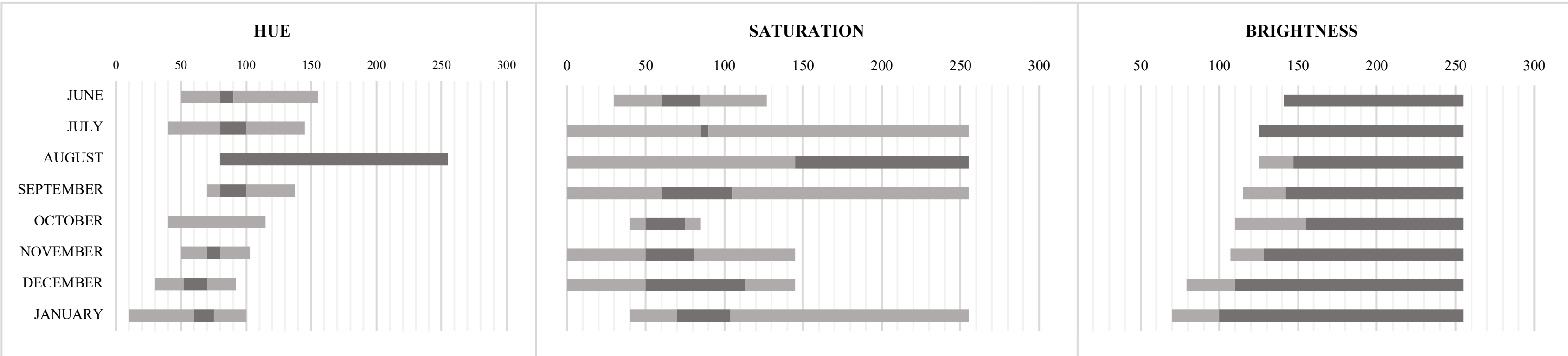


Figure 3.26 *Magnolia garrettii* image filtering keys

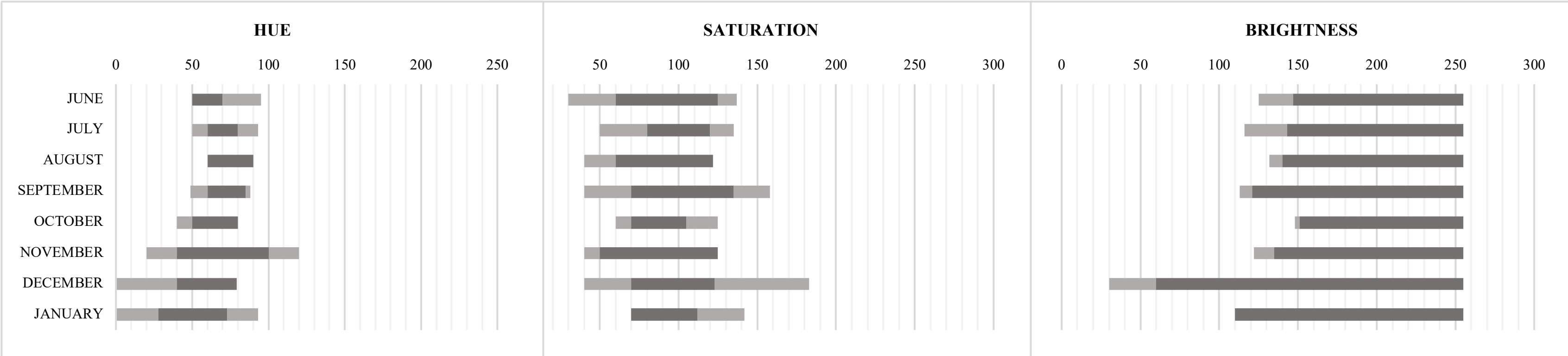


Figure 3.27 *Pinus kesiya* image filtering keys

** Darker bars represent where range of lower and upper values overlap, and lighter bars represents where they do not overlap*

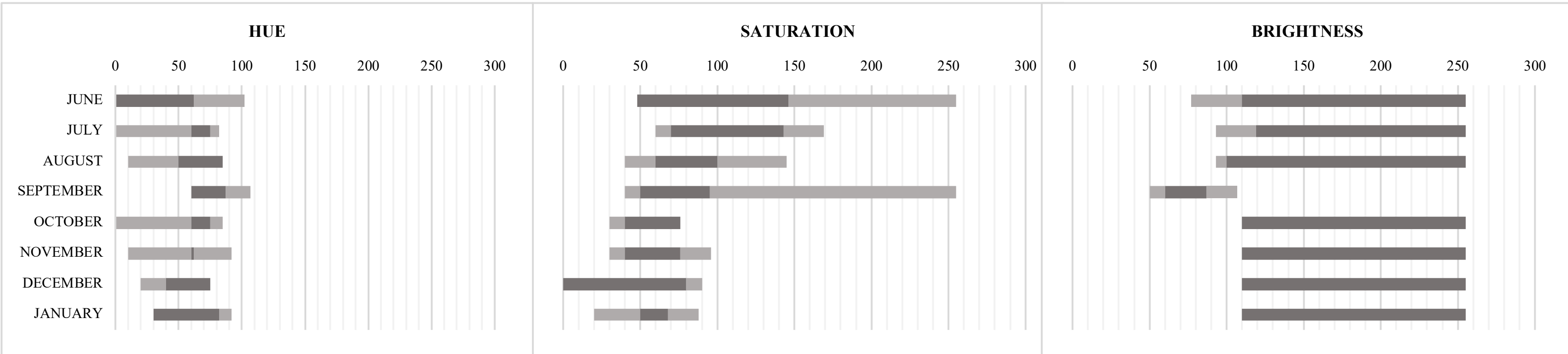


Figure 3.28 *Prunus cerasoides* image filtering keys

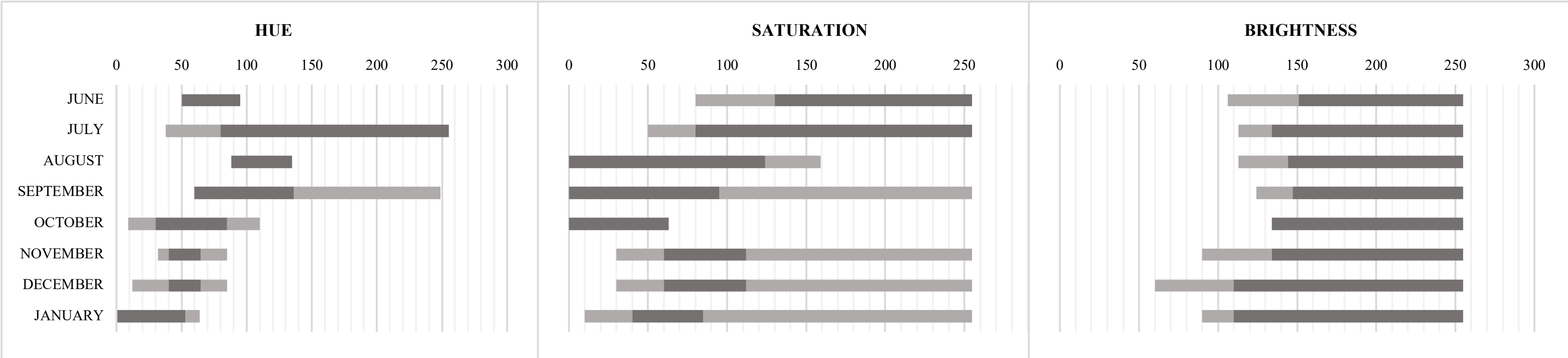


Figure 3.29 *Toona ciliata* image filtering keys

** Darker bars represent where range of lower and upper values overlap, and lighter bars represents where they do not overlap*

4. Monthly Tree Species Identification Keys

4.1. *Artocarpus gomezianus*

Table 3.17 *Artocarpus gomezianus* (June 2018)

Key descriptors	**Key description**
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Crenulated, FT rough, CC light greenish yellow
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC glossy dark green and yellow
Image J keys (Key C)	Hue: 70-80/135 Sat: 40-60/95-116 Bright: 127-159/255
Phenology	Leaf flushing

Table 3.18 *Artocarpus gomezianus* (July 2018)

Key descriptors	**Key description**
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Crenulated, FT rough, CC light greenish yellow
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC glossy dark green and yellow
Image J keys (Key C)	Hue: 40-70/103-115 Sat: 0-40/65-115 Bright: 95-140/245-255
Phenology	Leaf flushing

Table 3.19 *Artocarpus gomezianus* (August 2018)

Key descriptors	**Key description**
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Crenulated, FT rough, CC dark green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC glossy dark green
Image J keys (Key C)	Hue: 60/95 Sat: 10-20/65 Bright: 130-145/ 235-255
Phenology	

Table 3.20 *Artocarpus gomezianus* (September 2018)

Key descriptors	**Key description**
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Crenulated, FT rough, CC dull green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC glossy dark green
Image J keys (Key C)	Hue: 49-70/96-126 Sat: 1/77 Bright: 117-122/255
Phenology	

Table 3.21 *Artocarpus gomezianus* (October 2018)

Key descriptors	**Key description**
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Crenulated, FT rough, CC dull green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC glossy dark green
Image J keys (Key C)	Hue: 40-60/74-94 Sat: 0/54-64 Bright: 117-143/255
Phenology	

Table 3.22 *Artocarpus gomezianus* (November 2018)

Key descriptors	**Key description**
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Crenulated, FT rough, CC dull green with yellow spots
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC glossy dark green
Image J keys (Key C)	Hue: 0-50/85-95 Sat: 0/65 Bright: 125-142/255
Phenology	

Table 3.23 *Artocarpus gomezianus* (December 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Crenulated, FT rough, CC dull green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC glossy dark green
Image J keys (Key C)	Hue: 40-45/82-94 Sat: 1/65 Bright: 112-122/255
Phenology	

Table 3.24 *Artocarpus gomezianus* (January 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Crenulated, FT rough, CC dull green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC glossy dark green
Image J keys (Key C)	Hue: 0-41/69-109 Sat: 0/75 Bright: 110/255
Phenology	

4.2. *Castanopsis calathiformis*

Table 3.25 *Castanopsis calathiformis* (June 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Entire, FT rough, CC dull green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC glossy dull green and yellow
Image J keys (Key C)	Hue: 0/80-115 Sat: 0/65-101 Bright: 128-141/255
Phenology	Flowering

Table 3.26 *Castanopsis calathiformis* (July 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Entire, FT rough, CC yellowish dull green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC glossy dull green and yellow
Image J keys (Key C)	Hue: 0/80-115 Sat: 0/65-101 Bright: 128-141/255
Phenology	Flowering

Table 3.27 *Castanopsis calathiformis* (August 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Entire, FT rough, CC brownish green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC glossy dull green and yellow
Image J keys (Key C)	Hue: 40/89 Sat: 40/84-165 Bright: 110-122/255
Phenology	Flowering

Table 3.28 *Castanopsis calathiformis* (September 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Entire, FT rough, CC dull green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC glossy dull green and yellow
Image J keys (Key C)	Hue: 0-87/66-127 Sat: 0-60/107-137 Bright: 107-137/255
Phenology	

Table 3.29 *Castanopsis calathiformis* (October 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Entire, FT rough, CC dull green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC glossy dull green and yellow		
Image J keys (Key C)	Hue: 40-71/75-103	Sat: 30/68-78	Bright: 146/255
Phenology			

Table 3.30 *Castanopsis calathiformis* (November 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Entire, FT rough, CC dull green with yellow spots		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC glossy dull green and yellow		
Image J keys (Key C)	Hue: 30/76-112	Sat: 10/93-103	Bright: 125/255
Phenology			

Table 3.31 *Castanopsis calathiformis* (December 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Entire, FT rough, CC dull green with yellow patches		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC glossy dull green and yellow		
Image J keys (Key C)	Hue: 50/72-135	Sat: 0/95-145	Bright: 110-122/255
Phenology			

Table 3.32 *Castanopsis calathiformis* (January 2019)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Entire, FT rough, CC dull green with yellow patches		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC glossy dull green and yellow		
Image J keys (Key C)	Hue: 0/61-81	Sat: 0-50/74-126	Bright: 90-100/255
Phenology			

4.3. *Castanopsis tribuloides*

Table 3.33 *Castanopsis tribuloides* (June 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Slightly rounded, HCS Round, CM Entire, FT smooth, CC brownish green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS lanceolate, LC leathery dark green		
Image J keys (Key C)	Hue: 0/95	Sat: 0/75-95	Bright: 113/255
Phenology	Flowering		

Table 3.34 *Castanopsis tribuloides* (July 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Slightly rounded, HCS Round, CM Entire, FT smooth, CC brownish green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS lanceolate, LC leathery dark green		
Image J keys (Key C)	Hue: 40/85	Sat: 0-40/85	Bright: 140/255
Phenology	Flowering		

Table 3.35 *Castanopsis tribuloides* (August 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS Slightly rounded, HCS Round, CM Entire, FT smooth, CC brownish green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS lanceolate, LC leathery dark green		
Image J keys (Key C)	Hue: 40/87	Sat: 0-20/65-105	Bright: 130/255
Phenology	Flowering		

Table 3.36 *Castanopsis tribuloides* (September 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS Slightly rounded, HCS Round, CM Entire, FT smooth, CC bright green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS lanceolate, LC leathery dark green		
Image J keys (Key C)	Hue: 50/98-255	Sat: 80/255	Bright: 122/255
Phenology	Leaf flushing		

Table 3.37 *Castanopsis tribuloides* (October 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS Slightly rounded, HCS Round, CM Entire, FT smooth, CC light green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS lanceolate, LC leathery dark green		
Image J keys (Key C)	Hue: 50/85	Sat: 50/98	Bright: 140/255
Phenology	Leaf flushing		

Table 3.38 *Castanopsis tribuloides* (November 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, CS rounded, FT smooth, CC light green with yellow patches		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS lanceolate, LC leathery dark green		
Image J keys (Key C)	Hue: 40/85	Sat: 0/109	Bright: 128/255
Phenology			

Table 3.39 *Castanopsis tribuloides* (December 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS Slightly rounded, HCS Round, CM Entire, FT smooth, CC bright green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS lanceolate, LC leathery dark green		
Image J keys (Key C)	Hue: 0/69	Sat: 49/255	Bright: 110/255
Phenology	Leaf flushing		

Table 3.40 *Castanopsis tribuloides* (January 2019)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS Slightly rounded, HCS Round, CM Entire, FT smooth, CC bright green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS lanceolate, LC leathery dark green		
Image J keys (Key C)	Hue: 40/73-83	Sat: 50/255	Bright: 50-120/255
Phenology	Leaf flushing		

4.4. *Choerospondias axillaris*

Table 3.41 *Choerospondias axillaris* (June 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Elongated, FT smooth, CC light green with yellow spots		
Leaf keys (Key B)	LT compound, LA paripinnate, LS lanceolate with tapering end, LC light greenish yellow		
Image J keys (Key C)	Hue: 0-70/46-115	Sat: 0-30/85-255	Bright: 129-146/255
Phenology	Leaf flushing		

Table 3.42 *Choerospondias axillaris* (July 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Elongated, FT smooth, CC light green with yellow spots		
Leaf keys (Key B)	LT compound, LA paripinnate, LS lanceolate with tapering end, LC light greenish yellow		
Image J keys (Key C)	Hue: 30-70/70-115	Sat: 40-58/80-115	Bright: 70-130/255
Phenology	Leaf flushing		

Table 3.43 *Choerospondias axillaris* (August 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Elongated, FT smooth, CC light green with yellow spots		
Leaf keys (Key B)	LT compound, LA paripinnate, LS lanceolate with tapering end, LC light greenish yellow		
Image J keys (Key C)	Hue: 0-50/79-89	Sat: 20-50/92-132	Bright: 128-144/255
Phenology			

Table 3.44 *Choerospondias axillaris* (September 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Elongated, FT smooth, CC light green with yellow spots
Leaf keys (Key B)	LT compound, LA paripinnate, LS lanceolate with tapering end, LC light greenish yellow
Image J keys (Key C)	Hue: 19-47/64-78 Sat: 0-30/75-255 Bright:197-130/255
Phenology	

Table 3.45 *Choerospondias axillaris* (October 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Elongated, FT smooth, CC light green with yellow spots
Leaf keys (Key B)	LT compound, LA paripinnate, LS lanceolate with tapering end, LC light greenish yellow
Image J keys (Key C)	Hue: 39/59-79 Sat: 20-40/122 Bright: 154-162/255
Phenology	Leaf fall (Crown density=1/4)

Table 3.46 *Choerospondias axillaris* (November 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Elongated, FT smooth, CC light green with yellow spots
Leaf keys (Key B)	LT compound, LA paripinnate, LS lanceolate with tapering end, LC light greenish yellow
Image J keys (Key C)	Hue: 0-60/60-80 Sat: 0-50/114-144 Bright: 126-135/255
Phenology	Leaf fall (Crown density = 1/2)

Table 3.47 *Choerospondias axillaris* (December 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Elongated, FT smooth, CC visible branches with almost all leaves shed		
Leaf keys (Key B)	LT compound, LA paripinnate, LS lanceolate with tapering end, LC yellowish green		
Image J keys (Key C)	Hue: 0-40/55-94	Sat: 30-60/80-255	Bright: 80-90/255
Phenology	Leaf fall (Crown density=3/4)		

Table 3.48 *Choerospondias axillaris* (January 2019)

Key descriptors	Key description		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Elongated, FT smooth, CC visible branches with almost all leaves shed		
Leaf keys (Key B)	LT compound, LA paripinnate, LS lanceolate with tapering end, LC yellowish green		
Image J keys (Key C)	Hue: 10-40/59	Sat: 10-40/51-91	Bright: 80-110/255
Phenology	Leaf fall (Crown density=0)		

4.5. *Ficus altissima*

Table 3.49 *Ficus altissima* (June 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Flat, HCS Oval, CM Entire, FT smooth, CC dark green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC leathery dark green with prominent midrib		
Image J keys (Key C)	Hue: 47/81	Sat: 0/135-255	Bright: 121/255
Phenology	Leaf flushing		

Table 3.50 *Ficus altissima* (July 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Flat, HCS Oval, CM Entire, FT smooth, CC dark green with yellow spots		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC leathery dark green with prominent midrib		
Image J keys (Key C)	Hue: 70/155	Sat: 0/103-164	Bright: 99-124/255
Phenology	Flowering		

Table 3.51 *Ficus altissima* (August 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Flat, HCS Oval, CM Entire, FT smooth, CC dark green with yellow spots		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC leathery dark green with prominent midrib		
Image J keys (Key C)	Hue: 60/105	Sat: 20/65-113	Bright: 123/255
Phenology			

Table 3.52 *Ficus altissima* (September 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Flat, HCS Oval, CM Entire, FT smooth, CC dark green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC leathery dark green with prominent midrib		
Image J keys (Key C)	Hue: 70/135-255	Sat: 0/115-255	Bright: 143/255
Phenology			

Table 3.53 *Ficus altissima* (October 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Flat, HCS Oval, CM Entire, FT smooth, CC dark green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC leathery dark green with prominent midrib		
Image J keys (Key C)	Hue: 60/73-90	Sat: 26-60/100-137	Bright: 125-133/255
Phenology			

Table 3.54 *Ficus altissima* (November 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Flat, HCS Oval, CM Entire, FT smooth, CC bright green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC leathery bright green with prominent midrib		
Image J keys (Key C)	Hue: 30-50/105-142	Sat: 84-94/255	Bright: 116/255
Phenology	Leaf flushing		

Table 3.55 *Ficus altissima* (December 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Flat, HCS Oval, CM Entire, FT smooth, CC bright green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC leathery bright green with prominent midrib		
Image J keys (Key C)	Hue: 50/120-255	Sat: 80-90/255	Bright: 100-110/255
Phenology			

Table 3.56 *Ficus altissima* (January 2019)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS Flat, HCS Oval, CM Entire, FT smooth, CC bright green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS ovate, LC leathery bright green with prominent midrib		
Image J keys (Key C)	Hue: 60/77	Sat: 28-78/255	Bright: 50-119/255
Phenology			

4.6. *Magnolia garrettii*

Table 3.57 *Magnolia garrettii* (June 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS rounded, HCS Oval, CM Entire, FT smooth, CC dark green with yellow patches		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC leathery dark green		
Image J keys (Key C)	Hue: 50-80/90-155	Sat: 30-60/85-127	Bright: 141/255
Phenology	Fruiting		

Table 3.58 *Magnolia garrettii* (July 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Single, VCS rounded, HCS Oval, CM Entire, FT smooth, CC dark green with yellow patches		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC leathery dark green and yellow		
Image J keys (Key C)	Hue: 40-80/100-145	Sat: 0-90/85-255	Bright: 125/255
Phenology	Fruiting		

Table 3.59 *Magnolia garrettii* (August 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS rounded, HCS Oval, CM Entire, FT smooth, CC dark green with yellow patches		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC leathery dark green and yellow		
Image J keys (Key C)	Hue: 80/255	Sat: 0/145-255	Bright: 125-147/255
Phenology	Fruiting		

Table 3.60 *Magnolia garrettii* (September 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS rounded, HCS Oval, CM Entire, FT smooth, CC dark green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC leathery dark green and yellow		
Image J keys (Key C)	Hue: 50/98-255	Sat: 80/255	Bright: 122/255
Phenology			

Table 3.61 *Magnolia garrettii* (October 2018)

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS rounded, HCS Oval, CM Entire, FT smooth, CC dark green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC leathery dark green and yellow		
Image J keys (Key C)	Hue: 40-70/70-115	Sat: 40-50/75-85	Bright: 110-155/255
Phenology			

Table 3.62 *Magnolia garrettii* (November 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Single, VCS rounded, HCS Oval, CM Entire, FT smooth, CC dark green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC leathery dark green and yellow
Image J keys (Key C)	Hue: 50-70/80-103 Sat: 0-50/81-145 Bright: 107-128/255
Phenology	

Table 3.63 *Magnolia garrettii* (December 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Single, VCS rounded, HCS Oval, CM Entire, FT smooth, CC dark green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC leathery dark green and yellow
Image J keys (Key C)	Hue: 30-52/70-92 Sat: 0-50/113-145 Bright: 79-110/255
Phenology	Leaf fall (Crown density=1/4)

Table 3.64 *Magnolia garrettii* (January 2019)

Key descriptors	Key description
Tree crown keys (Key A)	CT Single, VCS rounded, HCS Oval, CM Entire, FT smooth, CC dark green
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC leathery dark green and yellow
Image J keys (Key C)	Hue: 10-60/75-100 Sat: 40-70/104-255 Bright: 70-100/255
Phenology	Leaf fall (Crown density=1/4)

4.7. *Pinus kesiya*

Table 3.65 *Pinus kesiya* (June 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Multiple, VCS More rounded, CM Elongated, FT rough, CC dark green with black spots		
Leaf keys (Key B)	LT simple, LA bundled, LS Needle-like, LC leathery dark green		
Image J keys (Key C)	Hue: 50/70-95	Sat: 30-60/125-137	Bright: 125-147/255
Phenology			

Table 3.66 *Pinus kesiya* (July 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Multiple, VCS More rounded, CM Elongated, FT rough, CC dark green with black spots		
Leaf keys (Key B)	LT simple, LA bundled, LS Needle-like, LC leathery dark green		
Image J keys (Key C)	Hue: 50-60/80-93	Sat: 50-80/120-135	Bright: 116-143/255
Phenology			

Table 3.67 *Pinus kesiya* (August 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Multiple, VCS More rounded, CM Elongated, FT rough, CC dark green with black spots		
Leaf keys (Key B)	LT simple, LA bundled, LS Needle-like, LC leathery dark green		
Image J keys (Key C)	Hue: 60/90	Sat: 40-60/122	Bright: 132-140/255
Phenology			

Table 3.68 *Pinus kesiya* (September 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Multiple, VCS More rounded, CM Elongated, FT rough, CC dark green with black spots
Leaf keys (Key B)	LT simple, LA bundled, LS Needle-like, LC leathery dark green
Image J keys (Key C)	Hue: 49-60/85-88 Sat: 40-70/135-158 Bright: 113-121/255
Phenology	

Table 3.69 *Pinus kesiya* (October 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Multiple, VCS More rounded, CM Elongated, FT rough, CC dark green with black spots
Leaf keys (Key B)	LT simple, LA bundled, LS Needle-like, LC leathery dark green
Image J keys (Key C)	Hue: 40-50/80 Sat: 60-70/105-125 Bright: 148-151/255
Phenology	

Table 3.70 *Pinus kesiya* (November 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT Multiple, VCS More rounded, CM Elongated, FT rough, CC dark green with black spots
Leaf keys (Key B)	LT simple, LA bundled, LS Needle-like, LC leathery dark green
Image J keys (Key C)	Hue: 20-40/100-120 Sat: 40-50/125 Bright: 122-135/255
Phenology	

Table 3.71 *Pinus kesiya* (December 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Multiple, VCS More rounded, CM Elongated, FT rough, CC dark green with black spots		
Leaf keys (Key B)	LT simple, LA bundled, LS Needle-like, LC leathery dark green		
Image J keys (Key C)	Hue: 0-40/79	Sat: 40-70/123-183	Bright: 30-60/255
Phenology			

Table 3.72 *Pinus kesiya* (January 2019)

Key descriptors	Key description		
Tree crown keys (Key A)	CT Multiple, VCS More rounded, CM Elongated, FT rough, CC dark green with black spots		
Leaf keys (Key B)	LT simple, LA bundled, LS Needle-like, LC leathery dark green		
Image J keys (Key C)	Hue: 0-28/73-93	Sat: 70/112-142	Bright: 110/255
Phenology			

4.8. *Prunus cerasoides*

Table 3.73 *Prunus cerasoides* (June 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT single, VCS More rounded, HCS Elongated, CM Entire, FT smooth, CC bright green with yellow spots		
Leaf keys (Key B)	LT simple, LA bundled, LS ovate-oblong, LC shiny bright green		
Image J keys (Key C)	Hue: 0/62-102	Sat: 48/146-255	Bright: 77-110/255
Phenology	Leaf flushing		

Table 3.74 *Prunus cerasoides* (July 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT single, VCS More rounded, HCS Elongated, CM Entire, FT smooth, CC bright green with yellow spots		
Leaf keys (Key B)	LT simple, LA bundled, LS ovate-oblong, LC shiny bright green		
Image J keys (Key C)	Hue: 0-60/75-82	Sat: 60-70/143-169	Bright: 93-119/255
Phenology	Leaf flushing		

Table 3.75 *Prunus cerasoides* (August 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT single, VCS More rounded, HCS Elongated, CM Entire, FT smooth, CC bright green with visible branches		
Leaf keys (Key B)	LT simple, LA bundled, LS ovate-oblong, LC shiny bright green		
Image J keys (Key C)	Hue: 10-50/85	Sat: 40-60/100-145	Bright: 93-100/255
Phenology			

Table 3.76 *Prunus cerasoides* (September 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT single, VCS More rounded, HCS Elongated, CM Entire, FT smooth, CC bright green with visible branches		
Leaf keys (Key B)	LT simple, LA bundled, LS ovate-oblong, LC shiny bright green		
Image J keys (Key C)	Hue: 60/87-107	Sat: 40-50/95-255	Bright: 50-60/87-107
Phenology			

Table 3.77 *Prunus cerasoides* (October 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT single, VCS More rounded, HCS Elongated, CM Entire, FT smooth, CC yellowish green with visible branches
Leaf keys (Key B)	LT simple, LA bundled, LS ovate-oblong, LC yellowish green
Image J keys (Key C)	Hue: 0-60/75-85 Sat: 30-40/76 Bright: 110/255
Phenology	Leaf fall (Crown density=1/4)

Table 3.78 *Prunus cerasoides* (November 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT single, VCS More rounded, HCS Elongated, CM Entire, FT smooth, CC light green with visible branches
Leaf keys (Key B)	LT simple, LA bundled, LS ovate-oblong, LC yellowish green
Image J keys (Key C)	Hue: 10-60/62-92 Sat: 30-40/76-96 Bright: 110/255
Phenology	Leaf fall (Crown density=1/2)

Table 3.79 *Prunus cerasoides* (December 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT single, VCS More rounded, HCS Elongated, CM Entire, FT smooth, CC branches visible almost all leaves shed
Leaf keys (Key B)	LT simple, LA bundled, LS ovate-oblong, LC yellowish green
Image J keys (Key C)	Hue: 20-40/75 Sat: 0/80-90 Bright: 110/255
Phenology	Leaf fall (Crown density=3/4)

Table 3.80 *Prunus cerasoides* (January 2019)

Key descriptors	Key description		
Tree crown keys (Key A)	CT single, VCS More rounded, HCS Elongated, CM Entire, FT smooth, CC branches visible with pink flowers		
Leaf keys (Key B)	LT simple, LA bundled, LS ovate-oblong, LC yellowish green		
Image J keys (Key C)	Hue: 30/82-92	Sat: 20-50/68-88	Bright: 110/255
Phenology	Leaf fall (Crown density=0); Flowering		

4.9. *Toona ciliata*

Table 3.81 *Toona ciliata* (June 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green with yellow spots		
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC bright green		
Image J keys (Key C)	Hue: 50/95	Sat: 80-130/255	Bright: 106-151/255
Phenology	Leaf flushing		

Table 3.82 *Toona ciliata* (July 2018)

Key descriptors	Key description		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green with yellow spots		
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC bright green		
Image J keys (Key C)	Hue: 38-80/255	Sat: 50-80/255	Bright: 113-134/255
Phenology	Leaf flushing		

Table 3.83 *Toona ciliata* (August 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC dull green
Image J keys (Key C)	Hue: 88/135 Sat: 0/124-159 Bright: 113-144/255
Phenology	Leaf flushing

Table 3.84 *Toona ciliata* (September 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC dull green
Image J keys (Key C)	Hue: 60/136-249 Sat: 0/95-255 Bright: 124-147/255
Phenology	

Table 3.85 *Toona ciliata* (October 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green with yellow patches & visible branches
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC dull green
Image J keys (Key C)	Hue: 9-30/85-110 Sat: 0/63 Bright: 134/255
Phenology	Leaf fall (Crown density=1/4)

Table 3.86 *Toona ciliata* (November 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green with yellow patches & visible branches
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC dull green
Image J keys (Key C)	Hue: 32-40/65-85 Sat: 30-60/112-255 Bright: 90-134/255
Phenology	Leaf shed (Crown density=1/2)

Table 3.87 *Toona ciliata* (December 2018)

Key descriptors	Key description
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green with yellow patches & visible branches
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC dull green
Image J keys (Key C)	Hue: 12-40/65-85 Sat: 30-60/112-255 Bright: 60-110/255
Phenology	Leaf fall (Crown density=3/4)

Table 3.88 *Toona ciliata* (January 2019)

Key descriptors	Key description
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green with yellow patches & visible branches
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC dull green
Image J keys (Key C)	Hue: 0/53-64 Sat: 10-40/85-255 Bright: 90-110/255
Phenology	Leaf fall (Crown density=0)

5. Results of Tree Species Identification by Photo-interpretation

5.1. Overall Tree Species Identification Accuracy

The overall tree species identification accuracy results are presented as follows:

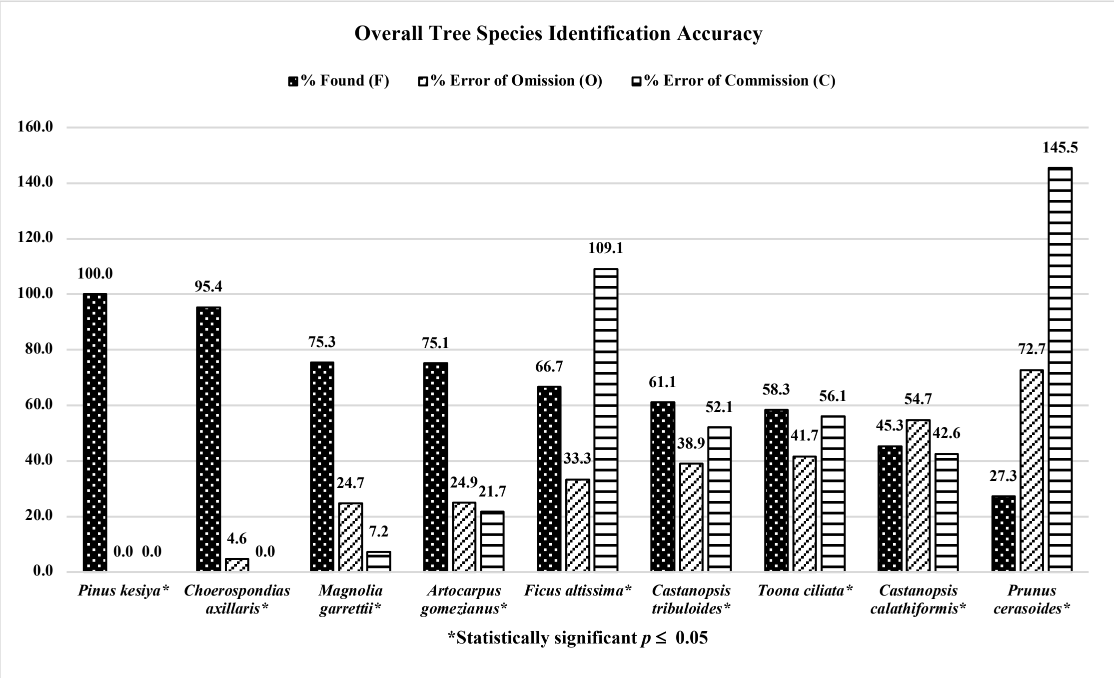


Figure 3.30 Overall Tree Species Identification Accuracy (high to low % F)

Overall tree species identification accuracy ranged from 27% to 100%. On average, more than 70% of the trees of 4 species: *Pinus kesiya, Choerospondias axillaris Magnolia garrettii* & *Artocarpus gomezianus* were correctly identified, whilst 50-70 % of the trees of 3 species: *Ficus altissima, Castanopsis tribuloides* & *Toona ciliata were* correctly identified. Only two species: *Castanopsis calathiformis* & *Prunus cerasoides* had mean identification success rates of 50% or less.

Pinus kesiya was most correctly identified at 100% identification accuracy and *Prunus cerasoides* with 27% was the least accurately identified. The highest % error of omission (O) and commission (C) was committed for *Prunus cerasoides* (Figure 3.30).

Table 3.89 Chi-Square test results for overall tree species identification accuracy

	Species	% Found	% Error of Omission	% Error of Commission
Chi-Square	123.552	18276.926	18276.926	33801.854
df	8	20	20	18
Asymp. Sig.	.000	.000	.000	.000

The correlation between tree species, % found, % error of omission and % error of commission is presented in Table 3.90.

Table 3.90 Correlation between Tree species, % Found, % Error of Omission and % Error of Commission

	% Found	% Error of Omission	% Error of Commission
% Found	1		
% Error of Omission	**-1.000**(**)	1	
% Error of Commission	**-.381**(**)	**.381**(**)	1

**Correlation is significant at the 0.01 level (2-tailed).

5.2. Overall Monthly Tree Species Identification Accuracy

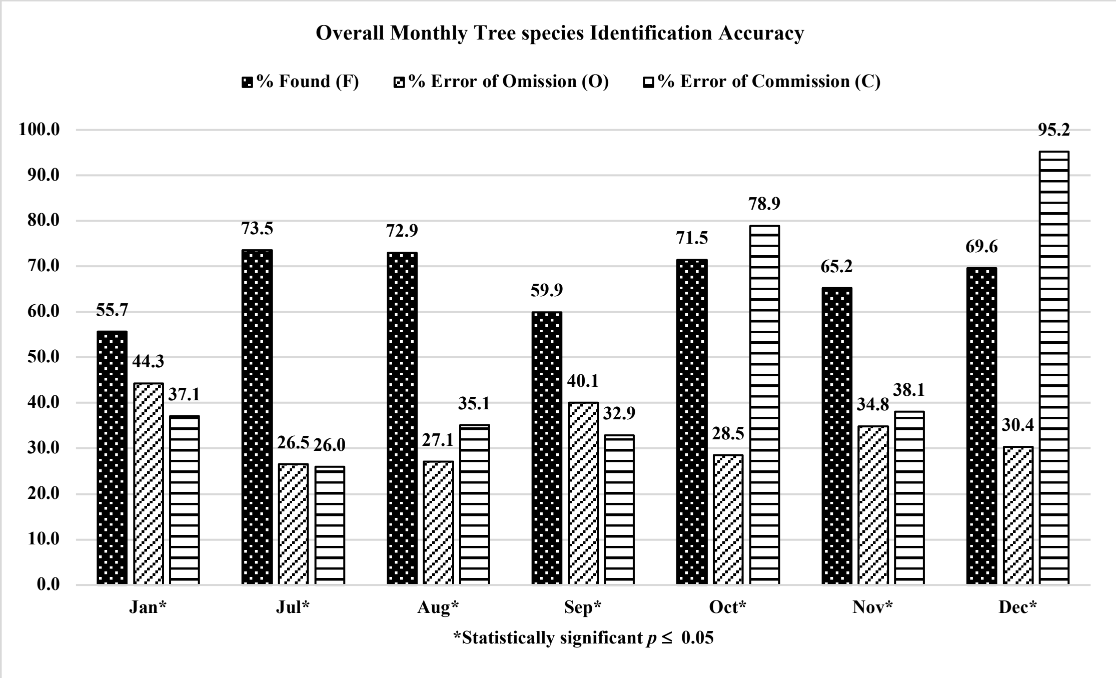


Figure 3.31 Overall Monthly Tree Species Identification Accuracy

The overall tree species identification accuracy was above 70% for the months July, August and October 2018. For the months of September, November, December 2018 and January 2019; the identification accuracy ranged between 55% to 70%.

The % error of omission (O) was highest in the month of January 2019 and lowest for July 2018. The % error of commission (C) was highest in the month of December and lowest for July 2018 (Figure 3.31).

Table 3.91 Chi-Square test results for monthly tree species identification accuracy

	Months	% Found	% Error of Omission	% Error of Commission
Chi-Square	222.908	37249.529	37249.529	43434.454
df	6	19	19	16
Asymp. Sig.	.000	.000	.000	.000

The correlation between months, % found, % error of omission and % error of commission is presented in Table 3.92.

Table 3.92 Correlation between Months, % Found, % Error of Omission and % Error of Commission

	%Found	**% Error of Omission**	**% Error of Commission**
% Found	1		
% Error of Omission	**-1.000**(**)	1	
% Error of Commission	-**.140**(**)	**.140**(**)	1

**Correlation is significant at the 0.01 level (2-tailed).

5.3. Species-wise Monthly Identification Accuracy

Species varied in the distinctiveness due to seasonal changes in their appearance due to flowering, leaf flush, phenology, etc. The results presented in this part shows, how identifiability changed with season and when each species was most identifiable. The months when the species were identified with highest identification accuracy are marked in bold with asterisk and are presented in Table 3.93. Those months marked with asterisk are recommended months to look for species using the approach developed in this study.

Table 3.93 Species-wise Monthly Identification Accuracy

SN	Species	Validation	Jan	Jul	Aug	Sep	Oct	Nov	Dec
1	*Artocarpus gomezianus*	% Found	40.0	80.0	79.6	75.0	**87.5***	75.0	75.0
		% Error of Omission	60.0	20.0	20.4	25.0	12.5	25.0	25.0
		% Error of Commission	20.0	0.0	10.4	0.0	12.5	25.0	150.0
2	*Castanopsis calathiformis*	% Found	0.0	**100.0***	41.7	-	59.8	41.7	10.0
		% Error of Omission	100.0	0.0	58.3	-	40.2	58.3	90.0
		% Error of Commission	0.0	100.0	36.1	-	8.3	112.5	10.0
3	*Castanopsis tribuloides*	% Found	50.0	66.7	62.5	50.0	50.0	80.0	**100.0***
		% Error of Omission	50.0	33.3	37.5	50.0	50.0	20.0	0.0
		% Error of Commission	50.0	0.0	0.0	50.0	166.7	40.0	0.0
4	*Choerospondias axillaris*	% Found	**100.0***	**100.0***	**100.0***	83.3	**100.0***	91.1	96.2
		% Error of Omission	0.0	0.0	0.0	16.7	0.0	8.9	3.8
		% Error of Commission	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	*Ficus altissima*	% Found	33.3	50.0	**100.0***	**100.0***	**100.0***	33.3	83.3
		% Error of Omission	66.7	50.0	0.0	0.0	0.0	66.7	16.7
		% Error of Commission	83.3	150.0	0.0	133.3	100.0	66.7	166.7

*Highest identification accuracy and recommended months to look for the species

Table 3.93 (Continued)

SN	Species	Validation	Jan	Jul	Aug	Sep	Oct	Nov	Dec
6	*Magnolia garrettii*	% Found	57.1	88.9	63.3	92.9	62.5	**100.0***	55.6
		% Error of Omission	42.9	11.1	36.7	7.1	37.5	0.0	44.4
		% Error of Commission	42.9	5.6	0.0	7.1	0.0	0.0	11.1
7	*Pinus kesiya*	% Found	**100.0***	**100.0***	**100.0***	**100.0***	**100.0***	**100.0***	**100.0***
		% Error of Omission	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		% Error of Commission	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	*Prunus cerasoides*	% Found	**100.0***	0.0	66.7	0.0	0.0	0.0	0.0
		% Error of Omission	0.0	100.0	33.3	100.0	100.0	100.0	100.0
		% Error of Commission	0.0	400.0	133.3	50.0	100.0	500.0	50.0
9	*Toona ciliata*	% Found	0.0	66.7	83.3	66.7	66.7	**75.0***	0.0
		% Error of Omission	100.0	33.3	16.7	33.3	33.3	25.0	100.0
		% Error of Commission	200.0	0.0	25.0	22.2	66.7	0.0	166.7

*Highest identification accuracy and recommended months to look for the species

Discussion

1. Tree Species Identification Accuracy

1.1. Tree species with Identification Accuracy of 100%

Pinus kesiya was the most correctly identified, at 100% identification accuracy and no errors of omission and commission (Figure 3.30). The high identification accuracy for *Pinus kesiya* was because it had the most distinctive and largest crowns, compared to other species. The trees were remnant mature trees, having grown up long before the framework species had been planted, which accounts for their emergent position in the forest canopy and their broad crowns. The whorls of needle leaves were very easily distinguished from the broad leaves of all the other species. *P. kesiya* is the only *Pinus* species in the area (Thailand's only other native *Pinus* – *P. merkusii* - is absent from the study site), so there was no opportunity to confuse it with any other species. Similar results were reported by Gonzalez-Orozco *et al.* (2010) and Garzon-Lopez *et al.* (2012) for palms trees, which looked very distinct compared to other tree families.

1.2. Tree species with Identification Accuracy of 75% to 95%

Choerospondias axillaris was identified with an accuracy of 95%. The error of omission was only 5% with no error of commission (Figure 3.30). *Magnolia garrettii* and *Artocarpus gomezianus* were both identified with an accuracy of 75% and error of omission was at 25%. The % error of commission for *Magnolia garrettii* was 7% and 22% for *Artocarpus gomezianus* (Figure 3.30). *Choerospondias axillaris, Magnolia garrettii* and *Artocarpus gomezianus* had relatively higher identification accuracy because they were the most abundant species (Table 2.5.) in the research plots (Gonzalez-Orozco *et al.*, 2010 and Garzon-Lopez *et al.*, 2012). However, this theory did not hold true for *Castanopsis calathiformis*; so therefore, other factors like uniqueness of crown and leaf characteristics might also have an influence on identification accuracy. *Magnolia garrettii* and *Artocarpus gomezianus* had larger leaves than those of other species, which might also have contributed to higher identification accuracy for these species (Figure 3.30).

1.3. Tree species with Identification Accuracy of 50% to 70%

Ficus altissima was identified with an accuracy of 67%, followed by *Castanopsis tribuloides* and *Toona ciliata*. The highest error of commission was committed for *Ficus altissima* at 109% followed by *Toona ciliata* and *Castanopsis tribuloides.* The error of omission was highest for *Toona ciliata* at 42%, followed by *Castanopsis tribuloides* and *Ficus altissima* (Figure 3.30). A very high error of commission in case of *Toona ciliata* was because most of the photo-interpreters misidentified it to be *Choerospondias axillaris,* as it looked very similar on photographs due to similar leaf type and arrangement.

One of the reasons for low identification accuracy of *Toona ciliata* was because it was a less abundant species. Similar findings were also reported by Gonzalez-Orozco *et al.* (2010) and Garzon-Lopez *et al.* (2012) for uncommon species.

1.4. Tree species with Identification Accuracy of 50% and below

Castanopsis calathiformis was identified at an accuracy of 45% followed by *Prunus cerasoides* at 27%. The error of omission was at 73% for *Prunus cerasoides* and 55% for *Castanopsis calathiformis.* The error of commission was 146% for *Prunus cerasoides* and 43% for *Castanopsis calathiformis* (Figure 3.30). One of the reasons for a very low identification accuracy and a very high % error of commission for *Prunus cerasoides* was because it was the rarest species in validation plot.

In addition, most of photo-interpreters committed high % error of commission for *Castanopsis calathiformis* as *Castanopsis tribuloides.* One of the reasons for this was because both of these species had similar looking crowns and leaf characteristics.

1.5. Phenology and Identification Accuracy

It was found that, the identification accuracy was highest for tree species at phenophases as presented below (Figure 3.31, Figure 3.32).

Table 3.94 Phenology and Identification Accuracy

SN	Species	Month/year	Phenophase	Identification Accuracy (%)
1	*Castanopsis calathiformis*	July 2018	Flowering	100%
2	*Choerospondias axillaris*	January 2019	Leaf fall	100%
3	*Prunus cerasoides*	January 2019	Flowering	100%
4	*Toona ciliata*	August 2018	Leaf flushing	83%

Our results were consistent to findings of Trichon & Julien (2006) and Garzon-Lopez *et al.* (2012) where they also reported that, tree species were easier to identify during the phenophases that were most visually striking.

Deciduous tree species presented a high % error of commission during dry season as all these species looked very similar with bare branches without leaves.

Figure 3.32 *Prunus cerasoides* flowering. Photographs of same tree crown taken in June 2018 (left) and in January 2019 (right).

2. Limitation and Challenges

2.1. Applicability of approach

Our approach to identify tree species works well only for species with tall trees, as the identification keys were developed based on visible upper layer of crowns. We assumed that crowns of taller species are only visible from top but however, we did not study any relationship in detail between the height of trees and identification accuracy. In addition, our approach is more suited for identification of abundant species except for *Castanopsis calathiformis* (Trichon *et al.*, 2006).

2.2. Inconsistencies in quality of digital aerial photographs

Certain inconsistencies in quality of digital aerial photographs were observed, which might have some influence in identification accuracy. These inconsistencies might have been because of inherent flaws in DJI Phantom Pro 4 camera and LITCHI app. In order to maintain uniformity in quality of all photographs, I used an identical autonomous flight plans and automatic camera setting for all our flights. However, for some months the photographs were over-exposed and with drift in position, away from the set coordinates. Weather, light conditions and light reflectance (Gonzalez-Orozco *et al.*, 2010) also contributed towards such inconsistencies.

2.3. Image geometric distortion

The angle of the image with respect to the ground causes image geometric distortion (Gonzalez-Orozco *et al.*, 2010). When the image axis was not completely vertical to the surface, objects appeared deformed – with tree tops pointing towards the edges or corners of the images. Excessive brightness (light reflectance) on the crown surface also complicated the recognition of the textural properties by eye. More specifically, high lateral light intensity created shadows, which reduced contrast and made it more difficult to identify the edges of the crowns. This affected visual judgement of the crowns that were located at the edge of photographs. Orthorectification and the construction of 3D (three-dimensional) models of the forest plots could overcome the distortion, but such orthorectified models lead to a drastic reduction in the detail visible in the images (e.g. individual leaves cannot be seen in 3D models) (Figure 3.33) and the software required to perform such orthorectification (e.g. Pix4D) is still prohibitively expensive (around 350 USD/month).

2.4. Topographic variation

Topographic variation in landscape (Gonzalez-Orozco *et al.*, 2010) also complicated the aerial identification of tree crowns. While looking at digital aerial photographs, the variation in slope is not obvious to human eyes as these photographs are in 2D (two-dimensional), making vertical and horizontal crown shape difficult to determine.

2.5. Photo-interpreters

For validation process of the identification keys, photo-interpreters were invited on voluntary basis. The photo-interpreters were briefed on development of keys, terminologies and 'how to use of Image J software' only on the day of validation.

Therefore, photo-interpreter's familiarity with the keys and Image J software might also have contributed to errors in identification accuracy which was also reported similarly by Gonzalez-Orozco *et al.* (2010).

2.6. Image J

In this research, I tried to look at the possibility to use of Image J software in tree species identification. It worked quite well for some of the species, but a lot of inconsistencies were observed as Image-J attributes (hue, saturation and brightness) were influenced by weather at the field (rainy, sunny, foggy, etc.).

Therefore, Image J keys cannot be used independently to identify tree species but could complement other keys.

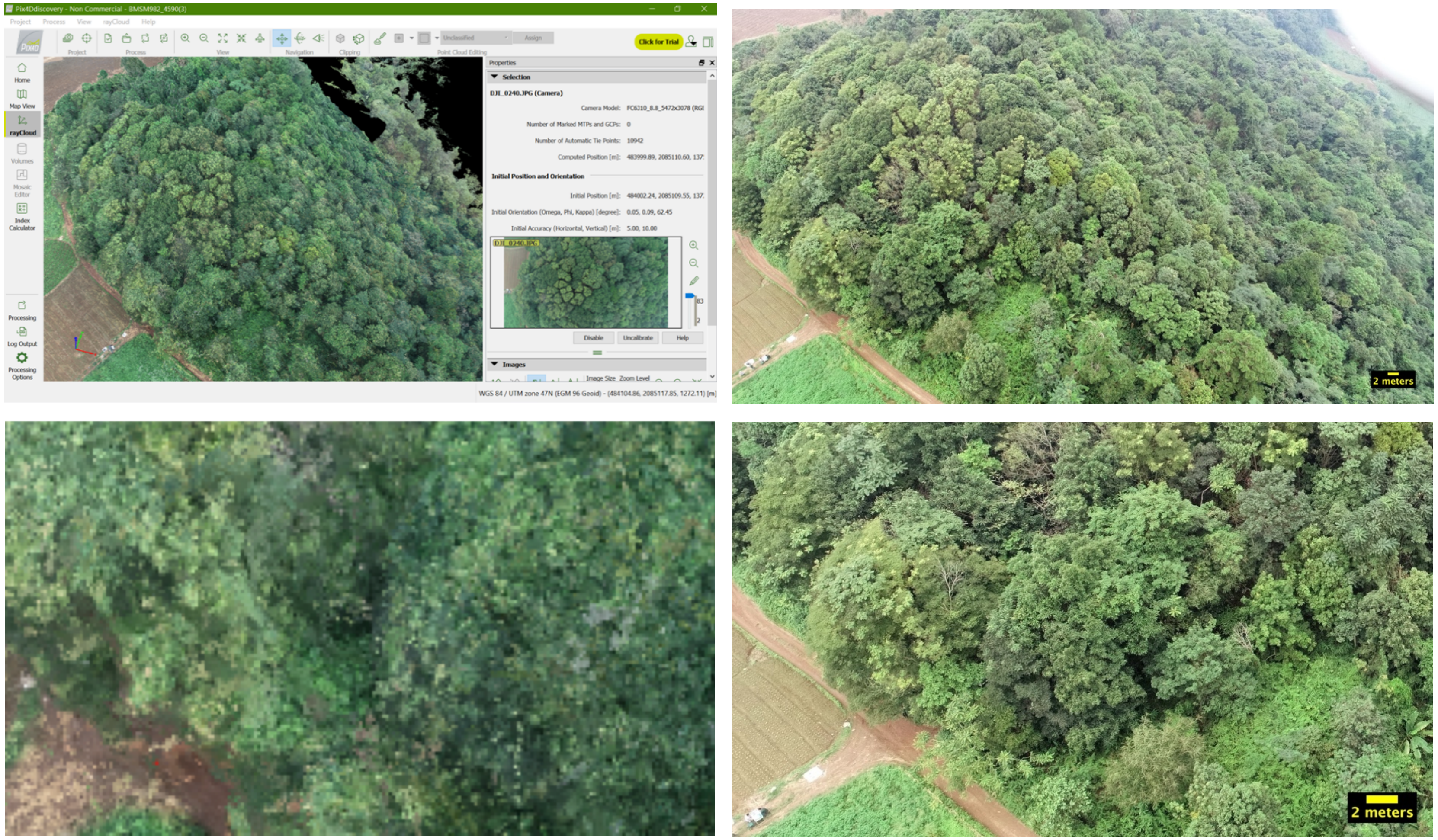


Figure 3.33 98.2 (BMSM Training plot) 3D model (Pix4D) –Orthorectified photographs (Left) and Original digital photographs (right)

2.7. Structural complexity of tree crowns

The shape of tree crowns varies between different species and within same species in relation to its course of development.

The crown shapes also vary widely depending on strata, ranging from more or less umbrella shaped crown in ‘A’ layer to isodiametric crowns in ‘B’ layer, to a narrow tapering crown at ‘C’ layer (Figure 3.34) (Richards, 1996). Striking differences were also observed between shape of crown in young and old trees of the same species in Malayan dipterocarps by Brunig (1974).

Tree crown features were more easily seen in trees on the edges of clearings and isolated individuals compared to the interior of forest where the form of the whole tree was often hard to determine (Richards, 1996). The canopy at the highest stratum with close-packed crowns showed crown-shyness with neighboring trees, i.e. they are usually separated by narrow gaps (Ng, 1977; Whitmore, 1984).

These structural complexities make it difficult to objectively apply crown delineation properties in our approach, which may also have contributed to errors to correctly identify target tree species (Gonzalez-Orozco *et al.* 2010).

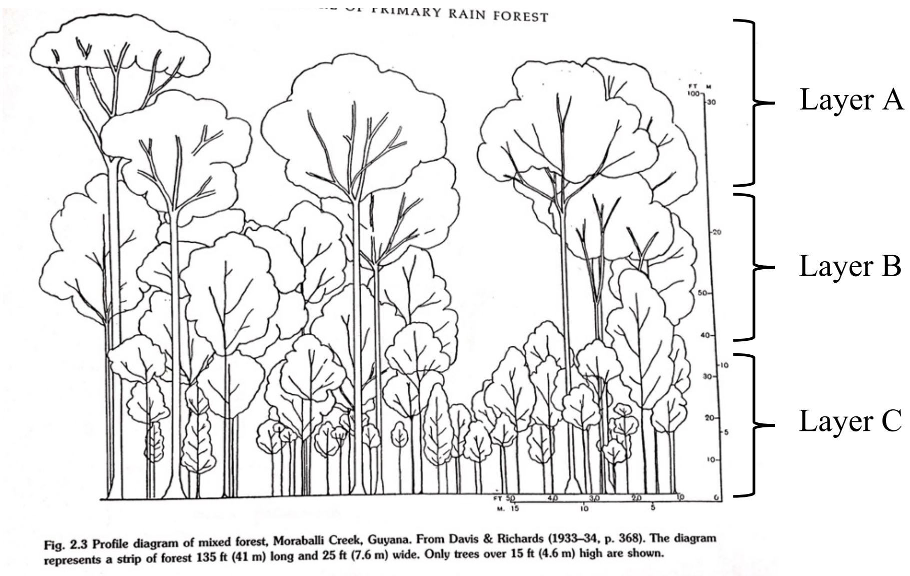


Figure 3.34 Profile diagram of mixed forest (Richards, 1996)

2.8. Automated tree species identification

The work presented here used visual keys to identify species – combining classical taxonomy with manual image filtering. The next step would be the development of automated tree identification. Technological advancements, such as machine learning and artificial intelligence are now making such automated classification of tree species using remotely sensed data possible. Much research has been carried out, using specialized hardware such as airborne hyperspectral, multispectral, and LiDAR sensors (Asner *et al.* 2007, 2008; Holmgren *et al.*, 2008) with UAV's rapidly becoming the preferred platform for such devices, since objective avoidance technologies now enable them to fly close to forest canopies and their operation cost are much lower compared with satellites or airborne based imaging systems (Koh & Wich, 2012; Anderson & Gaston, 2013; Getzin *et al.*, 2012).

Onishi & Ise (2018) used a publicly available deep learning package and constructed a machine vision system for the automatic classification of trees. They segmented basic digital RGB images acquired from unmanned aerial vehicle (UAV) of forest into individual tree crowns and carried out object-based deep learning. They could successfully classify 7 tree types (deciduous, evergreen and three species) at 89.0% accuracy. Their findings are notable and have potential to classify individual trees in a cost-effective way.

3. Application

Our approach has great potential to find trees of framework species especially for seed collection. Tree seed collection in most countries from remnant forest remains essential, but current methods are primitive. Collectors walk along forest trails, with binoculars pointed aloft, searching for ripe fruits amongst the minute fraction of the forest canopy that is visible from the ground. Even when a fruiting tree is found, the seeds may not be ripe, necessitating a tedious return trip. So, collectors tend to visit the same trees year after year, which narrows the genetic variety of the planting stock. Clearly, conventional seed collection is inefficient, unpredictable and consequently expensive.

Elliott *et al.* (2003) classified and ranked trees of framework species based on their field performance in restored plots of Ban Mae Sa Mai, Doi Suthep-Pui National Park, Northern Thailand. Four tree species (*Prunus cerasoides, Choerospondias axillaris, Ficus altissima, Magnolia garrettii*) which I studied were also listed in their research. Among these, *Prunus cerasoides* and *Choerospondias axillaris* were ranked as excellent, *Ficus altissima* as acceptable and *Magnolia garrettii* as marginal. The overall identification accuracy for *Choerospondias axillaris* was 95%, *Ficus altissima* was at 67%, *Magnolia garrettii* at 75% and *Prunus cerasoides* at 27%. Even though, *Prunus cerasoides* had lower overall identification accuracy but it was identified with 100% reliability during its flowering season (when the crowns turn pink). Therefore, our approach will enhance the efficiency and efficacy to look for trees of framework species and to subsequently monitor for fruit-set and ripeness for seed collection.

Another applicability of our approach is to monitor forest recovery in restoration projects. Our approach will help to determine the tree species composition (relative abundance) and also assess the long-term success or failure of individual species in terms of species diversity. Similar applications were also reported by Trichon & Julien (2006) and Gonzalez-Orozco *et al.* (2010).

Chapter 4

Conclusion

The combined use of dichotomous and monthly tree species identification keys (crown, leaf and image filtering) developed using digital aerial photographs from unmanned aerial vehicle (UAV) makes this research original.

In this research, I got an overall tree species identification accuracy of 67%, while error of omission was at 33% and error of commission at 48%. The overall species-wise identification accuracy for seven of nine species exceeded 50% of which, for four species (*Pinus kesiya, Choerospondias axillaris, Magnolia garrettii, Artocarpus gomezianus*), it was above 70%.

Our method might be a step closer to an approach called aerial taxonomy (Gonzalez-Orozco *et al.*, 2010), which linked photographic data with taxonomic knowledge to object-oriented classification technology. Therefore, in the future, more studies are needed to explore ways to link our keys to automatic species-identification approaches (Asner *et al.* 2007, 2008; Holmgren *et al.*, 2008; Lucas *et al.*, 2008; Baena *et al.*, 2017), object-oriented technologies (Gonzalez-Orozco *et al.*, 2010) and deep learning (Onishi & Ise, 2018).

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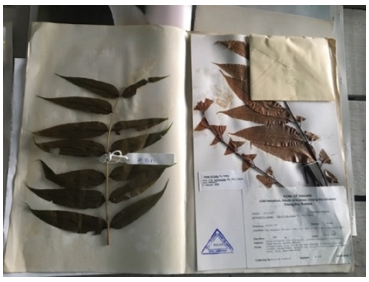
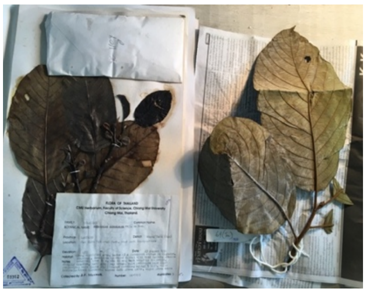
APPENDICES

Appendix A- Tree species identification photographs









Appendix B- Snapshots of field and validation documents

KRIS FLIGHT PLAN-1 98.2 220818 FLIGHT ALTITUDE…30…

Plot ID	DJI #	Tree ID		Coordinates		Drone Waypoints	Time		No. of Satellites	Drone Battery %	Drone Distance from Home	Pictures Taken (✓) or (✕)	Tree Species
		FORRU ID	Tree ID	Latitude	Longitude		Start	End					
	272	HOME				1	11:52 ~~9:34~~		12	94 - 92	4 meter		
R1.1	273	A-66-104	1	18.857450	98.848030	2	11:53			89		✓✓(2)	*Spondias axillaris*
R1.1	275		2	18.857480	98.848060	3	11:54		17	88	~~17~~	✓✓(2)	*Prunus cerasoides*
R1.1	278	A-72-58	3	18.857540	98.848010	4	11:55			88		✓✓(2)	*Ficus altissima*
R1.1	280	A-01-72	4	18.857550	98.847920	5	11:55		17	88	13.9	✓✓(2)	*Ficus altissima*
R1.1	282	A01-66-29	5	18.857520	98.847890	6	11:55		17	84	13.8	✓✓(2)	*Spondias axillaris*
R1.1	284	B335-37	7	18.857690	98.847760	7	11:56		17	81	14.8	✓✓(2)	*Castanopsis calathiformis*
R1.1	286		6	18.857610	98.847720	8	11:57		17	80	14	✓✓(2)	*Schima wallichii*
R1.1	288		8	18.857600	98.847720	9	11:57		17	75	13	✓✓(2)	*Schima wallichii*
R1.1	290	B66-138	12	18.857740	98.847680	10	11:57		17	74	13	✓✓(2)	*Spondias axillaris*
R1.1	292	B01-335	11	18.857930	98.847630	11	11:58		17	74	14	✓✓(2)	*Castanopsis calathiformis*
R1.1	294	B66-151	13	18.857980	98.847650	12	11:59		17	71	67	✓✓(2)	*Spondias axillaris*
R1.1	296	B71-60	14	18.857920	98.847750	13	11:59		17	68	70	✓✓(2)	*Prunus cerasoides*
R1.1	297	B71-62	14.1	18.857920	98.847720	14	12:00		17	66	60	✓✓(2)	*Prunus cerasoides*

Table 1 List of Photo-interpreter's

Sn	Date	Photo-Interpreter's Name	Address/Office/ Department	Signature
1	12/2/2019	Rattanamon Aisao	FORRU- CMU	[illegible]
2	12/2/19	Jarik Krobtong	FORRU	[illegible]
3	13/2/2019	Fletcher Kem	FORRU	[illegible]
4	13/2/2019	Derek ~~[illegible]~~ Tomlinson	CMU	[illegible]
5	13/2/19	Apirit Chansai	FORRU	[illegible]
6	13/2/19	Kathryn Harris	FORRU	[illegible]
7	13/2/19	Panipak Soetan	CMU	Panipak
8	14/2/19	Nout KANYAPHIM	CMU	[illegible]
9	14/2/19	Beeyaphat chaitlong	CMU	[illegible]
10	14/2/19	Miatta Kiawu	CMU/ESRC	MKiawu
11.	14/2/19	Khuanphirom Noruangsri	Bio CMU.	Khuanphirom

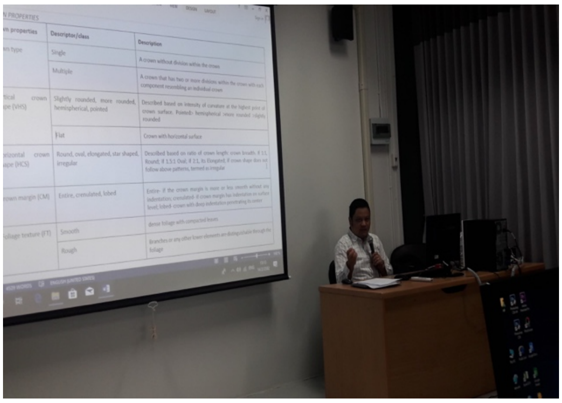
Appendix C- Key Validation Results

Name of Photo-interpreters	Nationality	Profession	Target species	Month of photograph (M/Y)	Total no. trees of target species in photographs	No. of trees Correctly identified of target species	No. of trees missed of target species	No. of trees incorrectly identified as target species	% Found	% Error of Omission	% Error of Commission
Derek	American	Undergraduate student	*Artocarpus gomezianus*	8/18	9	5	4	1	55.6	44.4	11.1
			Castanopsis calathiformis	10/18	11	6	5	0	54.5	45.5	0.0
			Castanopsis tribuloides	9/18	3	1	2	0	33.3	66.7	0.0
			Choerospondias axillaris	11/18	8	7	1	0	87.5	12.5	0.0
			Ficus altissima	12/18	2	1	1	1	50.0	50.0	50.0
			Magnolia garrettii	1/19	5	2	3	0	40.0	60.0	0.0
			Pinus kesiya	7/18	2	2	0	0	100.0	0.0	0.0
			Prunus cerasoides	8/18	1	0	1	4	0.0	100.0	400.0
			Toona ciliata	9/18	3	2	1	0	66.7	33.3	0.0
Fletcher	American	Undergraduate student	*Artocarpus gomezianus*	9/18	5	5	0	0	100.0	0.0	0.0
			Castanopsis calathiformis	11/18	3	1	2	6	33.3	66.7	200.0
			Castanopsis tribuloides	10/18	3	1	2	6	33.3	66.7	200.0
			Choerospondias axillaris	12/18	13	12	1	0	92.3	7.7	0.0
			Ficus altissima	1/19	2	0	2	2	0.0	100.0	100.0
			Magnolia garrettii	7/18	10	10	0	0	100.0	0.0	0.0
			Pinus kesiya	8/18	4	4	0	0	100.0	0.0	0.0
			Prunus cerasoides	9/18	1	0	1	1	0.0	100.0	100.0
			Toona ciliata	10/18	3	2	1	4	66.7	33.3	133.3
Apirit	Thai	FORRU Staff	*Artocarpus gomezianus*	7/18	5	3	2	0	60.0	40.0	0.0
			Castanopsis calathiformis	8/18	8	0	8	6	0.0	100.0	75.0
			Castanopsis tribuloides	8/18	4	2	2	0	50.0	50.0	0.0
			Choerospondias axillaris	10/18	8	8	0	0	100.0	0.0	0.0
			Ficus altissima	11/18	3	1	2	2	33.3	66.7	66.7
			Magnolia garrettii	12/18	8	8	0	0	100.0	0.0	0.0
			Pinus kesiya	1/19	2	2	0	0	100.0	0.0	0.0
			Prunus cerasoides	7/18	1	0	1	0	0.0	100.0	0.0
			Toona ciliata	8/18	3	2	1	0	66.7	33.3	0.0
Jarik	Thai	FORRU Staff	*Artocarpus gomezianus*	10/18	8	7	1	1	87.5	12.5	12.5
			Castanopsis calathiformis	12/18	10	1	9	1	10.0	90.0	10.0
			Castanopsis tribuloides	11/18	5	4	1	2	80.0	20.0	40.0
			Choerospondias axillaris	1/19	12	12	0	0	100.0	0.0	0.0
			Ficus altissima	7/18	4	2	2	6	50.0	50.0	150.0
			Magnolia garrettii	8/18	7	4	3	3	57.1	42.9	42.9
			Pinus kesiya	9/18	3	3	0	0	100.0	0.0	0.0
			Prunus cerasoides	10/18	1	0	1	5	0.0	100.0	500.0
			Toona ciliata	11/18	4	3	1	0	75.0	25.0	0.0

Name of Photo-interpreters	Nationality	Profession	Target species	Month of photograph (M/Y)	Total no. trees of target species in photographs	No. of trees Correctly identified of target species	No. of trees missed of target species	No. of trees incorrectly identified as target species	% Found	% Error of Omission	% Error of Commission
Rattanamon	Thai	FORRU Staff	*Artocarpus gomezianus*	9/18	4	2	2	0	50.0	50.0	0.0
			Castanopsis calathiformis	11/18	4	2	2	1	50.0	50.0	25.0
			Castanopsis tribuloides	10/18	3	2	1	4	66.7	33.3	133.3
			Choerospondias axillaris	12/18	8	8	0	0	100.0	0.0	0.0
			Ficus altissima	1/19	2	0	2	2	0.0	100.0	100.0
			Magnolia garrettii	7/18	7	6	1	1	85.7	14.3	14.3
			Pinus kesiya	8/18	3	3	0	0	100.0	0.0	0.0
			Toona ciliata	10/18	3	2	1	0	66.7	33.3	0.0
Panipak	Thai	Postgraduate student	*Artocarpus gomezianus*	8/18	5	5	0	1	100.0	0.0	20.0
			Castanopsis calathiformis	10/18	8	3	5	1	37.5	62.5	12.5
			Castanopsis tribuloides	9/18	2	1	1	1	50.0	50.0	50.0
			Choerospondias axillaris	11/18	8	8	0	0	100.0	0.0	0.0
			Ficus altissima	12/18	2	2	0	4	100.0	0.0	200.0
			Magnolia garrettii	1/19	6	6	0	0	100.0	0.0	0.0
			Pinus kesiya	7/18	2	2	0	0	100.0	0.0	0.0
			Prunus cerasoides	8/18	1	1	0	0	100.0	0.0	0.0
			Toona ciliata	9/18	3	2	1	2	66.7	33.3	66.7
Kathryn	American	Undergraduate student	*Artocarpus gomezianus*	8/18	6	5	1	0	83.3	16.7	0.0
			Castanopsis calathiformis	10/18	8	7	1	1	87.5	12.5	12.5
			Castanopsis tribuloides	9/18	3	2	1	3	66.7	33.3	100.0
			Choerospondias axillaris	11/18	7	6	1	0	85.7	14.3	0.0
			Ficus altissima	12/18	2	2	0	5	100.0	0.0	250.0
			Magnolia garrettii	1/19	4	2	2	0	50.0	50.0	0.0
			Pinus kesiya	7/18	2	2	0	0	100.0	0.0	0.0
			Prunus cerasoides	8/18	1	1	0	0	100.0	0.0	0.0
			Toona ciliata	9/18	3	2	1	0	66.7	33.3	0.0
Miatta	Liberian	Postgraduate student	*Artocarpus gomezianus*	11/18	4	3	1	1	75.0	25.0	25.0
			Castanopsis calathiformis	1/19	3	0	3	0	0.0	100.0	0.0
			Castanopsis tribuloides	12/18	2	2	0	0	100.0	0.0	0.0
			Choerospondias axillaris	7/18	6	6	0	0	100.0	0.0	0.0
			Ficus altissima	8/18	2	2	0	0	100.0	0.0	0.0
			Magnolia garrettii	9/18	9	5	4	1	55.6	44.4	11.1
			Pinus kesiya	10/18	3	3	0	0	100.0	0.0	0.0
			Prunus cerasoides	11/18	1	0	1	1	0.0	100.0	100.0
			Toona ciliata	12/18	3	0	3	5	0.0	100.0	166.7

Name of Photo-interpreters	Nationality	Profession	Target species	Month of photograph (M/Y)	Total no. trees of target species in photographs	No. of trees Correctly identified of target species	No. of trees missed of target species	No. of trees incorrectly identified as target species	% Found	% Error of Omission	% Error of Commission
Nout	Laotian	Postgraduate student	*Artocarpus gomezianus*	1/19	5	2	3	1	40.0	60.0	20.0
			Castanopsis calathiformis	8/18	6	2	4	2	33.3	66.7	33.3
			Castanopsis tribuloides	7/18	3	2	1	0	66.7	33.3	0.0
			Choerospondias axillaris	9/18	6	5	1	0	83.3	16.7	0.0
			Ficus altissima	10/18	1	1	0	1	100.0	0.0	100.0
			Magnolia garrettii	11/18	8	5	3	0	62.5	37.5	0.0
			Pinus kesiya	12/18	2	2	0	0	100.0	0.0	0.0
			Prunus cerasoides	1/19	1	1	0	0	100.0	0.0	0.0
			Toona ciliata	7/18	3	2	1	0	66.7	33.3	0.0
Preeyaphat	Thai	Postgraduate student	*Artocarpus gomezianus*	12/18	4	3	1	6	75.0	25.0	150.0
			Castanopsis calathiformis	7/18	4	4	0	4	100.0	0.0	100.0
			Castanopsis tribuloides	1/19	4	2	2	2	50.0	50.0	50.0
			Choerospondias axillaris	8/18	6	6	0	0	100.0	0.0	0.0
			Ficus altissima	9/18	3	3	0	4	100.0	0.0	133.3
			Magnolia garrettii	10/18	3	3	0	0	100.0	0.0	0.0
			Pinus kesiya	11/18	2	2	0	0	100.0	0.0	0.0
			Prunus cerasoides	12/18	1	0	1	4	0.0	100.0	400.0
			Toona ciliata	1/19	3	0	3	6	0.0	100.0	200.0
Khuanphirom	Thai	Postgraduate student	*Artocarpus gomezianus*	7/18	6	6	0	0	100.0	0.0	0.0
			Castanopsis calathiformis	8/18	12	11	1	0	91.7	8.3	0.0
			Castanopsis tribuloides	8/18	4	3	1	0	75.0	25.0	0.0
			Choerospondias axillaris	10/18	6	6	0	0	100.0	0.0	0.0
			Ficus altissima	1/19	2	2	0	1	100.0	0.0	50.0
			Magnolia garrettii	12/18	9	7	2	1	77.8	22.2	11.1
			Pinus kesiya	1/19	2	2	0	0	100.0	0.0	0.0
			Prunus cerasoides	7/18	1	0	1	1	0.0	100.0	100.0
			Toona ciliata	8/18	4	4	0	2	100.0	0.0	50.0

Appendix D- Validation day photographs



Appendix E- Aerial taxonomic keys

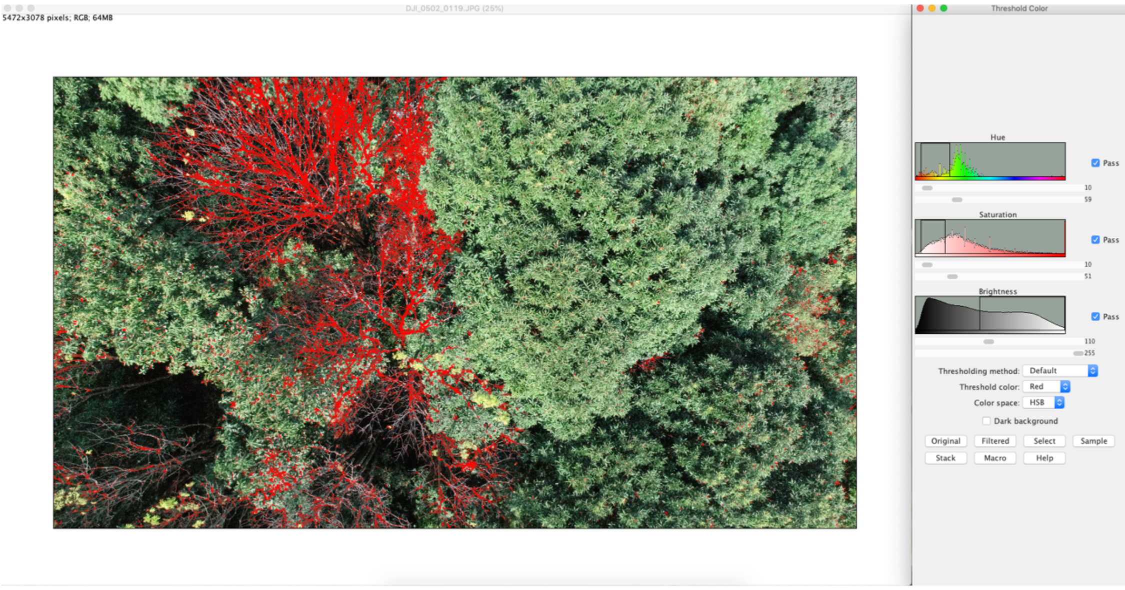
1. ***Prunus cerasoides (January)***

Key descriptors	Key description		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green with yellow patches & visible branches		
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC dull green		
Image J keys (Key C)	Hue: 0/53-64	Sat: 10-40/85-255	Bright: 90-110/255
Phenology	Leaf fall (Crown density=0)		
Identification Accuracy	100% (January)		
Recommendation	Fly drone at 50m above ground in January		

2. ***Castanopsis calathiformis (July)***

Key descriptors	**Key description**		
Tree crown keys (Key A)	CT Single, VCS More rounded, HCS Oval, CM Entire, FT rough, CC yellowish dull green		
Leaf keys (Key B)	LT simple, LA alternate spiral, LS elliptic, LC glossy dull green and yellow		
Image J keys (Key C)	Hue: 0/80-115	Sat: 0/65-101	Bright: 128-141/255
Phenology	Flowering		
Identification Accuracy	100% (July)		
Recommendation	Fly drone at 50m above ground in July		

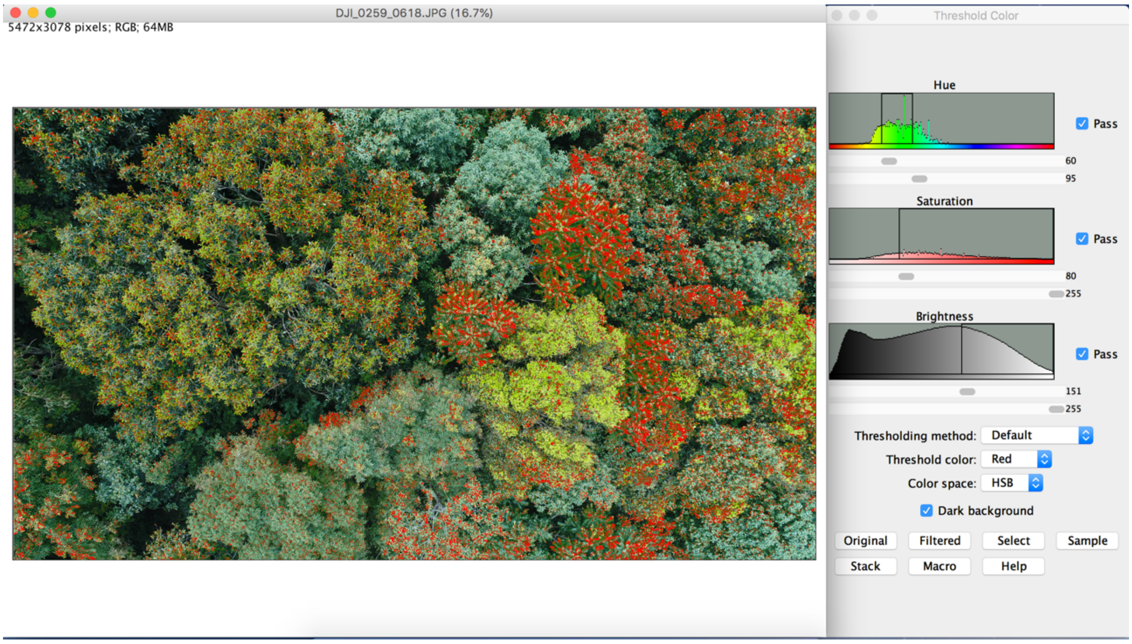
3. ***Choerospondias axillaris (January)***



Key descriptors	Key description		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Elongated, FT smooth, CC visible branches with almost all leaves shed		
Leaf keys (Key B)	LT compound, LA paripinnate, LS lanceolate with tapering end, LC yellowish green		
Image J keys (Key C)	Hue: 10-40/59	Sat: 10-40/51-91	Bright: 80-110/255
Phenology	Leaf fall (Crown density=0)		
Identification Accuracy	100% (January)		
Recommendation	Fly drone at 50m above ground in January		

4. *Toona ciliata (August)*



Key descriptors	**Key description**		
Tree crown keys (Key A)	CT multiple, VCS Flat, HCS Irregular, FT rough, CC dull green		
Leaf keys (Key B)	LT compound, LA imparipinnate, LS narrowly ovate with tapering end, LC dull green		
Image J keys (Key C)	Hue: 88/135	Sat: 0/124-159	Bright: 113-144/255
Phenology			
Identification Accuracy	83% (August)		
Recommendation	Fly drone at 50m above ground in August		

Appendix F- Statistical Test Results

1. *Artocarpus gomezianus*

ANOVA one-way results

		Sum of Squares	df	Mean Square	F	Sig.
% Found	Between Groups	106409.881	6	17734.980	67.398	.000
	Within Groups	216300.350	822	263.139		
	Total	322710.232	828			
% Error of Omission	Between Groups	106409.881	6	17734.980	67.398	.000
	Within Groups	216300.350	822	263.139		
	Total	322710.232	828			
% Error of Commission	Between Groups	1310202.422	6	218367.070	53417.608	.000
	Within Groups	3360.273	822	4.088		
	Total	1313562.695	828			

2. *Castanopsis calathiformis*

ANOVA one-way results

		Sum of Squares	df	Mean Square	F	Sig.
% Found	Between Groups	763426.032	5	152685.206	856.554	.000
	Within Groups	146704.074	823	178.255		
	Total	910130.106	828			
% Error of Omission	Between Groups	763426.032	5	152685.206	856.554	.000
	Within Groups	146704.074	823	178.255		
	Total	910130.106	828			
% Error of commission	Between Groups	1740390.041	5	348078.008	178.434	.000
	Within Groups	1605454.185	823	1950.734		
	Total	3345844.227	828			

3. *Castanopsis tribuloides*

ANOVA one-way results

		Sum of Squares	df	Mean Square	F	Sig.
% Found	Between Groups	280161.863	5	56032.373	2102.862	.000
	Within Groups	19264.887	723	26.646		
	Total	299426.750	728			
% Error of Omission	Between Groups	280161.863	5	56032.373	2102.862	.000
	Within Groups	19264.887	723	26.646		
	Total	299426.750	728			
% Error of Commission	Between Groups	1748130.444	5	349626.089	121.591	.000
	Within Groups	2078942.520	723	2875.439		
	Total	3827072.964	728			

4. *Choerospondias axillaris*

ANOVA one-way results

		Sum of Squares	df	Mean Square	F	Sig.
% Found	Between Groups	22223.962	6	3703.994	228.809	.000
	Within Groups	13306.654	822	16.188		
	Total	35530.617	828			
% Error of Omission	Between Groups	22223.962	6	3703.994	228.809	.000
	Within Groups	13306.654	822	16.188		
	Total	35530.617	828			
% Error of Commission	Between Groups	.000	6	.000	.	.
	Within Groups	.000	822	.000		
	Total	.000	828			

5. *Ficus altissima*

ANOVA one-way results

		Sum of Squares	df	Mean Square	F	Sig.
% Found	Between Groups	464171.349	5	92834.270	104.084	.000
	Within Groups	734046.610	823	891.916		
	Total	1198217.959	828			
% Error of Omission	Between Groups	464171.349	5	92834.270	104.084	.000
	Within Groups	734046.610	823	891.916		
	Total	1198217.959	828			
% Error of Commission	Between Groups	2590505.907	5	518101.181	185.967	.000
	Within Groups	2292870.245	823	2785.991		
	Total	4883376.152	828			

6. ***Magnolia garrettii***

ANOVA one-way results

		Sum of Squares	df	Mean Square	F	Sig.
% Found	Between Groups	214108.060	5	42821.612	187.203	.000
	Within Groups	188256.496	823	228.744		
	Total	402364.556	828			
% Error of Omission	Between Groups	214108.060	5	42821.612	187.203	.000
	Within Groups	188256.496	823	228.744		
	Total	402364.556	828			
% Error of Commission	Between Groups	95265.762	5	19053.152	957.018	.000
	Within Groups	16385.000	823	19.909		
	Total	111650.762	828			

7. ***Pinus kesiya***

ANOVA one-way results

		Sum of Squares	df	Mean Square	F	Sig.
% Found	Between Groups	.000	6	.000	.000	1.000
	Within Groups	.000	822	.000		
	Total	.000	828			
% Error of Omission	Between Groups	.000	6	.000	.	.
	Within Groups	.000	822	.000		
	Total	.000	828			
% Error of Commission	Between Groups	.000	6	.000	.	.
	Within Groups	.000	822	.000		
	Total	.000	828			

8. ***Prunus cerasoides***

ANOVA one-way results

		Sum of Squares	df	Mean Square	F	Sig.
% Found	Between Groups	730011.601	6	121668.600	366.709	.000
	Within Groups	272727.273	822	331.785		
	Total	1002738.873	828			
% Error of Omission	Between Groups	730011.601	6	121668.600	366.709	.000
	Within Groups	272727.273	822	331.785		
	Total	1002738.873	828			
% Error of Commission	Between Groups	22654834.515	6	3775805.753	582.842	.000
	Within Groups	5325133.402	822	6478.264		
	Total	27979967.917	828			

9. ***Toona ciliata***

ANOVA one-way results

		Sum of Squares	df	Mean Square	F	Sig.
% Found	Between Groups	580884.539	6	96814.090	1913.774	.000
	Within Groups	41583.375	822	50.588		
	Total	622467.914	828			
% Error of Omission	Between Groups	580884.539	6	96814.090	1913.774	.000
	Within Groups	41583.375	822	50.588		
	Total	622467.914	828			
% Error of Commission	Between Groups	3199945.115	6	533324.186	390.488	.000
	Within Groups	1122677.136	822	1365.787		
	Total	4322622.251	828			

Curriculum vitae

Author's name	Mr. Krishna Bahadur Rai
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Education	2002, Indian School Certificate, Class XII, Jigmesherubling Higher Secondary School, Khaling, Trashigang, Bhutan 2006, Bachelor's Degree in Science with Major in Zoology, St. Joseph's College, North Point, Darjeeling, West Bengal, India
Scholarship	(2017-2019) Partial funding by Thailand International Cooperation Agency (TICA) & Bhutan Power Corporation Limited (BPC)
Experience	(2007-till date) Environmental Officer at Bhutan Power Corporation Limited (BPC), Thimphu, Bhutan
Training/Conferences attended	December 10-14, 2007; Training workshop on Environment Impact Assessment (EIA), Ministry of Economic Affairs and National Environment Commission (NEC), Phuentsholing, Bhutan May 20-25, 2009; Training on Green House Inventory and Mitigation Assessment, Paibare Inc., Metro Manila, Philippines August 10-12, 2010; Basic PI Solving Training, JICA, Thimphu, Bhutan

Training/Conferences attended (Continued)	October 19-25, 2010; Training on EIA and GIS Application, DFI Training Services, Makati city, Philippines July 16-24, 2012; Training program for Management Excellence in Environmental Risk Mitigation, Management, Monitoring and Evaluation, DFI Training Services, Makati city, Philippines September 2-6, 2013; Training on Environmental Impact Assessment and Environmental Management for Power Transmission Line Projects, National Environment Commission (NEC) & Centre for Science and Environment (CSI)-New Delhi, Paro Bhutan. September 8-13, 2013; Training workshop on Compliance Monitoring Processes and Protocol towards Environment Mainstreaming and Emission Reduction, National Environment Commission (NEC) & Centre for Science and Environment (CSI)-New Delhi, Phuentsholing, Bhutan March 19-20, 2014; Conference on Environment Friendly Best Practices in Industrial Estates and Waste Management, DHI-INFRA, Thimphu, Bhutan March 26 to April 4, 2014; Training program on SAR ERP Project System, Bhutan Power Corporation Limited, Thimphu, Bhutan

Training/Conferences attended (Cont'd.)	May 12-14, 2014; Training Program on Environmental Management of Power Transmission Line Projects, National Environment Commission (NEC), Thimphu, Bhutan May 19-22, 2014; Training on Fundamentals of Climate Change Adaptation, WWF Bhutan, Thimphu, Bhutan May 11-14, 2015; Conference of International Association for Impact Assessment (IAIA 16), Aichi-Nagoya, Japan. December 13-18, 2015; Study Tour to Power Corporations in Philippines; Paibare Inc., Metro Manila, Philippines June 30- July 2, 2016; Intensive course on HO REN SO, MASLOW Trainers and Consultants-Malaysia, Thimphu, Bhutan March 6-17, 2017; Training on Social Impact Assessment (SIA) and Basics of SPSS, Athang Training Academy, Thimphu, Bhutan