AN ASSESSMENT OF ASIAN ELEPHANT POPULATION STATUS IN THE MAIN FOREST COMPLEXES OF NORTHERN PENINSULAR MALAYSIA

OR OI CHING

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ABSTRACT

The Asian elephant (*Elephas maximus*) is recognised for its important ecological role in maintaining the health of forest ecosystems as well as its cultural importance in many countries. Various causes, including habitat loss and fragmentation, human-elephant conflicts, and inadequate comprehension of their population dynamics, have been identified as threats to their existence and obstacles to conservation initiatives. Malaysia has the potential to protect this endangered species, but effective conservation requires a comprehensive understanding of its population and environment. This study focuses on the forest complexes in the northern region of Peninsular Malaysia that are known to be habitats for elephants. This study aims to provide scientific evidence to support the national elephant conservation action plan, with three main objectives: i) population density estimates; ii) habitat use prediction; and iii) population viability assessment in four main forest complexes across northern Peninsular Malaysia. The mean density estimate for wild elephants in the Greater Ulu Muda Forest Complex (GUMFC) is 0.17 elephants per km^2 (CI 95%, 0.11-0.25), and the population size ranges from 185 to 420 elephants in an area of 1,629.31 km^2. The findings highlight the significance of GUMFC as a vital landscape that supports the elephant population in the north. Habitats use predictions for three forest complexes (i.e., Gunung Inas-Bintang Hijau Forest Complex (GIBHFC), Royal Belum State Park (RBSP), and Temengor Forest Complex (TFC) proved that almost all areas in these forest complexes are suitable for elephants, but with a different degree of suitability. The ‘elevation’ and ‘distance to plantations’ showed a negative correlation with elephant habitat utilisation. Distance to the settlement was negatively associated with elephant habitat use in a quadratic manner. Finally, the population viability analysis conducted for the elephant population in GUMFC based on 52 scenarios revealed that it is at risk of extinction, mainly due to changes in carrying capacity (due to forest cover) and the removal of elephants from the landscape. This study emphasises the importance of elephant conservation initiatives to prioritise the preservation and conservation of elephants' natural habitats, and develop effective human-elephant conflict management strategies, to ensure the viability of elephants in Peninsular Malaysia.

This Ph.D. is dedicated to my beloved family members, especially my parents, Mr. Or Chee Kuang and Madam Teng Sow Kee, who were my first teachers who taught me to stand on real ground, be honest and be kind, and always supported me with their pure wishes. My sisters and brothers supported me in the way that they could.

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Conferences attended:

i. 19th International Elephant Conservation and Research Symposium, 2023, Chiang Mai, Thailand. Presenter: Wild Asian elephant habitat uses and their relationship to biophysical factors across forest complexes in northern Peninsular Malaysia.
ii. 10th ASESG Members meeting, Young Professionals Workshop, 6th Dec 2019, Sabah, Malaysia. Presenter - An assessment of wild Asian elephant population status in Peninsular Malaysia
iii. SCB's 29th International Congress for Conservation Biology (ICCB 2019). Presenter - An assessment of the wild Asian Elephant population and distribution in Peninsular Malaysia.
iv. Conference of the Association for Tropical Biology & Conservation 2018, Sarawak. Participant.

Workshops and events attended:

Biodiversity Conservation Society Sarawak (BCSS): Boot camp in wildlife study design and data analysis (10 days), 2018.

Interviews and documentaries in which this study was featured:

i. Astro Shuang Xing CH307, 2022. 'The Conservationist- Asian Elephant, Episode 3.
ii. Astro AEC, 2021. Stay Hungry, Stay Foolish: Stories of Malaysian Scientists, Episode 5.

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CHAPTER 1: GENERAL INTRODUCTION

1.1 BACKGROUND

In the Anthropocene, biodiversity crashes around the world are happening and are inevitable. It has been reported that in future decades, one million species could face extinction if efforts are not made to prevent it (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2019). Biodiversity conservation organisations in the world are racing against time and other challenges, such as climate change, to save the affected wild flora and fauna from further harm before it is too late. In this context, conservation needs to be supported by science to ensure its effectiveness and to measure its impact. This included understanding aspects of species-specific ecological knowledge such as population status, habitat suitability, foraging behaviour, and other ecological needs. Such science-based knowledge can then shape national and international governmental legislation and policies.

Large animals (known as 'megafauna') are particularly at risk. This is because they need large and connected areas to sustain healthy populations (Ripper et al., 2019). Many large mammals went extinct during the Quaternary period (i.e., during and since the ice ages of the Pleistocene and during the present Holocene epoch). These extinctions may have been due to overhunting by humans and severe climate fluctuations (Koch et al., 2006; Martin et al., 1984)., In addition, the more recent modifications of natural habitats threaten megafauna.

One important group of threatened megafauna is elephants. This group includes the remaining three elephant species, namely the African bush elephant (*Loxodonta africana*), the African forest elephant (*L. cyclotis*), and the Asian elephant (*Elephas maximus*). Elephants perform essential ecological functions as both umbrella and keystone species, significantly influencing biodiversity and ecosystem stability. Elephants help in defining the entire ecosystem by dispersing seeds, especially that of megafaunal-syndrome plants (Campos-

Arceiz et al., 2012), creating pathways for smaller animals (Fritz, 2017), and hence influencing the structure, composition and diversity of vegetation (Terborgh et al., 2018). Elephants are regarded as an umbrella species because efforts made to protect elephants and their habitat are also beneficial for other wildlife that share the same landscape (Yang et al., 2023). In addition to their ecological functions, elephants hold considerable symbolism and cultural significance (Locke and Buckingham, 2016).

However, despite their ecological and cultural importance, elephants are at risk of extinction. In particular, the global population of Asian elephants continues to decline (Choudhury et al., 2008). Elephants are primarily threatened by habitat loss, fragmentation and degradation (Koch et al., 2006; Ripper et al., 2019), poaching and illicit trade in live animals and body parts including ivory (Dasgupta, 2017; Clements et al., 2010), retaliation killing due to conflicts with human (mainly due to crop depredation by elephants), and human population growth (Leimgruber et al., 2003; Hedges et al., 2005; Choudhury et al., 2008; Department of Wildlife and National Parks Peninsular Malaysia, 2013; Asian Elephant Range States, 2017). Small isolated elephant populations are likely to go extinct if no attention is given to maintaining their population, such as by reintroducing habitat connectivity via a wildlife corridor (Saaban et al., 2020). A study by Hedges et al. (2005) found that only four out of 12 elephant populations persisted on the island of Sumatra after 20 years due to habitat loss and fragmentation.

Malaysia is one of the 13 countries that have wild Asian elephant populations. Malaysia has a history of land-use changes linked to resource extraction, such as tin mining and deforestation of rubber and oil palm. At the same time, there have long been several conservation measures taken to protect wild elephants. However, it is not known whether these measures will be sufficient for the long-term survival of Peninsular Malaysia's wild elephants

(Department of Wildlife and National Parks Peninsular Malaysia, 2023; Department of Wildlife and National Parks Peninsular Malaysia, 2013).

Robust scientific study is important to ensure reliable data, especially when the data is to be used for species conservation (Blake and Hedges, 2004). The use of unreliable data (i.e., elephant density and distribution) has been highlighted as one of the main challenges in the conservation of Asian elephants. Unreliable data could lead to conservation challenges in prioritizing the conservation efforts (Blake and Hedges, 2004; Asian Elephant Range States, 2017).

1.2 PROBLEM STATEMENT

There are several knowledge gaps related to the management and conservation of the wild Asian Elephant in rapidly developing Malaysia. In Peninsular Malaysia, these knowledge gaps have been identified in the Government of Malaysia's National Elephant Conservation Action Plan (NECAP 1.0 (2013-2023) and NECAP 2.0 (2024-2030)). Three particularly pressing knowledge gaps are as follows:

i. There are no robust population estimates of elephants in the northern forest complex.

ii. There is a lack of information on the habitat use of wild elephants in the Main Range of the Central Forest Spine (CFS) landscape.

iii. There has been no population viability analysis (PVA) for elephants in the northern forest complex.

1.3 AIM AND OBJECTIVES

Given these knowledge gaps, this study aims to provide science-based information on the status of elephant ecology in Peninsular Malaysia and, hence, support the government's existing conservation and monitoring efforts, including the ongoing National Elephant Survey (NES). The three objectives of this study are as follows:

I. To establish the density estimate of wild Asian elephants in the Greater Ulu Muda Forest Complex (GUMFC), Kedah (part of the northern forest complex).

II. To assess the distribution and habitat use of wild Asian elephants in the Main Range of the Central Forest Spine.

III. To conduct a population viability analysis of wild elephants in the northern forest complex.

1.4 THESIS STRUCTURE

This thesis includes the present introduction, a review chapter, and three chapters presenting the findings of research on each of the three research objectives. The interlinkages between the chapters are presented in the figure below.

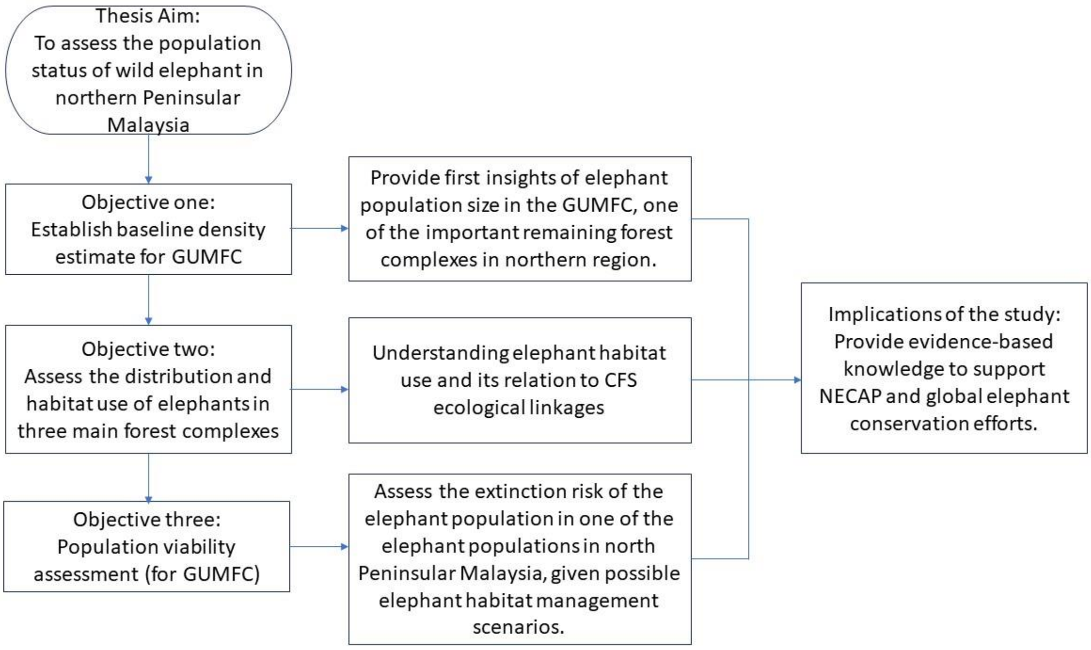


Figure 1.1 Diagram of the main components of the thesis.

Chapter One is the general introduction to the thesis, which provides the problem statement, aim, and objectives, and outlines the structure of the thesis.

Chapter Two reviews the literature related to elephant conservation, with a focus on three research topics: (i) elephant density estimation, (ii) elephant distribution and habitat preferences, and (iii) population viability analysis. It also provides an introduction to the study site.

Chapter Three covers the first baseline estimate of elephant density for the Greater Ulu Muda Forest Complex based on the study of elephant genetic material. The findings confirm that GUMFC is a vital area for elephants and should be further protected.

Chapter Four examines the effect of environmental variables (both natural and anthropogenic) on elephant habitat preferences for three forest areas in Peninsular Malaysia. The implications of these habitat preferences are presented in the context of planned regional land-use changes, including the loss of intact elephant habitat.

Chapter Five looks into the viability of the GUMFC elephant population. It incorporates Chapter Three's findings regarding the population density estimate and land-use changes in this particular landscape. The population viability analysis compares the local density estimate with the overall density estimate for Asian elephants. The PVA considers varying habitat-management scenarios (e.g., alterations in carrying capacity) and varying species-management conditions (e.g., varying threats to elephants). The PVA results indicate the need to enhance protection of the GUMFC. Findings from this Chapter can be used to complement the assessments of elephant populations in the rest of the northern forest complex and within Peninsular Malaysia as a whole.

Chapter Six presents a general discussion connecting the findings of all three research topics. It highlights the contribution of this study to Asian elephant conservation at national and international levels. It also presents my hope that my findings contribute to Malaysia's ability to thrive in a balance between nature protection and development by informing Malaysia’s biodiversity-related policies and plans.

CHAPTER 2: ELEPHANT CONSERVATION: A REVIEW OF CURRENT KNOWLEDGE AND BEST PRACTICE

2.1 INTRODUCTION

2.1.1 Overview

This chapter reviews the literature on the knowledge and best practices related to elephant conservation. The chapter gives an overview of elephant conservation in Peninsular Malaysia and highlights the latest work on my three research topics: i) elephant density estimation, ii) elephant distribution and habitat preferences, and iii) population viability analysis. The review provides an overview of global best-practice methods in conservation biology, as well as an assessment of the extent to which these topics have been previously examined in Malaysia.

2.1.2 Forests in Peninsular Malaysia

Peninsular Malaysia encompasses 13.21 million hectares (132,265 km^2) of land mass, or 40% of the total area of Malaysia. East Malaysia (the states of Sabah and Sarawak) constitutes another 60% of the land area. Peninsular Malaysia's altitude ranges from sea level to the highest peak of 2,187m a.s.l. The forested area in Peninsular Malaysia constitutes about 5.73 mil ha (43.38% of the total land area of Peninsular Malaysia), with three major forest types, namely inland forest, mangrove forest, and peat swamp forest (Department of Forestry Malaysia, 2019).

Forest resources in Peninsular Malaysia are managed in three main categories known as Permanent Forest Reserve (PFR), State land forest (SLF), and Totally Protected Areas (TPA). Approximately 4.81 million hectares of the total land area (83.92% of forested land) of Peninsular Malaysia is gazetted as PRF, and they are further divided into Protection Forest (37.8%; 1.82 million hectares) and Production Forest (62.2%; 2.99 mil. hectares) (The Department of Forestry Malaysia, 2017).

Under the Malaysian Federal Constitution (Article 74(12)), forests are under the responsibility of the individual States, thus PFRs are managed by the State governments (National Forestry Act, 1984; TRAFFIC International, 2004). Whilst TPAs such as National Parks and wildlife sanctuaries are managed by federal government agencies, mainly the Department of Wildlife and National Parks Peninsular Malaysia (e.g., Taman Negara, Krau Wildlife Reserve, etc.). Forested land faces demand for Malaysia's economic development, including agriculture expansion, commercial logging, and mining (Jomo et al., 2004). This presents a challenge to maintain forest complexes intact as the country continues to develop and generate revenues from natural resources (Jomo et al., 2004). According to Nagulendran et al. (2016), Malaysia faces trade-offs in its efforts to balance national economic development with biodiversity conservation.

2.1.3 Threats to Elephants in Peninsular Malaysia

The main threats to elephants in Peninsular Malaysia are (i) habitat loss and fragmentation, and (ii) displacement due to human-elephant conflict (HEC). Fragmentation and loss of forest cover across Peninsular Malaysia continue to occur (Ministry of Natural Resources and Environment, 2016). In the last six decades, Peninsular Malaysia has lost 46,000 km^2 of forested areas, a significant reduction from 95,000 km^2 in 1954 to 49,000 km^2 in 2015 (Forestry Department of Peninsular Malaysia, 2017). Remaining forested areas are vulnerable to the risks of being fragmented or converted into other land use or mining for natural resources, resulting in the disturbed and degraded ecological connectivity, which affects animal and plant populations (Ministry of Natural Resources and Environment, 2016).

Shrinking natural habitat and habitat fragmentation lead to increased HEC, which leads to the second threat to elephants: displacement due to HEC. In Peninsular Malaysia, HEC caused an estimated loss of MYR 39.9 million (approximately USD 8.4 million), 10 deaths, and 6 injuries during the 5-year period of 2018 to 2022 (Mahaizura, 2023). The government initially responded to HEC by culling elephants. In 1974, a special Elephant Unit (*Unit Gajah*) was created by the wildlife department to shoot-and-chase away (*tembak-halau*) elephants into the forest, and if this attempt continues to fail, conflict elephant will be translocated to other forested forest as the last solution (Khan, 2012; Department of Wildlife and National Parks Peninsular Malaysia, 2013; Saaban et al., 2011; Khan, 2012; Department of Wildlife and National Parks Peninsular Malaysia, 2017b). Up to today, at least 800 wild elephants have been translocated from the conflict area to three designated release sites: Belum-Temengor Forest Complex (northern Peninsular), Taman Negara (central Peninsular) and Kenyir Forest Reserve in Terengganu (east-coast of Peninsular).

However, there have been found to be problems with translocation. A recent study of the movement of translocated elephants by Wadey (2020) shows that translocation of elephants is not a solid solution to HEC, as some translocated elephants found their way back home to their original habitat. Furthermore, translocations of elephants can also introduce problems to the local community living in and around the release site (Samad B. Jeranggong, per comms.). The local indigenous communities living in the Belum Temengor Forest Complex have highlighted the distinctive behaviour of native (residence) elephants and translocated elephants, in which they claimed the latter (translocated elephants) are tame and will not move away when they tried to scare elephants away (Samad B. Jeranggong, per. comms; Kamel B. Alang, per. comms.). Resident elephants were said to move away if people scare them away with noise and smoke.

2.1.4 Elephant Conservation in Peninsular Malaysia

Several national and international measures have been implemented to conserve Asian elephants. At the global scale, Asian elephants are listed in Appendix I of CITES (Convention on International Trade in Endangered Species), where commercial trade is prohibited by the signatory parties to CITES. Recognizing that immediate and widespread attention is needed to save Asian elephants, all 13 range countries' representatives have signed the Jakarta Declaration for Asian Elephant Conservation during the Asian elephant range States meeting in Indonesia in 2017, pledging to work together to save this magnificent herbivore.

In Peninsular Malaysia, Asian elephants are listed under Schedule II of the Wildlife Conservation Act 2010, which means the species is Totally Protected in Peninsular Malaysia, and no hunting, selling, and buying of the animal and its parts are allowed under the act. In addition, the government has adopted a species management plan for elephant conservation. The first National Elephant Conservation Action Plan (NECAP 1.0; for 2013-2022) was launched in 2013 to guide stakeholders in their conservation efforts to create an environment that allows humans and elephants to co-exist in Peninsular Malaysia. The vision of NECAP 1.0 is *"Wild elephants thrive across their current and recoverable range in Peninsular Malaysia while co-existing with people in ecologically functional landscapes"* (Department of Wildlife and National Parks Peninsular Malaysia, 2013). NECAP 1.0 was published in line with the National Policy on Biological Diversity and the National Policy on the Environment, in which both policies call for better management of Malaysian biodiversity. Seven long-term goals (100 years) and five short-term goals (10 years and 5 years) were stipulated in NECAP 1.0. In accordance with NECAP, reliable monitoring of all priority elephant populations and their habitats is required to ensure the country is informed of its population trends, as well as to measure the effectiveness of its conservation approaches (Department of Wildlife and National Parks Peninsular Malaysia, 2013). Subsequently, NECAP 2.0 was launched in 2023 to continue the effort to save the species for the period of 2023 to 2030, in which the vision for coexistence remains the same and the goal is to have "*healthy elephant populations sustainably managed and conserved with shared responsibility at all levels of community*". National

Elephant Conservation Action Plan (Volume 1: 2013-2022; Volume 2: 2023-2033) remains as the main guidebook for the conservation of elephants in Peninsular Malaysia.

NECAP 1.0 identified three Managed Elephant Ranges (MERs) (Figure 2.1). All three MERs are located within forest complexes and ecological linkages identified in Central Forest Spine (CFS), a master plan created by the Federal government of Malaysia for biodiversity conservation. The CFS aims to reduce negative impacts of forest fragmentation on biodiversity by re-establishing, maintaining and enhancing connectivity between the most significant remaining areas of forests in Peninsular Malaysia, from the north to south via a network of ecological linkages (forest corridors for wildlife) (Department of Town and Country Planning Peninsular Malaysia, 2010; Department of Town and Country Planning Peninsular Malaysia, 2022) (Figure 2.2). This master plan was first introduced in the National Physical Plan in 2005, in which forest fragmentation was recognised as *"a major threat to the conservation and maintenance of biodiversity*" (Department of Town and Country Planning Peninsular Malaysia, 2010).

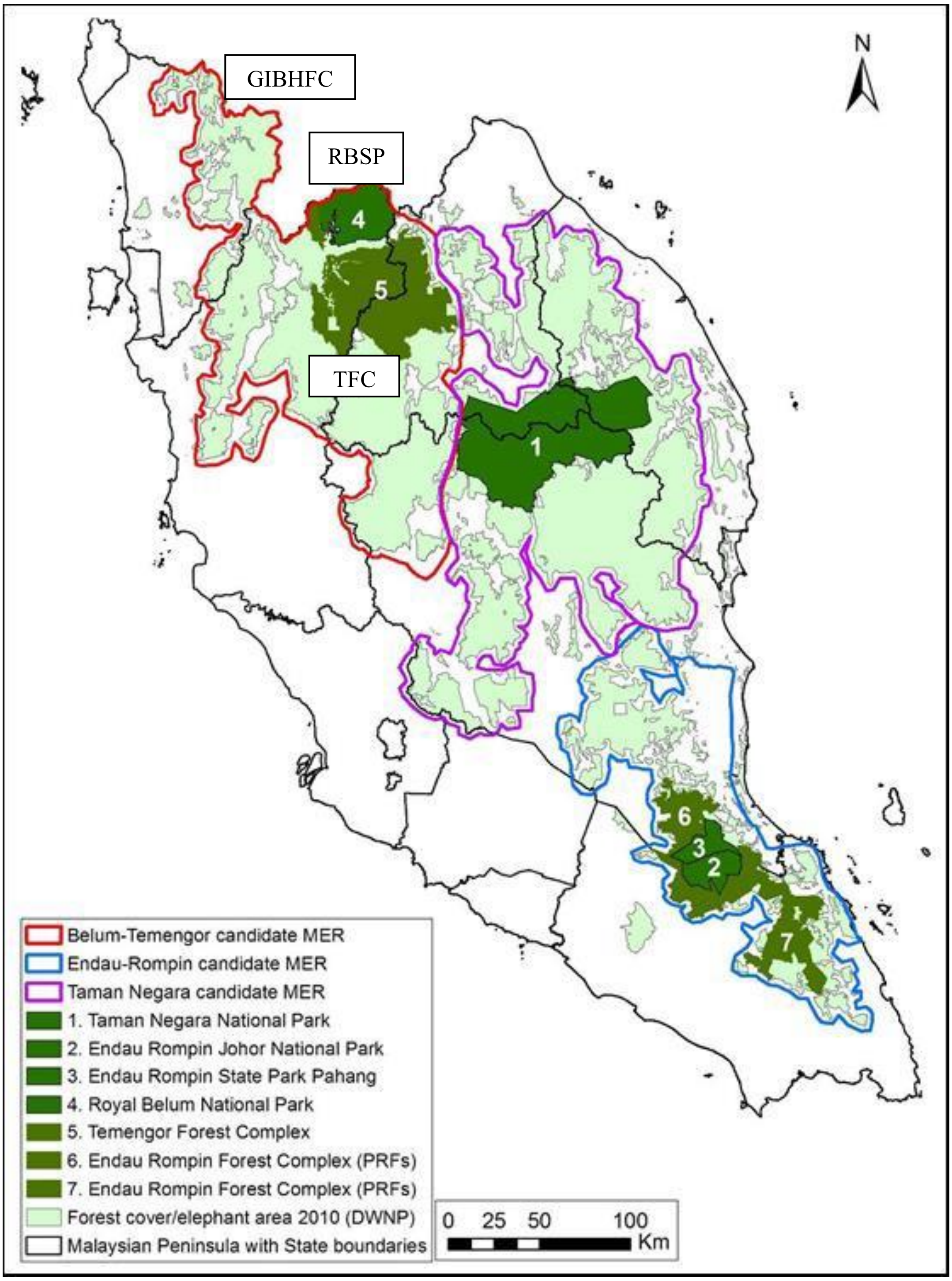


Figure 2.1 Forested areas identified as Managed Elephant Ranges (MERs). All the study areas are within the Belum-Temengor candidate for MER. Source NECAP 1.0, Department of Wildlife and National Parks, 2013.

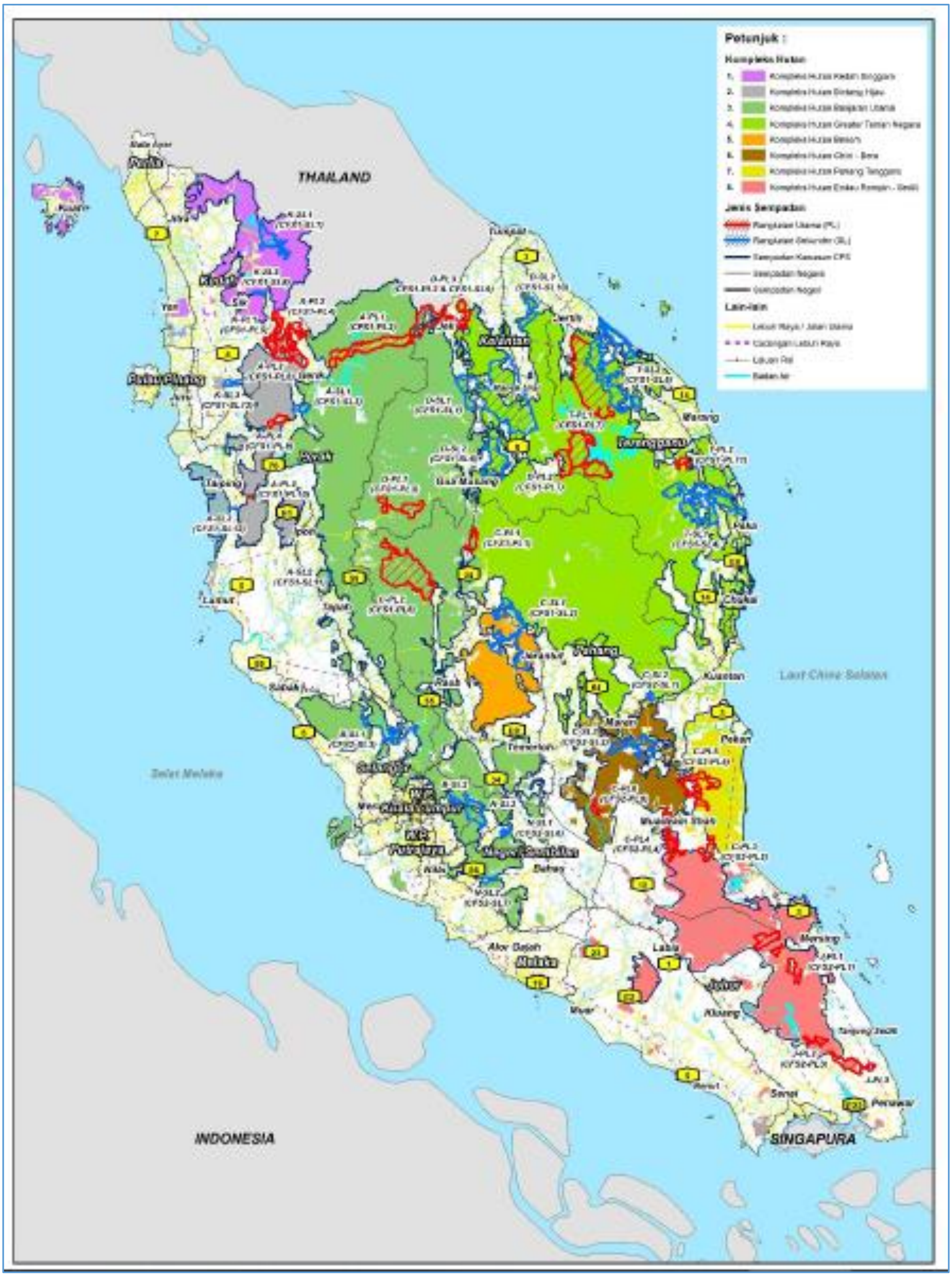


Figure 2.2 Central Forest Spine ecological linkage identified across Peninsular Malaysia. Source: Department of Town and Country Planning Peninsular Malaysia, 2022.

2.2 ELEPHANT POPULATION DENSITY ESTIMATION

2.2.1 Global Population Estimates

The estimated Asian elephant population ranges between 41,410 and 52,345 animals (Choudhury et al., 2008). Amongst all the range countries, India has the highest number of wild elephants with an estimated 30,000 individuals or nearly 60 % of the entire wild Asian elephant population. This is followed by Sri Lanka with over 5,000 individuals, Thailand and Malaysia with over 3,000 individuals respectively, Myanmar and Indonesia with between 1,000 – 2,000 individuals, and the rest of the range countries have below 1,000 individuals (Asian Elephant Range State, 2017). The largest known elephant population in Southeast Asia was recorded in Peninsular Malaysia in 2008, in which 631 elephants were estimated to be living in a forest complex with a size of 4,343 km^2 (Department of Wildlife and National Parks Peninsular Malaysia, 2013).

The accuracy of the global elephant population estimates has been questioned because few national estimates were based on scientific research methodologies (Blake and Hedges, 2004). According to Mr. Vivek Menon, the Chair of the IUCN Asian Elephant Specialist group (AsESG) during the range countries meeting in 2017, only 6% of these estimates are based on methods that stand up to scientific scrutiny (Asian Elephant Range States, 2017). To date, scientifically defensible population estimates of wild elephant populations are still absent in many range countries (Blake and Hedges, 2004). In 2017, representatives of the Asian Elephant Range States held a special meeting in Jakarta in which they identified the lack of reliable population estimates as the main challenge to saving the species (Asian Elephant Range States, 2017; Saaban et al., 2011).

2.2.2 Population Estimates in Malaysia

Malaysia is home to two Asian elephant subspecies, *E. m. indicus* that occurs in the mainland Peninsular and *E. m. borneensis* in the state of Sabah on the island of Borneo. With an overall estimation of over 3,000 elephants, Malaysia is one of the strongholds for the conservation of Asian elephants in the region (Department of Wildlife and National Parks Peninsular Malaysia, 2013; Asian Elephant Range States, 2017). The current census estimated that 1,223 to 1,677 wild elephants roam Peninsular Malaysia (Saaban et al., 2011), and 1,000 to 1,500 wild elephants occur in Sabah (Sabah Wildlife Department, 2020). However, these figures are not considered to be a robust estimate of the actual population size (Saaban et al., 2011; Goossens et al., 2016). Obtaining reliable population estimates and understanding their distribution in forested areas are therefore critical for long-term monitoring and effective management of Asian elephants.

2.2.3 Population Density Estimation Methodologies

However, the 2011 estimate was conservative due to the lack of robust survey methods for elephant population and distribution status in the past (Saaban et al., 2011). To date, the most robust estimates of the elephant population are those for Taman Negara (central Peninsular Malaysia) (Saaban et al., 2011), Endau Rompin (southern Peninsular Malaysia) (Saaban et al., 2020), and Sabah (east Malaysia) (Sabah Wildlife Department, 2020; Alfred et al., 2010). In these sites, dung-pile transect sampling was carried out between 2007-2009. In 2023, the Department of Wildlife and National Parks (PERHILITAN) Peninsular Malaysia produced the first genetically based population estimation study for elephants in the Taman Negara National Parks, and identified 217 elephants (Karuppannan et al., 2023).

Existing population estimates of elephants in Peninsular Malaysia are based on non-standardized data surveys collected during routine biodiversity inventory by the wildlife department (Mohd, 2012), with exceptions to two estimates in Taman Negara and Endau-Rompin, whereby dung count line transect surveys were conducted (Saaban et al., 2011; Asian Elephant Range States, 2017).

Reliable scientific data requires defensible and replicable research that is achievable through good experimental design and realistic to be carried out considering logistics, cost, time, and manpower that are available (Blake and Hedges, 2004). The study of elephant population estimation has evolved from direct sighting and count methods such as counting at water holes and block-count, and examination of elephant signs such as footprints via occupancy or dung count line transect survey to the use of non-invasive approaches to obtain genetic materials (e.g., faecal-based DNA capture-recapture) of animals to estimate their population size (Hedges and Lawson, 2006; Alfred et al., 2010; Hedges, 2012b; Jathanna et al., 2015b). In fact, non-invasive genetic methods have been increasingly applied in species population studies in recent years for various taxa such as elephants (Eggert et al., 2003; Ahlering et al., 2011; Hedges et al., 2013; Gray et al., 2014; Moßbrucker et al., 2015), bears (Dreher et al., 2007), mountain goats (Mowat, 2012), otters (Lampa and Henle, 2011; Lampa et al., 2015) and bobcats (Morin et al., 2018) due to its accuracy and cost effective estimates (Mckelvey and Schwartz, 2004). This method allows identification of individual animals in the population based on the animals' genetic materials. Nevertheless, common risks such as allelic dropout or false (mistaken) alleles in the genotyping process to identify identical individual animals should be taken into consideration, and necessary cautions should be applied to minimize the risks (Petit and Valiere, 2006; Gray et al., 2011; Lampa et al., 2013, Lampa et al., 2015; Gray et al., 2014; Kongrit, 2017). Various measures to overcome genotyping errors in non-invasive genetic capture-recapture method such as analytical tests and modelling, adequate cautions during genetic samples collection to avoid contaminations as well as stringent laboratory works have been known to reduce the problems in producing reliable population estimates, see Mckelvey and Schwartz (2004), Petit and Valiere (2006), Lampa et al. (2013) and, Kongrit (2017) for more details. Subsequently, for density estimation, this study uses a spatially explicit capture-recapture framework.

2.3 ELEPHANT DISTRIBUTION AND HABITAT PREFERENCES

2.3.1 Distribution

Asian elephants are distributed across 13 countries within three regions of Asia. They are found in South Asia (i.e., Nepal, India, Sri Lanka, Bangladesh and Bhutan), East Asia (i.e., China), and South-east Asia (i.e., Lao PDR, Cambodia, Vietnam, Myanmar, Thailand, Malaysia (Peninsular Malaysia and Sabah) and Indonesia (Kalimantan and Sumatra)) (Choudhury et al., 2008). Historically, Asian elephants were also found in West Asia along the Iranian coast, further east in South-east Asia (including Java), and deeper into China (as far as the Yangtze River) (Choudhury et al., 2008). Their geographical distribution range has reduced significantly over recent decades and is now confined to selected areas within the region (Choudhury et al., 2008).

In Malaysia, the Department of Wildlife and National Parks Peninsular Malaysia (2013), notes that the current geographical distribution of elephants inside and outside of priority conservation areas (i.e., Protected Areas, Permanent Forest Reserves, forests on State land) is not accurately known. Elephants are believed to be distributed across forested landscapes, and connected via the central forest spine ecological networks (Table 2.1). A study by Leimgruber et al. (2003), where the Asian elephant's geographic range was analysed, found that only 29,106 km2 of wild lands remain inside Malaysia's elephant geographical range of 57,237 km^2. Habitat loss and fragmentation are the main threats to the survival of Asian elephants (Asian Elephant Range States, 2017).

There has been a significant reduction in the range of elephants in Peninsular Malaysia (Payne, 1992; Clements et al., 2010; Thaufeek et al., 2014; Tan, 2017). Elephants are currently found in seven States (Saaban et al., 2011), whereas their historical distribution was once throughout Peninsular Malaysia (comprises 11 States and two federal territories), except on the island of Penang in the 19th century (Olivier, 1978a) (Figure 2.3). A study by Tan (2017) about the past and present distribution of elephants in human-dominated landscapes throughout Peninsular Malaysia revealed that 65% of elephants' range within human-dominated landscapes was lost in just 40 years.

2.3.2 Ranging Requirements

For megafauna such as tigers and elephants that have larger home ranges, a bigger roaming area is required to sustain the population. Studies of elephants in Malaysia show various home range sizes with an average of 100 km^2 to 200 km^2 (Saaban and Othman, 2006), and up to 600 km^2 (Wadey, 2020) for an elephant. In India, the reported elephant home range was between 200 km^2 and 800 km^2 (Baskaran, 1998), but this takes into consideration seasonal changes that affect the availability of natural resources required by elephants. A recent study by Kaliyappan (2023) about elephant movements and space use within agricultural and forested landscapes reported mean home ranges (95% utilization) of 245 km^2. This implies that elephants need large habitats and can move further from their natural landscape in order to support their ecologically functioning population.

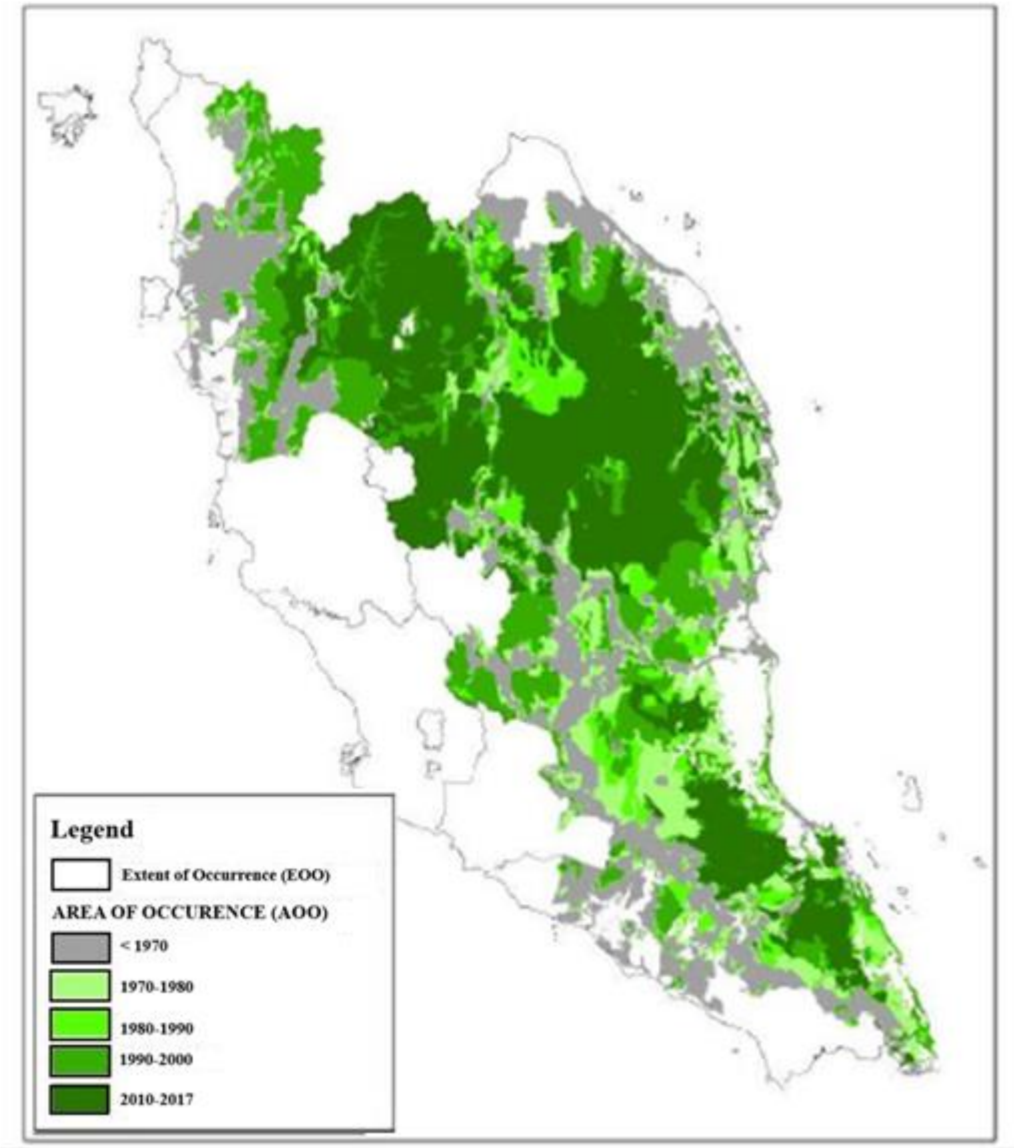


Figure 2.3 Changes in elephant distribution across Peninsular Malaysia from 1970 to 2017. Source: Red List of Mammals of Peninsular Malaysia, Department of Wildlife and National Parks Peninsular Malaysia, 2017a.

2.3.3 Habitat requirements

Habitat requirements are defined as "the resources and conditions present in an area that produce occupancy, including survival and reproduction by a given organism" (Krausman, 2002). Habitat analysis is considered the most important step in planning and management of protected areas. This is especially the case when human-elephant conflict is involved (Tikhile et al., 2013).

For elephants, habitat selection is influenced by several factors. These include ecological factors (i.e., diet, foraging behaviour, climate, biophysical parameters), biological factors (i.e., sex, age, social structure, etc.), and anthropological factors (i.e., human-related disturbance such as settlements, infrastructure developments, logging activities, poaching, etc.) (Baskaran et al., 2010; Campos-Arceiz and Blake, 2011; Hedges, 2012a; Yamamoto-Ebina et al., 2016; Terborgh et al., 2018; Wadey et al., 2018). The combination of these factors determines elephant habitat selection, hence the suitability of the habitat for their survival.

Asian elephants are distributed over a variety of habitats within and outside of Protected Areas, wildlife reserves, ecological corridors, as well as human-dominated landscapes that are close to forest, scrubland and grasslands (Williams et al., 2020). In Malaysia, several studies have looked at elephant habitat preferences. These studies have looked at diet and foraging behaviour (Chew et al., 2014; Yamamoto-Ebina et al., 2016; Othman, 2017; Suba et al., 2018; Terborgh et al., 2018), use of mineral licks (Bashir Ali, 2014; Ning, 2017) and elephant movement (Aini et al., 2015; Wadey et al., 2018; Wadey, 2020). These studies conclude that all elephants can live in several types of forested landscapes. Such forests provide shelter, survival resources, as well as roaming and breeding areas for elephants. Elephants inhabit intact rainforest complexes, fragmented forest patches (including logged-over forests) and in plantations that are fringing larger forested landscapes. These landscapes include the lowlands (< 300m a.s.l.) to mountainous forest (>1500m a.s.l.), with elephants having a preference for lowland secondary forest (Alfred et al. 2010). This is consistent with findings for Asian elephants in India, where elephants commonly use areas with altitudes between 300 -1,200m a.s.l., and hardly any areas above 1,300m (Varma et al. 2001). Similar findings were reported by Wall et al. (2006), who showed that African Savannah elephants avoid areas of high elevation.

In Peninsular Malaysia, a study by Aini et al. (2015) on habitat utilisation by a single translocated male elephant suggested that elephants tend to prefer secondary forest and are not so constrained by topographical parameters (i.e., slope and elevation). In contrast, camera trap data presented by Sagtiasiwan (2019) suggest that elephants have little occupancy in high-elevation areas. Similarly, Wadey (2020) found that peninsular elephants tend to avoid steep slopes and high elevations.

There is now a need to build on these existing studies to understand the influences of landscape properties (e.g., ecological parameters) on elephant distribution (Gaucherel et al., 2010). There is a need to examine both natural (e.g., vegetation types, food and water sources, elevation, terrain ruggedness, forest cover, etc.) and anthropogenic factors (e.g., human-related factors such as settlements, the presence of agricultural lands, roads, etc.).

Such a study is important given that the Peninsula's Main Range Forest Complex is made of ridges with the highest peak recorded at nearly 2200 m a.s.l., which may hinder elephants from using such high elevation areas in their movement or daily activity. Such a study would provide evidence-based information about the suitability of current designated MERs and ecological linkages for elephant conservation.

2.3.4 Habitat use based on occupancy framework

Occupancy can be defined as the proportion of an area occupied by a species or fraction of landscape units where the species is present (MacKenzie et al., 2017). The occupancy framework method has been widely used to study species distribution, abundance index and habitat use. The occupancy framework can be carried out in conventional temporal replication (requires revisit to the study area) or spatial replication framework (single-occasion sampling at the same area using spatial replicates) to determine detection probability (Lakshminarayanan et al., 2015). Spatially replicated surveys in the occupancy framework have been used for studying elephant habitat use in India (Lakshminarayanan et al., 2015; Jathanna et al., 2015b.) Data on fresh dung piles, indicative of elephant presence at any given point in time and space, show that elephants occur at a particular area (Alfred et al., 2010). Occupancy modelling allows detection/ non-detection data of animal signs, while attending to the issue of imperfect detection during data collection using the probability of detection (MacKenzie et al., 2017). The occupancy method works well for many wildlife species that generally occur at low local densities and large spatial scales and could yield robust estimates of the probability of occupancy (psi) and how it can be predicted by environmental variables associated with the occurrence of the animal signs to represent habitat-use (Srivathsa et al., 2014). For this project, I explore the use of a spatially replicated survey in the occupancy framework to investigate elephants' response to ecological and anthropogenic factors in three study areas thought to be suitable habitat for elephants and identified as important managed elephant ranges (MERs).

2.4 POPULATION VIABILITY ANALYSIS

2.4.1 Overview

Population viability analysis (PVA) is a popular approach to predict the extinction risk of a species (Arckarya et al., 2000). PVA has also been used to evaluate different conservation strategies (Hamilton and Moller, 1995; Haines et al., 2006; Moßbrucker et al., 2016; Andersen et al., 2017). PVA is a primary tool used by the International Union for Conservation of Nature (IUCN) Red List to classify the conservation status of species. Conventionally, PVA allows researchers to predict the species' survival rate in future generations. PVA uses demographic parameters such as population size, sex ratio, mortality rates and reproductive rates, hence indirectly assessing the suitability of current conservation efforts in ensuring the viability of the species (Keedwell, 2004). However, species-specific population viability analysis can also be carried out by using various other data such as population estimates, occurrence (distribution), and habitat use data to inform conservation efforts, especially when it is impossible to make a thorough assessment of demographic parameters over a large area (Haines et al., 2006; Linkie et al., 2006).

2.4.2 PVA for elephants

In the context of elephant conservation, PVA has been used to study the viability of several wild populations (Armbruster and Lande, 1993; Sukumar and Santiapillai, 1993; Varma et al., 2008; Moßbrücker et al., 2016). PVA has also been used to assess populations of captive elephants (Myroniuk, 2004; Leimgruber et al., 2008; Suter et al., 2014). The global elephant population estimates are well above the rough estimates of minimum viable populations that were proposed in the early years of conservation biology (Franklin,1980; Soulé, 1980). However, since 1986, PVA has suggested that the Asian elephant meets the IUCN category of 'Endangered' due to at least a 50% reduction in its population size over the last three generations (an elephant generation being 20-25 years) (Choudhury et al., 2008). This highlights the need for national and sub-national PVAs to identify priorities for elephant conservation (Blake and Hedges, 2004; Linkie et al., 2006; Wall et al., 2006; Akcakaya and Brook, 2009; Hedges, 2012; Department of Wildlife and National Parks Peninsular Malaysia, 2013).

Other challenges identified by range countries are human-elephant conflicts (which often led to intentional/retaliation killing), habitat loss, fragmentation and degradation (that could lead to genetic and demographic problems due to small and isolated populations), trans-boundary issues and captive breeding programmes (Asian Elephant Range States, 2017). The presence of scientific knowledge that is elephant-specific and targeted at its original habitat is crucial for an informed species-conservation-based landscape management. This is particularly important for megafauna such as the Asian elephant which has had at least 75% of habitat shrinkages in the past decades (Williams et al., 2020).

2.4.3 PVA for elephants in Peninsular Malaysia

In the 1970s, the number of elephants in Peninsular Malaysia was estimated at 3,000 – 6,000 animals (Olivier, 1978b). By 2011, it was estimated that there had been a reduction of nearly 50% of the elephant population numbers over 40 years (Saaban et al., 2011). The elephant is listed as Vulnerable in the National Red List of Mammals for Peninsular Malaysia 2.0 (Department of Wildlife and National Parks Peninsular Malaysia, 2017a). Elliza et al. (2015) in their study of DNA materials from 21 elephants originating from five regional habitats in Malaysia (i.e., Terengganu, Kelantan, Perak, Johor and Pahang) discovered a low genetic diversity. Karuppannan et al. (2019a) found a similarly low value of genetic diversity for samples collected in the National Park (Taman Negara).

One robust PVA for elephants is a study that looked at elephants in the southern state of Johor (Saaban et al., 2020). The researchers used over 200 combinations of scenarios (low to high elephant removal/ killed, mortality rate, catastrophes (flood and disease), natality rate, etc.) and projected it over a 100-year period (Saaban et al., 2020). The study considered scenarios involving the displacement of elephants from their habitat due to human activities, including poaching and translocation.

Table 2.1 Summary of Central Forest Spine ecological linkages that are connected to study areas in the state of Perak (Belum-Temengor Forest Complex, and Gunung Inas -Bintang Hijau Forest Complex) and Kedah (Greater Ulu Muda Forest Complex). Information obtained from the Department of Town and Country Planning, Peninsular Malaysia (2022).

State	2022	Size (ha)	Name of Ecological Corridor
Kedah	K-PL1	8,563	HS Ulu Muda-HS Gunung Inas
	K-SL1	10,064	HS Ulu Muda-HS Bukit Saiong-HS Pedu-HS Chebar
	K-SL2	1,125	HS Ulu Muda- HS Rimba Telui
	K-SL3	1,632	HS Gunung Bongsu-HS Gunung Inas
Perak	A-PL1	24,835	HS Temengor-HS Amanjaya-HS Belum
	A-PL3	15,806	HS Belukar Semang-HS Kenderong-HS Bintang Hijau
	A-PL4	3,649	HS Bintang Hijau (Larut and Matang)-HS Bintang Hijau (Hulu Perak)
	A-SL1	3,642	HS Bintang Hijau-HS Papulut-HS Piah

CHAPTER 3: POPULATION DENSITY ESTIMATION FOR WILD ASIAN ELEPHANTS IN THE GREATER ULU MUDA FOREST COMPLEX, KEDAH, PENINSULAR MALAYSIA.

ABSTRACT

Population density estimates inform management and conservation efforts of elephants, yet it is challenging to observe elephants in the dense tropical rainforest. A comprehensive assessment of elephant density based on faecal-DNA was carried out for the Greater Ulu Muda Forest Complex (GUMFC), a highly significant forest complex in the northern area of Peninsular Malaysia. A total of 128 (26.3%) of 487 DNA samples were successfully amplified. Of these, 118 samples were subsequently used for elephant individual identification, with a total of 92 unique genotypes, and 26 recaptured individuals were identified. Based on the Spatially Explicit Capture-Recapture (SERC) method, the mean population density estimate for GUMFC is 1.17×10^{-3}/ha (min 1.14×10^{-3}/ha, max 2.58×10^{-3}/ha). Based on this density estimate, the mean population size of elephants in GUMFC is estimated at 279 individuals (0.17 animal/km^2), with a population size ranging from 185 elephants to 420 elephants in an area of 1,629.31 km^2. The study also indicates that the results are influenced by the temporal variability (*t*) in capture probability. This study provides empirical evidence demonstrating the significance of GUMFC as a vital forest complex that supports the elephant population in the northern region of Peninsular Malaysia. Therefore, it is imperative to prioritise wildlife conservation efforts for this area.

Keywords: Asian elephant, elephant density, faecal DNA, spatially explicit capture-recapture, Greater Ulu Muda Forest Complex

3.1 INTRODUCTION

Malaysia is one of the 13 Asian countries that is home to endangered Asian elephants. With its overall population estimate of 1,226-1,667 elephants occurring across Peninsular Malaysia (Saaban et al., 2011) and 1,000-1,500 elephants in Borneo (Sabah Wildlife Department, 2020), Malaysia has a good potential to preserve this species. The conservation of Asian elephants in Malaysia holds both national and international significance due to their vital ecological roles, as well as their cultural and religious value. Previously widespread throughout the whole mainland (Olivier, 1978a, Khan, 2012), elephants in Peninsular Malaysia are now limited to seven States: Kedah and Perak in the north, Pahang, Kelantan, and Terengganu in the centre, and Negeri Sembilan and Johor in the south (Saaban et al., 2011).

Asian elephant populations are under threat from habitat loss, poaching, human-elephant conflicts, and other threats such as road kills due to linear transportation infrastructure. The National Elephant Conservation Action Plan (NECAP) was developed specifically to protect this endangered species in 2013. NECAP (version 1.0 (2013-2022) & 2.0 (2023-2033)) contains several actions and strategies addressing the threats to Asian elephants, as well as promoting peaceful coexistence with elephants. However, insufficient ecological knowledge regarding the population status of elephants has emerged as a hindrance to effectively supporting conservation efforts aimed at conserving the remaining elephant populations (Department of Wildlife and National Parks Peninsular Malaysia, 2013). Robust population estimates for elephants across Peninsular Malaysia, particularly for the northern region, are still lacking. For example, little is known about elephant density and population size in the Greater Ulu Muda Forest Complex (GUMFC) in the state of Kedah, a significant forested area located in the northern region that shares borders with Malaysia and Thailand. The local knowledge alone regarding the existence of elephants in and near GUMFC did not provide any further value to inform the conservation efforts of these animals in this specific forest complex.

Accurate estimates of elephant population density in the northern region would enhance the comprehensive understanding of elephant populations throughout Peninsular Malaysia. Previous population estimates for the central region (specifically Taman Negara National Parks (TNNP)) and the southern region (specifically Endau Rompin Landscape) were obtained more than ten years ago (Saaban et al., 2011) using a systematic dung count survey with transects. In a recent study, Karuppannan et al. (2023) produced the first genetically based population study for elephants in the TNNP, and reported a total of 217 elephants from 223 faecal samples, with three recaptured individuals. This marks the use of genetic studies in assessing the elephants in Peninsular Malaysia.

In addition to enhancing our comprehension of the elephant population as a whole, studying the population in GUMFC is crucial due to their probable isolation from larger forest complexes and, hence, other elephant populations. Although there are secondary ecological connections that have been identified to reconnect GUMFC with other forested regions (Department of Town and Country Planning Peninsular Malaysia, 2022), it is important to examine the elephant population in this specific area.

Non-invasive sampling methods using genetic materials have been used in various wildlife studies, including carnivores (Morin et al., 2018) and herbivores like elephants (Fernando et al., 2000; Vidya and Sukumar, 2005; Hedges et al., 2012; Moßbrucker et al., 2015). However, obtaining samples of tissue, body fluids, or hair from free-ranging wild elephants in tropical rainforests is logistically challenging, thus, extracting DNA materials from dung has become the practice (Fernando et al., 1999; Hedges et al., 2012; Moßbrucker et al., 2015; De et al., 2022). The genotyping method is known for its ability to provide accurate population estimates, as long as each step of the procedure (e.g., sample collection and preservation techniques, laboratory technicality, etc.) is carefully executed to minimize genotyping errors (Fernando et al., 2003a; Lampa et al., 2013; Galpern et al., 2012; Morin et al., 2018). In recent years, spatially explicit capture-recapture (SECR) has been used to estimate the population density of wildlife as it can combine genetic data with spatial information and provide a better understanding of how wildlife is spread across the landscape (Efford, 2022). Therefore, by employing a combination of the non-invasive faecal-DNA genotyping technique to identify individual elephants and utilizing spatially explicit capture-recapture methods, a reliable estimate of the elephant population could be obtained.

This study aims to provide the first scientific estimates of wild elephant density for the northern region of Peninsular Malaysia. The main objectives of this study are i) to establish the baseline population density estimate for wild elephants in the Greater Ulu Muda Forest Complex, and ii) to explore the use of faecal-based DNA and spatially explicit capture-recapture in the population study. The findings are expected to contribute valuable scientific insights into the size of the elephant population in the northern region and inform the conservation efforts for elephants in this crucial forest complex while addressing the knowledge gap identified in the National Elephant Conservation Action Plan (NECAP). The findings can guide long-term monitoring of the elephant population in this forested landscape and serve as a reference for elephant conservation in Malaysia. The methods applied in this study could also be replicated to study elephant populations in other habitat areas or expanded into a broader genetic study. Importantly, evidence from this study will be used to support informed decision-making involving Managed Elephant Ranges (MERs) in the north of Peninsular Malaysia. The protection of elephant habitat will indirectly also protect the needs of other species that share the same landscape.

3.2 MATERIALS AND METHODS

3.2.1 Study area

The elephant density research was conducted in the Greater Ulu Muda Forest Complex (GUMFC), one of the large contiguous forest landscapes in northern Peninsular Malaysia (Figure 3.1). It borders Thailand in the provinces of Yala and Songkla. Situated in the State of Kedah, GUMFC (6 °06'38.22" N 100°58'23.61" E) comprises seven forest reserves with a total area of 1,629.31 km^2 made of lowland dipterocarp forest, hill dipterocarp forests, upper dipterocarp forest as well as riparian and limestone vegetation (Suksuwan, 2008) (Table 3.1). Three man-made lakes (dams), namely Pedu Lake (52 km^2), Ahning Lake (12 km^2) and Muda Lake (15.5 km^2) were built within this forest complex in 1960s to provide irrigation water for agriculture industries (i.e., mainly for paddy plantations) and domestic use for three States in the northern region of Peninsular (i.e., State of Kedah, Penang and Perlis) (Lembaga Sumber Air Negeri Kedah, 2021). The Ulu Muda Forest Complex (formed a major part of GUMFC) was identified as an Environmentally-Sensitive Area Rank 1 (Suksuwan, 2008), but the larger part of this forest complex is not legally protected for conservation and received little attention from researchers at the time this study was proposed (2018). This forest complex is believed to be one of the remaining important habitats that support elephants in the northern region, but their population status is not known and requires attention. In terms of forest management, forests in GUMFC are categorized into various categories, including forests for timber production, forests for water catchments, and a gazettement of Ulu Muda State Parks in 2018. Despite its importance for ecosystem services and the conservation of fauna species as identified in the CFS master plan 1.0 (CFSI-Primary Linkages 5), this forest complex has been ecologically disconnected from the rest of the forested area in Peninsular Malaysia. This forest complex experiences two distinct seasons, the wet season (May and October) and the dry season (between December to March) (Suksuwan, 2008).

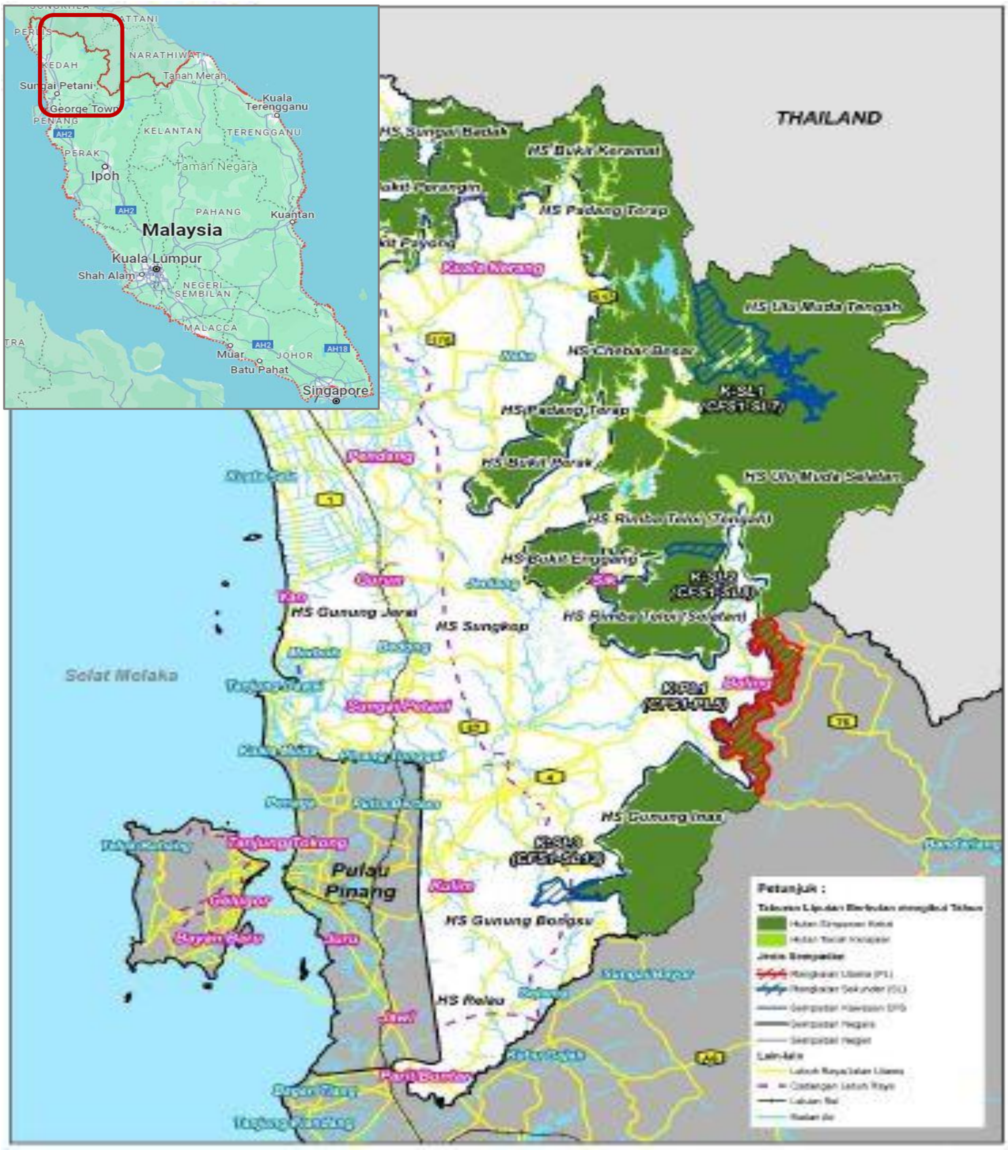


Figure 3.1 The Greater Ulu Muda Forest Complex is located in the northern east of Peninsular Malaysia. Map modified from Department of Town and Country Planning Peninsular Malaysia, 2022.

Table 3.1 List of forest reserves included in the Greater Ulu Muda Forest Complex.

Name of Forest Reserve	Size of Area (km^2)
Ulu Muda Forest Reserve	1050.60
Pedu Forest Reserve	152.99
Padang Terap Forest Reserve	127.85
Bukit Keramat Forest Reserve	102.26
Chebar Besar Forest Reserve	88.27
Bukit Saiong Forest Reserve	81.91
Chebar Kecil Forest Reserve	11.84
Proposed Ulu Muda Forest Reserve (addition)	13.59
Total area	**1629.31**

3.2.2 Field sampling designs and data collection

This study involved the non-invasive collection of DNA materials (faecal DNA) from elephant dung. The study area is overlaid with grid cells with each sampling unit of 25 km^2 (5 km x5 km) to cover a large area (GUMFC, 1629.31 km^2). The selection of grid size was based on the ecological relevance, as elephants have large home ranges (~250 km^2), and to ensure the coverage of a large enough area to be ecologically meaningful in this study. The grid cells are thereafter referred to as study sites. The faecal-DNA sampling method was conducted from 19th February to 31st July 2019 (over 5.5 months), and 11 sampling trips were completed. The research team was split into two groups, and each group consisted of four or five individuals who would start the sample collection at different study sites. The length of each transect is 1 km; however, three readings were recorded at zero distance, 500 m, and at 1 km (completion of a transect). Given the topography of the area, it is essential to note that it is challenging to have a straight-line transect while walking through the forest. Any elephant dung encountered along the transect was inspected, and DNA samples were collected from suitable dung piles (following Hedges and Lawson, 2006). A new transect starts immediately after the 1 km transect was completed, and the same process continues until the evening of the day (if the weather permits). Sampling areas were assessed by foot, boat, and 4WD vehicle, depending on the accessibility to each location.

To improve the chances of finding the dung piles, previous studies recommended surveying along elephant-used trails within the forest (Eggert et al., 2003; Hedges et al., 2005; Hedges et al., 2012a). This approach was adopted during sampling to optimize dung collection, as detecting elephant dung in tropical rainforests can be difficult without targeting frequently used areas (e.g., identifiable elephant trails and known hotspots such as lakesides, floodplain riparian areas, and mineral licks). These areas were selected based on prior knowledge and the presence of recent elephant signs (information provided by the local communities). Some of the sampling sites were visited more than once due to the concentrations of elephants using the area, during a particular season (i.e., post-monsoon riparian areas, between March and May 2019). Additionally, random exploratory walks were conducted at the broader sampling sites to enhance the spatial representativeness of the sampling effort and minimize bias resulting from preferential trail-following. The sample collection was completed within six months to avoid violation of the closed population assumption that applies to Spatially Explicit Capture-recapture (SECR) analysis for the density estimate.

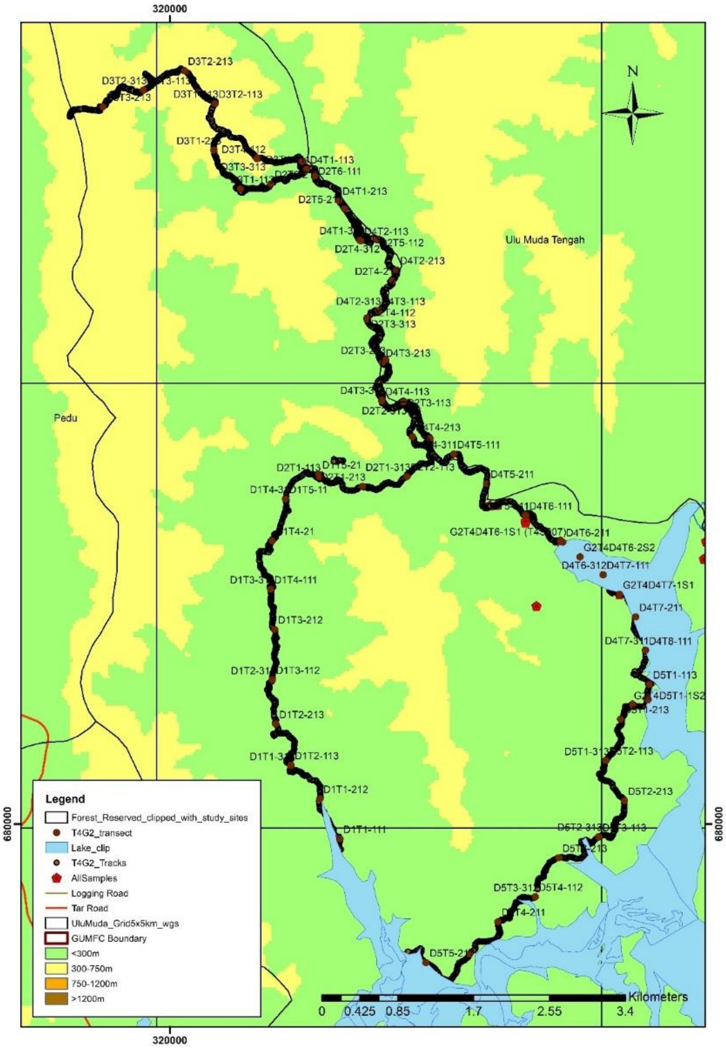


Figure 3.2. The illustration of transects that were marked during faecal sample collections across the study sites (5km x 5km) during one of the sampling trips.

The freshness of elephant dung (the period between defecation and collection of the sample) determines the quality of DNA materials, thus the sampling of faecal DNA samples involved the collection of "fresh" (<48 hours) to "reasonably fresh" (< 14 days) elephant dungs following the freshness definition by Hedges and Lawson (2006). The sample freshness is further divided into five categories (1= ≤ 24 hours, 2= > 24 hours to 3 days, 3= 4 to 5 days, 4= 6 to 7 days, and 5= 7 to 14 days), based on detailed observation of the dung and its environment, such as fresh signs of elephants in the surrounding areas. The dung observation was made by field assistants (of the indigenous tribe whose village is located in a forested environment) who were used to seeing elephant trails, tracks, and dung.

The DNA was collected from one bolus per dung pile to avoid sampling error (Hedges and Lawson, 2006). However, in unavoidable cases, dung samples were collected from two dung boluses of the same confirmed dung pile when a single dung bolus might not be in good condition for complete sample collection. Two techniques were used to collect and preserve the sample: I) Whatman FTA card (dry sample), and II) molecular graded ethanol absolute 99.8% (wet sample). The use of the FTA card requires straightforward smearing the card on the surface of the dung and letting it dry before storage. However, we acknowledged its limitations, particularly with dry or degraded samples. A packet of silica beads was added to the sealed plastic bag containing the sample to absorb the humidity. The FTA card was chosen as the collection technique due to its practicality and ease of use for the ground team. However, given the varying skill levels among sample collectors and to minimize the risk of sample degradation due to handling errors, we decided to use both the FTA card and absolute ethanol preservation methods.

For the second method, approximately 10-15 g of elephant dung from the outermost layer of intact dung boli (containing residues of endothelial cells from the elephant) was scraped using a tool and immersed in ethanol. In the condition that elephant dung was too dry (e.g., under hot sun) or too wet (e.g., after rain, half-soaked in the river) for use with the FTA card, only wet samples were collected. The selection of sampling techniques considered both practicality and ease of use in the field, especially for teams with varying skill levels; therefore, to ensure reliability, samples were also collected using the conventional ethanol preservation method as a backup. Samples from each different dung pile are labelled with a unique identification code. GPS coordinates (spatial information) of each sample were recorded. Dung piles that have been sampled were torn up to avoid accidental re-sampling of the same dung piles. Both dry and wet samples were stored at room temperature and transported to the University's laboratory for proper storage. Signs of elephant presence (i.e., footprint, rub marks on trees, elephant trails, dung, and feeding signs) in each sampling site were recorded as additional data.

3.2.3 Data analysis

The analysis of elephant density based on faecal DNA involved two phases of analysis. The first part of the analysis involves the DNA genotyping processes to produce identifiable samples to allow the capture and recapture of elephant individuals. (section 3.2.3.1 & 3.2.3.2). The second part of the analysis involves the application of the spatially explicit capture-recapture method to estimate the density of elephants in the study areas (section 3.2.3.3).

3.2.3.1 Genotyping faecal DNA for individual identification

The genotyping laboratory procedures were executed by Mr. Tan Wei Harn (MSc.), a Research Associate with experience in genetics. Prior to the laboratory work, Mr. Tan received hands-on training in genotyping procedures, including DNA extraction, purification, quantification, PCR amplification, and fragment analysis scoring under the guidance of Dr. Kayal Vizi Karuppannan, a collaborator from the Department of Wildlife and National Parks

(PERHILITAN) Peninsular Malaysia, Wildlife Forensic Unit. Samples were processed at the laboratory of the University of Nottingham (Malaysia campus) and the National Wildlife Forensic Laboratory (NWFL) in Kuala Lumpur as required by the permit issued by the Department of Wildlife and National Parks (PERHILITAN) Peninsular Malaysia. The DNA was extracted primarily from the dry sample (FTA cards), and wet samples were used when the dry samples were unavailable. The samples went through standard procedures of DNA extraction and purification, and quantification processes. The DNA extraction procedures were performed using the DNA extraction kit- QIAamp DNA Stool Mini Kit (QIAGEN, Germany), and followed the manufacturer's protocol. The NanoDrop 2000 Spectrophotometer (Thermo Fisher Scientific, Singapore) is used to quantify the extracted nucleic acid. Each group of extraction was accompanied by control blanks as a standard procedure (Eggert, 2003). Some of the DNA samples were extracted twice if the first extraction yielded no results. Extracted DNA samples were then tested against a universal primer to confirm the presence of DNA materials.

In the next step, polymerase chain reaction (PCR) was performed to amplify the extracted elephant DNA to ensure sufficient quantities for analysis. Two PCR machines used were 1) the Bio-Rad T100 Thermal Cycler, and 2) the Eppendorf Master Cycler (nexus gradient). In the initial PCR procedure, 23 microsatellite (nuclear marker) primers that were based on previous studies of Asian and African elephants were identified and tested against our samples (Appendix I). Ultimately, only 11 of these primers were selected for the final fragment analysis. Microsatellite primers were selected based on their amplification success and the stability of the primers in response to our DNA samples. Standard PCR cycle protocols were followed. Initial denaturation step at 94°C for 10 minutes. This is followed by a 40-cycle process of denaturation at 94°C for 30 seconds, followed by annealing using the respective gradient temperatures (56 °C, 57 °C and 58°C) for 30 seconds, and lastly extension at 72°C for

30 seconds. The standard PCR mix is shown Table 3.2. The PCR products were then examined by using the Bio-Rad ChemiDoc MP imaging system to check if the DNA binds to the primers. Subsequently, PCR was performed on a multiplex basis (combination of primers), and if it was successful for both loci in the trial run, second optimization steps were carried out to improve the yield of PCR products. In this step, the ratios for primers were adjusted and may include the process of increasing DNA concentration or lowering the primer concentration in the PCR mix. Control extraction blanks were included in each of the amplification processes, to which no DNA was added (Eggert et al., 2003). Samples for fragment analysis were prepared (Table 3.3) and outsourced for fragment analysis at an external laboratory, Apical Scientific, a leading life science service provider in Malaysia, as we do not have the capacity and facilities to perform it. Manual peak scoring of the fragment analysis results was performed using Peak Scanner™ Software v1.0 (Thermo Fisher Scientific, 2006) to confirm allele readings. Electropherogram outputs were carefully examined by manually scoring each allele to ensure accuracy in genotype interpretation. The scoring process was conducted under the guidance of Dr. V.K. Kayal from the Department of Wildlife and National Parks (PERHILITAN), Peninsular Malaysia. Quality control steps were taken to minimize genotyping errors. Specifically, we used Micro-Checker (Van et al., 2014) to identify potential null alleles, stuttering, and significant allele dropout.

At the final stage, only eight microsatellites were selected for the individual identification process due to high allelic dropout. (Table 3.4). The final data was then binned using the software TANDEM (Matschiner and Salzburger, 2009), and used in the elephant identification processes in the next phase of analysis.

Table 3.2 The standard PCR mix used in this study.

Component	Volume	Concentration
PCR pre-mix	12.5ul	1 X
Forward primer 1	0.6ul	0.024uM
Reverse primer 1	0.6ul	0.024uM
Forward primer 2	0.6ul	0.024uM
Reverse primer 2	0.6ul	0.024uM
Double distilled water	8.1	NA
DNA	2ul	5-20ng/ul

Note: Control vial used double distilled water.

Table 3.3 Multiplex combinations that were sent for fragment analysis. Only eight microsatellites (bolded) were selected for final analysis based on fragment analysis results.

Multiplex ID	Microsatellite primers
Multiplex mixture 1	**EMU13**, EMU14
Multiplex mixture 2	EMU3, **EMU7**
Multiplex mixture 3	**EMX2, LafSM02**
Multiplex mixture 4	**EMU17, LafSM05**
Multiplex mixture 5	EMU10, EMU12
Single microsatellite	**EMU15**

Table 3.4 Characterization of eight microsatellite loci used in the elephant identification processes.

Locus	Repeat motif	Bases pair	Allele sizes	References	Accession no.
EMU07	$(TG)_{15}$	di-nucleotide	100-124	Kongrit, C. et al. (2008)	EF643829
EMU10	$(CA)_{17}$	di-nucleotide	94-107	Kongrit, C. et al. (2008)	EF643832
EMU13	$(GT)_{17}$	di-nucleotide	100-110	Kongrit, C. et al. (2008)	EF643835
EMU15	$(AC)_{14}$	di-nucleotide	142-154	Kongrit, C. et al. (2008)	EF643837
EMU17	$(GT)_{16}$	di-nucleotide	119-137	Kongrit, C. et al. (2008)	EF643838
EMX2	$(GTT)_{5}$	tri-nucleotide	217-223	Fernando, P. et al. (2001)	DQ198459
LafMS02	$(AC)_{16}$	di-nucleotide	149	Nyakaana, S. and Arctander P. (1998)	AF061841
			148-156	Thitaram et al. (2009)	
			124-181	Marasinghe et al. (2021)	
LafMS05	$(AC)_{11}$	di-nucleotide	160	Nyakaana, S. and Arctander P. (1998)	AF061844
			156-172	Thitaram et al. (2009	

3.2.3.2 Individual elephant identification

GenAlEx 6.5 (Peakall and Smouse, 2012) was used to calculate number of alleles per locus (Na), observed (Ho) and expected (He) heterozygosities, Fis, pairwise and Fst values between loci. The microsatellite data was tested for deviation from Hardy–Weinberg equilibrium (HWE) and for linkage disequilibrium (LD) using Genepop 4.8.3 (Rousset, 2008).

Next, the elephant individual identification was conducted using the R package 'allelematch' (Galpern et al., 2023) in R version 4.1.2 (R Core Team, 2019). This package was chosen because it has a key feature in accommodating genotyping errors and missing data while identifying unique genotypes (Galpern et al., 2012). In this study, two analyses were performed. First, 'AmUnique' was performed for all the samples, followed by the "Pairwise" analysis that looks into samples that have multiple duplications (or 'technically' linked to other samples). A pairwise analysis approach in which each profile is compared against all other profiles was recommended because the AmUnique analysis still faces challenges in grouping profiles according to their similarity (Galpern et al., 2012). Allelematch analysis was performed for samples with different degrees of missing values to assess the initial result of unique genotypes and multi-matches. To reduce the genotyping errors, samples with 50% or more missing values (four pairs of loci) were excluded from the final analysis for density estimates. Eliminating samples with missing data is a suggested measure to reduce genotyping error (Galpren et al., 2012). Besides that, one of the important parameters in allelematch analysis is determining the value of the mismatching loci. The difficulty lies in determining the appropriate threshold for the mismatch value. If the value is set too low, distinct genotypes will not be adequately distinguished since profiles with genotyping errors would be mistakenly labelled as unique, thereby inflating the count of unique genotypes (Galpren et al., 2012). On the opposite, if the mismatch value is set too high, it will result in too many profiles identified as the same unique genotypes when in fact they are different, and this results in different genotypes being treated as multiple matches (recaptures) (Galpren et al., 2012). The recent study by De et al. (2022) indicates that the correct assignment of genotypes scores up to 95.2% accuracy with three mismatches, compared to 81.7% using one locus mismatch, and 45.9% with no mismatch. Therefore, the mismatching loci (alleleMismatch (m-hat)) is set at three mismatches after reviewing the results of mismatched loci of 0 to 7 (Appendix II).

The definitive elephant individual is required to ensure that the estimation of the elephant population in GUMFC is robust enough; thus, various techniques were applied in the process of cross-validating samples with multi-matches. According to the package manual (Galpren, 2012), the output tables need to be manually collated to produce a final and authoritative unique genotype list (inclusive of information about identical pairs, as well as those that match at most loci). The sex (male or female) of the animals is usually used to corroborate the information during manual checks of the samples' identification. However, in this study, the sexes of elephants were not determined due to time constraints. Thus, for the manual validation of genotype status, I combined field records to help improve the accuracy of identifying individual genotypes for multiple matches and unclassified samples (based on pairwise analysis). Pieces of information that were reviewed to determine whether these samples were recaptures or not included differences in the circumference of the dung, the date and time of sample collection, the sampling locations, and any additional field records such as the distribution of dung piles and whether they were presumed to be from a herd of elephants or a single elephant. The average circumference of elephant dung was chosen as the main indication, as it has been found to be correlated with elephant age (Kongrit and Siripunkaw, 2017; Mohanarangan et al., 2022; Karuppannan et al., 2023). Any measurements with average circumference differences of more than 10 cm indicate distinct individuals, potentially belonging to different age groups (Mohanarangan et al., 2022), in combination with other pieces of information stated above. However, it is recognized that the size of the dung can be affected by the nutrition and health of the elephant, but it still serves as a reliable reference.

3.2.3.3 Elephant density estimation

The density estimate of the elephant population was analysed using the Spatially Explicit Capture-Recapture (SECR) modelling version 4.5.10 (Effort, 2019) in R version 4.1.3 (R Core Team, 2019). SECR is usually used to estimate the population density of free-ranging animals and could provide spatial data (where individuals are in space) (Efford, 2011; Borchers, 2012; Efford et al., 2013). The basic principles of SECR are i) each individual theoretically occupies a fixed home range whose activity centre is an unknown point, and ii) a detection results when an individual interacts with a detector (such as a device or observer) at a known spatial location and with known properties. Thus, by including the locations of both the animal and detector as an integral part of the model, it has become possible to estimate density directly and to avoid the negative effects of unmodelled spatial variation in non-spatial models (conventional capture-recaptures) (Borchers and Fewster, 2014; Efford, 2019).

In this study, revisits to the same sampling sites more than once, which occurred mainly between March and May 2019 due to concentrated elephant activity during the post-monsoon season, were not treated as independent transects. Instead, each revisit was logged as a separate survey occasion within the same spatial transect, reflecting the repeated sampling effort over time. In the SECR framework, these repeated visits were incorporated as multiple occasions for the same transect, ensuring consistency with the model's assumptions. This approach aligns with the spatially explicit capture–recapture (SECR) framework, which emphasizes the importance of accurate spatial configuration and detection history over random detector placement (Efford, 2011). Although the sampling was not entirely random, SECR models can accommodate non-uniform effort if the spatial arrangement of detectors and occasions is properly recorded (Efford, 2022). Repeated visits to the same transect were treated as multiple occasions within the SECR framework, maintaining consistency with model assumptions.

For the analysis, the 'polygon' detector type in SECR analysis was used, as it provided a better fit to the data compared to other models, such as the transect detector, following an initial attempt with the 'transect' detector. The polygon detector was chosen to reflect the continuous nature of the search effort and to account for the spatial extent of the study area (Efford, 2019). This detector type is particularly suited for data collected from searches within one or more defined areas (polygons) and is compatible with both individually identifiable cues (e.g., a discrete sign identifiable to an individual animal by means such as microsatellite DNA), such as dung samples, and direct observations of individuals (Efford, 2022). The SECR model fitting framework is based on maximum likelihood estimation, allowing robust estimation of detection probability and density within the surveyed polygons (Efford, 2022). In accordance with SECR-polygon detector guidelines (Efford, 2019; Efford, 2022), multiple polygons were created to cover the overall study area. The implementation of the SECR-polygon detector allows any number of "disjunct polygons" (the term disjunct polygons refers to multiple, separate (non-contiguous) search areas that are treated as a single detector type in the analysis) that fit the criteria. The criteria were: i) polygons may be irregularly shaped, but may not be concave in an east-west direction, meaning they should not intersect a vertical line more than twice, ii) polygons must be free of internal voids or holes, and iii) the polygons used on any one occasion should not overlap (Efford, 2022).

Although the entire polygon was not uniformly surveyed, approximately 70% of the total number of sites (each site is 25 km^2) was actively covered during fieldwork (Figure 3.3). The 70% is calculated by counting the number of study sites visited. The surveyed regions were spatially distributed across the polygon in a manner that reasonably approximates uniform coverage, minimizing spatial bias in detection probability. A model was fitted using the following default parameters: i) D, density of animals per hectare, ii) g0, an encounter rate at an animal's activity centre, and iii) sigma, a scale parameter that describes the decline of encounter rate with increased distance from an animal's activity centre. This approach allows for robust estimation of animal density while maintaining consistency with the spatial structure of the data. Elephant recaptures were defined as instances where the same unique genotype (representing an individual elephant) was detected more than once, regardless of the sampling period, spatial location or survey occasion.

To account for variations in detection probability, this study modelled population density estimates (animals per hectare) using pre-defined model structures in secr (i.e., *t* and *h*) corresponding to 'time' and 'heterogeneity', respectively. These are two factors that could be believed to affect the density estimation, as heterogeneity (*h*) represents differences in capture probability between individual elephants, and time (*t*) accounts for variation in capture probability across different sampling periods (Effort, 2019). It is worth noting that, due to the absence of sex-specific data, the analysis did not model males and females separately. Instead, a single detection function was applied across all individuals. To account for potential variability in individual detection probabilities, a finite mixture model was incorporated using the heterogeneity (*h*) parameter, which addresses unobserved individual differences and improves model fit and reliability.

The perimeter used in the SECR analysis is as follows: buffer=89,200 (calculated based on the home range size of Asian elephants of 250 km^2), method = 'Neder-Mead', CL=TRUE, trace= FALSE. Finally, the Akaike Information Criterion (AIC) was used to identify the best model. The model with the lowest AIC value is considered the most parsimonious model in this study. Using the density estimate from the best-fitting SECR model, the elephant population size within the GUMFC was calculated by multiplying the estimated density by the total area of the study area (1,629.31 km²). The assumption of this calculation is that the density is uniform throughout the study area.

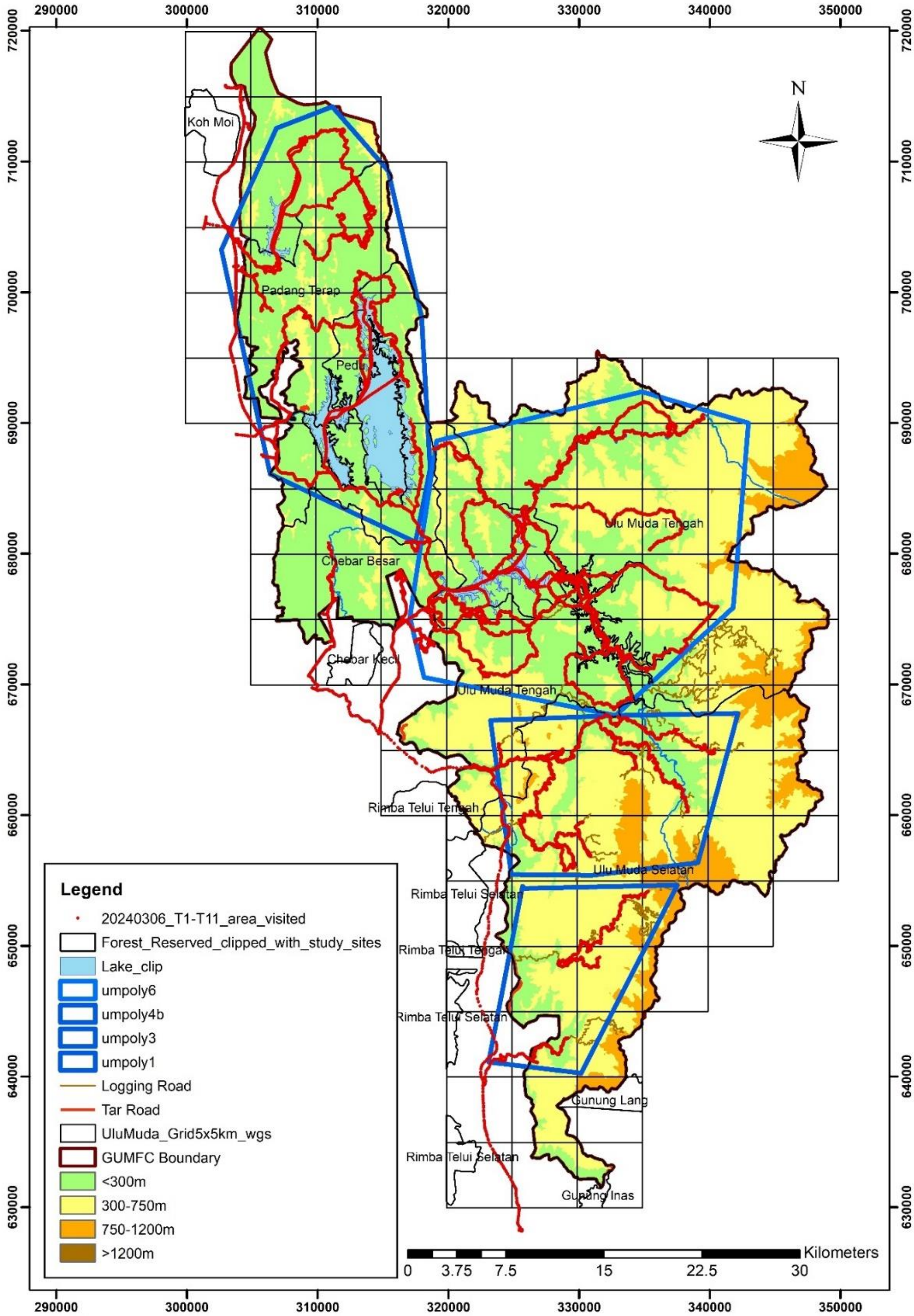


Figure 3.3 The area searches across the study area, and the sec-polygon detectors used in the analysis. The polygons were created based on the search areas.

3.3 RESULTS

3.3.1 Field results and elephant individual identification

A total of 487 faecal samples were collected during the sampling period of over 5.5 months, with the area visited covering nearly 70% (1,150 km^2) of the study area (Appendix III). The distribution of the sample across the Greater Ulu Muda Forest Complex (GUMFC) is shown in Figure 3.4. In general, the number of collected wet samples (479) was higher than the dry samples (449) due to the suitability of dung conditions during sample collection. A total of 128 samples (26.3%) out of 487 samples were successfully amplified using eight pairs of microsatellite primers and sent for fragment analysis. Most of the samples that yielded successful amplification were samples reported as 'very fresh' to 'fresh' based on the freshness rating (categories 1 and 2) (Table 3.5). However, after fragment analysis, only 118 samples (24.2%) were selected for the elephant individual analysis, after removing samples with 50% of missing values (≥ 4 pairs of loci).

From the eight loci used, the number of alleles ranged from 5 to 12, with an average of 8.125 ± 0.789 (SE). The average observed heterozygosity across the eight loci was 0.272 ± 0.056 (SE), with the highest value being 0.472. The average expected heterozygosity across the 8 loci was 0.496 ± 0.068 (SE), with the highest value being 0.796. All loci in the dataset were not in Hardy–Weinberg equilibrium (HWE). Linkage disequilibrium was significant in 14 out of 28 pairwise comparisons (Table 3.6).

The initial result of the allele match analysis produced 76 unique, 55 multiple-matches, and two unclassified genotypes (Table 3.7). A manual validation process, primarily performed on multiple matches and unclassified samples, ultimately yielded a total of 92 unique genotypes (representing individual elephants) and 26 recaptures from 12 elephants (Appendix III). The allelic diversity suggests that, on average, there are 6.6 different alleles per locus in the population (Table 3.7).

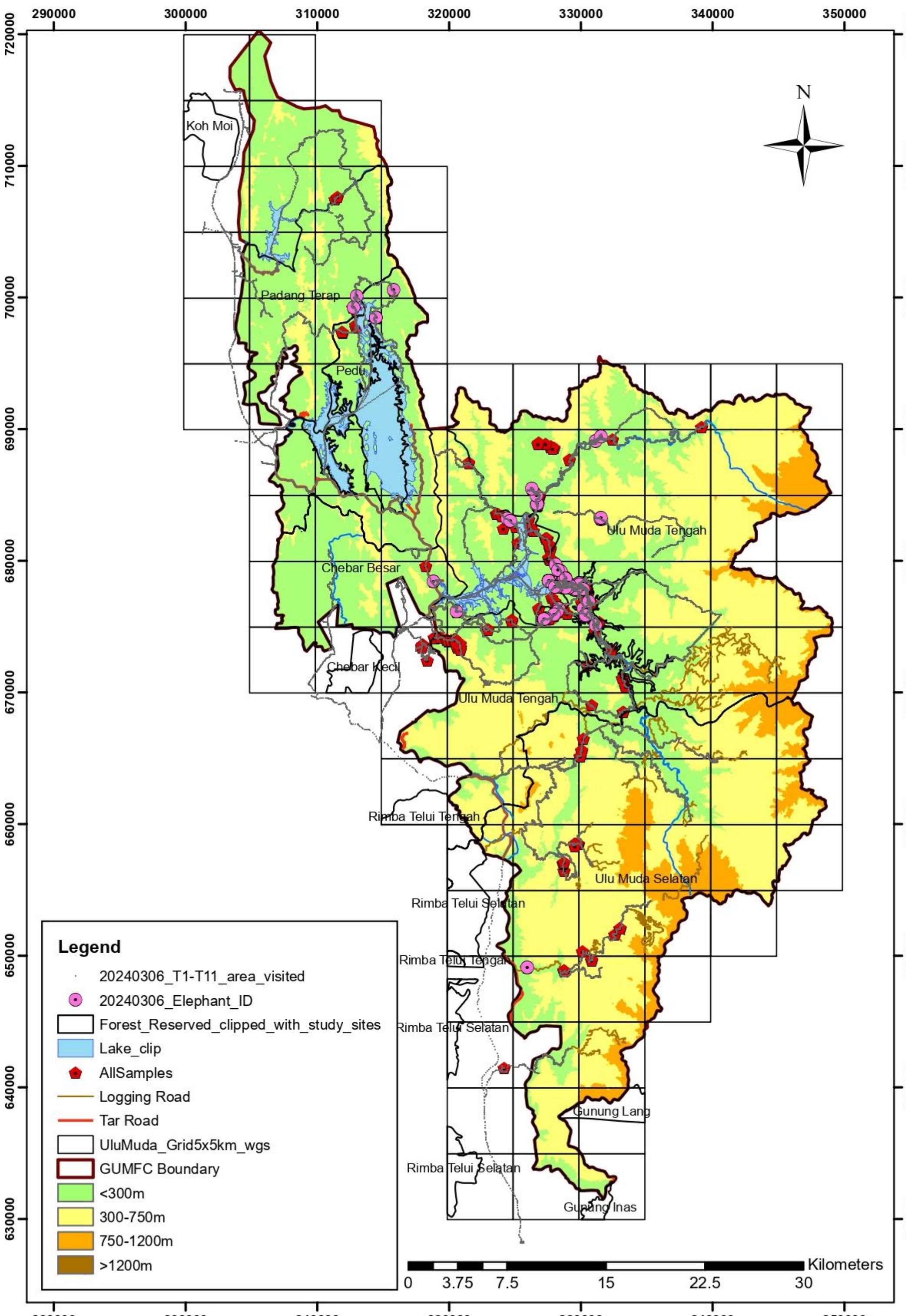


Figure 3.4 The distribution of dung samples (n=487) collected across the Greater Ulu Muda Forest Complex.

Table 3.5 The number of faecal-based DNA samples collected across GUMFC and the number of samples successfully amplified according to the freshness categories.

Freshness	T1 (n=15)	T2 (n=39)	T3 (n=78)	T4 (n=11)	T5 (n=160)	T6 (n=19)	T7 (n=71)	T8 (n=55)	T9 (n=2)	T10 (n=25)	T11 (n=12)	Total Samples (n=487)	Number of successfully amplified samples, based on freshness
1	0	17	29	3	88	11	42	50	1	2	5	248	105 (42.3%)
2	4	10	26	1	39	7	15	2	0	0	7	111	21 (18.9%)
3	5	10	22	3	31	1	14	2	1	10	0	99	0 (0%)
4	0	0	1	4	1	0	0	0	0	13	0	19	1 (5.3%)
5	4	0	0	0	0	0	0	0	0	0	0	4	0 (0%)
Not Rated (N/A)	2	2	0	0	1	0	0	1	0	0	0	6	1 (16.7%)
Number of successfully amplified samples	0	13	11	4	74	5	8	9	0	2	2	487	128 (26.2%)

Note: Only fresh samples (<48 hours) and reasonable fresh dung (<14 days) were collected, following Hedges and Lawson (2006). T1 refers to the first sampling trip.

Table 3.6 Genetic diversity parameters for eight microsatellite loci used in elephant identification.

Locus	Na	Ho	He	HWS	PID	PISibs
LafMS02	6	0.418	0.575	0.000	0.24	0.52
LafMS05	5	0.066	0.227	0.000	0.61	0.79
EMX2	9	0.263	0.418	0.000	0.37	0.63
EMU7	10	0.340	0.542	0.000	0.25	0.54
EMU10	12	0.111	0.307	0.000	0.49	0.72
EMU13	7	0.394	0.698	0.000	0.14	0.44
EMU15	8	0.113	0.401	0.000	0.38	0.64
EMU17	8	0.472	0.796	0.000	0.07	0.37
Mean	8.125	0.272092	0.495542			
SE	0.789156	0.055849	0.068432			

Note: Na = Number of Different Alleles; Ho = Observed Heterozygosity; He = Expected Heterozygosity; HWS- Summary of Chi-Square Tests for Hardy-Weinberg Equilibrium (significant level, $p<0.001$)

Table 3.7 The sample classification metrics based on allelematch analysis.

alleleMismatch	matchThreshold	cutHeight	samples	unique	unclassified	multiple Match	guess Optimum	missing DataLoad	allelic Diversity
0	1	0	118	114	0	0	FALSE	0.153	6.6
1	0.9375	0.0625	118	113	0	16	FALSE	0.153	6.6
2	0.875	0.125	118	104	0	37	FALSE	0.153	6.6
3	**0.8125**	**0.1875**	**118**	**76**	**2**	**55**	**FALSE**	**0.153**	**6.6**
4	0.75	0.25	118	49	2	76	FALSE	0.153	6.6
5	0.6875	0.3125	118	31	8	70	TRUE	0.153	6.6
6	0.625	0.375	118	21	3	74	FALSE	0.153	6.6

Note: Result from the alleleMismatche = 3 was selected for the population density estimate.

3.3.2 Population density estimates

All three models show a variation in the density estimates per hectare, with the model incorporating heterogeneity showing the highest mean density estimate (secrh = 5.56×10^{-3}/ha, SE 3.11×10^{-3}), while the null model (secrstart) and model incorporating time (secrt) shows the same value of 1.71×10^{-3}/ha (or 0.17 elephants/ km^2), but with different SE values of 3.66×10^{-4} and 3.61×10^{-4}, respectively (Table 3.8). The lower SE in secrt model indicates that while temporal variation in detection probability slightly improves the precision of density estimates, it doesn't drastically change the overall density estimate compared to the null model. In terms of the best-fitted model, the model accounting for temporal variation in capture probability (secrt) shows the lowest AIC value (5213.36) and an AIC weight of 1 (Table 3.8), thus can be considered the best model compared to secrh (5242.73) and secrstart (5274.07). I also considered the dAICc rule, where models within two units of the lowest AIC are generally regarded as having substantial support and may be similarly plausible. However, in the analysis, we found that the model incorporating time (secrt) had a dAICc of -29.365 relative to the next best model of secrh (Table 3.8). Therefore, secrt is the best model selected for the density estimates. This model also has the lowest SE (3.61×10^{-4}), which indicates that this model provides the most precise estimate of elephant density, thus higher confidence in reflecting the actual population. Therefore, in this study, the mean density estimate of the elephant population in GUMFC can be considered as 0.17 elephants/ km^2 (95% CI [0.11-0.25]). Based on this density estimate, the population size of elephants in this forested landscape is estimated to have a posterior mean of 279 individuals, with a 95% credible interval ranging from 185 to 420 elephants. The 95% credible interval indicates that there is a 95% probability that the true population size lies within this range, based on the posterior distribution.

Despite these results, several limitations of the SECR polygon detector approach warrant consideration, particularly for application in similar ecological contexts. One key limitation is the assumption of uniform search effort across each polygon, which is often difficult to achieve, especially in large or logistically complex landscapes. Uneven effort within polygons can lead to underestimated detection probabilities and, consequently, conservative bias in density estimates (Efford et al., 2013). Nevertheless, the analysis conducted in this study remains valid, as the polygon detector was the most appropriate given the structure and nature of the available data. Future studies could enhance estimation accuracy by incorporating effort covariates, using transect or point detectors to better capture actual search paths, or refining the delineation of polygons to more closely match areas where sampling occurred.

Table 3.8 Model selection criteria and fit statistics for SECR models.

		model		detectfn	npar	logLik	AIC	AICc	dAICc	AICcwt
secrt	lambda0~t	sigma~1	hazard	halfnormal	4	-2602.68	5213.36	5213.82	0	1
secrh	lambda0~h2 sigma~1	pmix~h2	hazard	halfnormal	4	-2617.36	5242.73	5243.19	29.365	0
secrstart	lambda0~1	sigma~1	hazard	halfnormal	2	-2635.03	5274.07	5274.20	60.38	0

Table 3.9 Elephant density estimates using SECR models in R.

	Density estimate (D)	SE.estimate	lcl	ucl	CVn	CVa	CVD
secrstart, null model							
D	1.71E-03	3.66E-04	0.0011332	0.00259333	9.001133	0.1863959	0.213572
secrh, incorporate heterogeneity, h							
D	5.56E-03	3.11E-03	0.0019968	0.01545828	0.104257	0.5499895	0.5597839
secrt, incorporate time, t							
D	1.71E-03	3.61E-04	0.0011383	0.00257891	0.104257	0.1833507	0.2109195

Note:

Null model (secrstart): A basic model without accounting for variations in capture probability.

Model with individual heterogeneity (secrh): This model incorporates differences in capture probability between individual elephants.

Model incorporating time (secrt): This model accounts for variation in capture probability across different sampling periods.

The density estimation is in the hectare (ha).

3.4 DISCUSSION AND CONCLUSION

This is the first study to estimate the density of wild Asian Elephants in the Greater Ulu Muda Forest Complex, in the state of Kedah, north of Peninsular Malaysia. According to the literature, using the conventional method of compiling elephant population numbers reported from various forest reserves in the state, the number of elephants in Kedah was estimated to be approximately 90 elephants in the 1960s and further recorded as 50 to 60 elephants in 2008 (Saaban et al., 2011). It is important to note that these estimates were based on a combination of various methods, including biodiversity inventory and dung count survey (see Saaban et al., 2011 for more details). Using the DNA spatially explicit capture-recapture (SECR) method, this study estimates an elephant density of 0.17 elephants/km^2 in GUMFC, with a 95% credible interval (CI) ranging from 0.11 to 0.26 elephants/km^2, corresponding to an estimated average of 279 elephants across the 1.629 km^2 study area. The density estimate obtained for GUMFC is slightly higher than the records of other studies of Asian elephants in West (Peninsular) Malaysia, but lower than the study of elephants in East Malaysia (in the state of Sabah). It is important to note that the density of wild Asian elephants in tropical rainforests varies across different landscapes and is affected by factors such as habitat quality, human disturbance, as well as topographic factors (Alfred et al., 2010). In 2008, a study of elephant population estimates in the southern Peninsular using a dung-count survey estimated elephant density of 0.0538 (95% CI [0.0322_0.0901]) elephants/ km^2 and estimated the population size as 135 (95% CI [80_225]) elephants in the 2,500 km^2 study area (Saaban et al., 2011). Another study of elephant population estimates for the Taman Negara National Park, which forms the major forest complex (4,343 km^2) in the central part of Peninsular Malaysia, was reported to be home to 631 elephants (with the 95% CI, ranging from 436 to 915 elephants) (Saaban et al., 2011). The density estimation of Asian elephants from various forest reserves in Sabah (east Malaysia) recorded densities ranging from 0.12 to 3.69 elephants/ km^2 reported (Alfred et al., 2010). In India, the density estimate for wild elephants in the forest was reported as 0.1 elephants/ km^2 (Sukumar, 2003). In a recent study by Karuppannan et al. (2023) using microsatellite markers, a total of 217 individual elephants were identified from a total of 223 faecal samples collected from the Taman Negara National Parks (NTTP).

For density estimates using genetic materials, the accuracy of the estimate could be affected by genotyping errors, a common factor highlighted in the literature (Lampa et al., 2013; Morin et al., 2018; De et al., 2022). Genotyping errors in elephant faecal-based DNA can be due to several factors, such as sample quality (DNA quality and possible degradation), allelic dropout, false alleles ('ghost' individuals), inappropriate sample storage, problems related to microsatellite markers, and laboratory technicality (De et al., 2022; Bourgeois et al., 2019; Lampa et al., 2013; Kongrits et al., 2008). If not addressed, genotyping errors could lead to overestimation or underestimation of a population size (De et al., 2022; Lampa et al., 2013). In this study, despite the challenges in the genotyping processes, mitigation strategies to minimize genotyping error and to improve population density estimates have been performed; however, we acknowledge the possibility of unaware genotyping errors. One limitation of this study is the absence of a formally quantified genotyping error rate, as repeated genotyping of a subset of samples was not done more than 2 or 3 times. Such error rates are typically used to inform the threshold for allowable mismatches when identifying unique individuals from genotype data. In this study, we adopted a conservative approach based on values reported in similar studies, allowing for a small number of mismatches (e.g., 1–2 loci) when comparing genotypes. To further reduce potential bias, loci with consistent amplification issues or evidence of null alleles (as identified via Micro-Checker) were excluded from the final analysis. While these steps help mitigate the risk of misidentification, we acknowledge that undetected genotyping errors could still influence the accuracy of individual identification and density estimates. The quality of the DNA collected could be affected by environmental elements in its surroundings and the handling process. Thus, the DNA sample collection in the field adhered to rigorous guidelines to avoid any unnecessary contamination of the sample. Despite the collection of a substantial number of samples (n=487), the success rate of DNA extraction and amplification in this study is strongly influenced by the freshness of the dung samples, which is a crucial component in achieving successful genotyping (Lampa et al., 2013; Karuppannan et al., 2023). During the sampling, dung was found in various environmental conditions that could degrade its quality. For instance, dung was found on the dry and wet forest floor, partially submerged in the river, exposed to hot sun (UV rays) in open areas, and washed by rain. In such conditions, even fresh dung may not produce adequate or good-quality DNA materials. For the dung that has been defecated for an extended period, it could be further contaminated by various biological components, such as fungi, and insects such as the dung beetle (Goh et al., 2019). Despite the inherent difficulties in locating fresh elephant dung within dense forest landscapes, a total of 118 samples were successfully used for density estimation. The application of SECR methods allows a reliable and unbiased density estimate provided that spatial recaptures are well-distributed and the study area is sufficiently covered (Borchers, 2012; Efford and Fewster, 2013; Borchers and Fewster, 2016). In this study, our recaptures are mainly from the nearby sampling site within the same polygon detector. An additional limitation of this study is the absence of simulation-based planning to determine the optimal sample size for the specific study design. Simulation studies are increasingly recommended for complex models like SECR, as they allow researchers to assess the precision and bias of parameter estimates under varying conditions and to tailor sample size decisions to the specific context of the study (Efford, 2011; Efford, 2022**).** Without such simulations, there is a risk that the sample size, while seemingly adequate, may not fully capture the variability or complexity of the population being studied. Future studies should take into consideration the application of a simulation model to assist in defining sample size. Additionally, this study acknowledges the limitation of not incorporating sex-specific information in the analysis, which could have enabled more refined modelling of detection processes.

Within the GUMFC, a vast study area (70%) was explored to gather a substantial amount of dung, covering all seven forest reserves within GUMFC with repeated surveys at known areas with elephants. The SECR model demonstrates that the inclusion of temporal variability (*t*) as the most suitable model accurately accounts for the probability of detecting an individual elephant, which varies over different time intervals (Efford, 2022; Efford, 2023). These conditions can be affected by a range of factors, including environmental changes and behavioural responses of elephants, such as their movement patterns and daily activity patterns. The model also validated the fact that the DNA detection probability on the ground is not constant (Efford, 2022). This could be further explained by the fact that the samples were mainly discovered and gathered in the riparian zone during the post-monsoon season, specifically during Trips 3, 5, 7, and 8. The riparian zone along the river (Sg. Muda) has a rapid growth of grasses, and there were clear signs of elephants. On the other hand, despite walking the pathways presumedly used by elephants, certain sites explored in this forest complex did not yield a significant amount of dung samples. Based on this fact, I assume that optimizing the collection of dung in certain areas where elephants are frequently found, as done in this study (and suggested by Hedges et al., 2012), may have resulted in the gathering of dung from various elephants, as opposed to tracking their specific paths. Nevertheless, this could be due to other factors such as limited studies and understanding about elephant habitat use, and elephant movements during the sampling period, with some very remote areas (e.g., southern region of Ulu Muda Forest Reserve) that were difficult to access repeatedly during the sampling period.

In terms of the use of microsatellite markers, steps were taken to select eight primers that performed well with the collected samples. The use of eight microsatellite markers in this study can be considered adequate for individual identification, as supported by various studies on elephants (Fernando et al., 2003a; De et al., 2022) and other large mammals (Arandjelovic et al., 2010). In addition to the quantity of microsatellite primers, alternative methods have been proposed to improve genotyping accuracy and could be explored in future studies. De et al. (2022) suggested the application of a blind test approach to screen microsatellite panels for their accuracy in assigning the identities of faecal DNA samples from known individuals. Another study suggested the use of single-nucleotide polymorphisms (SNIPs) could provide better accuracy for elephant individual identification (Zimmerman et al., 2020). In Peninsular Malaysia, the SNIPs panel is being developed by the Department of Wildlife and National Parks (PERHILITAN) Peninsular Malaysia, for the planned national elephant survey across Peninsular Malaysia (Department of Wildlife and National Parks Peninsular Malaysia, 2023).

Asian elephant population growth is closely linked to its environment, in which habitat availability is one of the core aspects in the preservation of the elephant population. As the largest terrestrial species, elephants require large areas of suitable habitat to thrive. Habitat is shrinking due to various factors because of human activities (e.g., agriculture, urbanization, infrastructure developments, timber production, expansion of human settlements, mining, etc.), and this could potentially threaten the remaining elephant populations in Peninsular Malaysia (Department of Wildlife and National Parks Peninsular Malaysia, 2013; Department of Wildlife and National Parks Peninsular Malaysia, 2023; Department of Town and Country Planning Peninsular Malaysia, 2022). The challenging habitat conditions for elephants in disturbed, fragmented, and degraded forest landscapes could be a factor affecting the concentration of elephants in a particular habitat. A reduction in habitat availability could be indicated by the high density of elephants in a particular area. For instance, a study of Bornean elephants indicates that elephant density was highest in areas where natural habitats have been removed, in which elephants ought to be concentrated in the remaining forest areas (Alfred et al., 2010). Therefore, the availability of quality habitat that could fulfil the biological needs of elephants, such as providing plenty of food resources, water, shelter, and opportunity to mate, is a priority in elephant conservation to support a thriving population of elephants. GUMFC is one such landscape where elephant conservation and state development need to strike a balance. Although the estimated population size of elephants in GUMFC is 185 to 420 elephants with an allelic diversity of 6.6 (considered high), which may not show any alarming concern for now, the prolonged disconnectivity of this forest complex from other elephant populations could pose a risk to the population's health in the long term. Even though allelic diversity of elephants in GUMFC indicates a healthy level of genetic variation, which is crucial for a population's long-term potential for adaptability and persistence toward environmental changes, and diseases (De et al., 2022; Fuller et al., 2016; Greenbaum et al., 2014; Caballero and García-Dorado, 2013), the isolation of this landscape should be a concern for long term preservation of elephant populations. The concept of the Central Forest Spine ecological linkages, which aims to connect this forest complex to another forested area, should be prioritised to ensure it is ecologically functioning (Figure 2.2). Nevertheless, the protection of this important forest complex needs to be continued, and its significant role in preserving the elephant population needs to be made known to decision-makers.

In the context of the accuracy and precision of SECR estimates, the sampling design has a strong influence. Key factors include the spatial configuration and spacing of sampling locations (e.g., transects), which must align with the scale of animal movement to ensure sufficient spatial recaptures (Effort, 2011). Uneven or sparse sampling effort may lead to biased density estimates due to incomplete spatial detection coverage. Additionally, the detection function in SECR is sensitive to the placement of detectors relative to animal home ranges, making consistent effort and spacing across the study area essential (Efford, 2022).

A potential concern in this study is the non-random nature of the sampling effort, due to reliance on elephant trails and known hotspots for dung collection. This strategy was necessary to improve the likelihood of encountering fresh dung, given the challenges of detecting elephant signs in dense tropical rainforest environments (Hedges, 2012a; Eggert et al., 2003). Nonetheless, such preferential sampling raises the question of potential bias in density estimates derived from SECR models. Importantly, SECR is robust to non-uniform sampling effort, provided that the spatial arrangement of detectors and survey occasions is clearly documented and incorporated into the model (Efford, 2011; Efford, 2022). The model relies primarily on the spatial pattern of detections and the distance between detections and animal activity centres, rather than requiring strictly random sampling placement.

In this study, repeated visits to the same transects were treated as separate sampling occasions within the SECR framework, rather than as independent sampling events. This approach allowed for appropriate accounting of cumulative effort while avoiding inflation of the number of sampling units and potential bias in detection probability. While some trail-based sampling took place, it was complemented by exploratory surveys conducted across the broader study area. This combination, along with careful documentation of effort, helped maintain the validity of SECR assumptions and supported the reliability of the resulting density estimates.

Beyond statistical considerations, the effectiveness of elephant population surveys also depends on the accessible resources, including financial means, time availability, expertise, as well as the natural conditions of the specific locations, to facilitate the effective survey of elephant populations. To improve estimates of elephant population density in new survey areas, it will be advantageous to integrate additional research methods such as social science (e.g., local knowledge), identification of individual elephants based on physical markings, analysis of camera trap footage, and even collaboration with the neighbouring county that shares the forest boundary. By considering these elements, we can ensure that elephant population monitoring and management activities are thorough and have taken into account all important aspects that may affect the preservation of the remaining elephant populations.

In conclusion, this study presents scientific evidence that emphasises the importance of GUMFC as a crucial forest complex that sustains the elephant population in the northern region of Peninsular Malaysia, therefore, it should continue to be protected. These findings also highlight the current status of elephants in the northern region of Peninsular Malaysia, which should be monitored and managed. This study further demonstrates the effectiveness of combining faecal-based DNA sampling with SECR methods to estimate elephant density in tropical rainforests. However, the successful application of non-invasive genetic sampling depends on maintaining high standards for genotyping accuracy. One limitation of this study is the absence of a formally quantified genotyping error rate, which may affect the precision of individual identification. Future research should incorporate replicate genotyping to calculate error rates, enabling the use of more accurate mismatch thresholds and improving the reliability of population estimates.

CHAPTER 4: WILD ASIAN ELEPHANT HABITAT USE AND ITS RELATIONSHIP TO BIOPHYSICAL FACTORS ACROSS THREE FOREST COMPLEXES IN NORTHERN PENINSULAR MALAYSIA.

ABSTRACT

The shrinking habitat of the Asian elephant (*Elephas maximus*) is considered one of the main factors contributing to the decline of its populations in all 13 range countries, including Malaysia. Understanding the relationship between biophysical factors and elephant habitat use is important to provide evidence-based insights for the conservation of the species that is now distributed across a limited forested landscape in Peninsular Malaysia. This study assessed the relationship between elephant occurrence and environmental variables, including natural and anthropogenic factors. The spatial sign-survey occupancy framework was conducted in three main forested landscapes (i.e., Royal Belum State Park, Temengor Forest Complex, and Gunung Inas-Bintang Hijau Forest Complex) in northern Peninsular Malaysia. These forest complexes are considered the primary habitats for elephants and are linked to seven of the national central forest spine ecological corridors for wildlife. Elephant habitat use was modelled using 12 environmental covariates, and spatial autocorrelations are considered in the analysis. Elephant habitat use was significantly ($p<0.05$) influenced by three covariates: i) elevation, ii) distance to plantations, and iii) distance to indigenous settlement areas (linear and quadratic relationships). Elevation and distance to plantations were negatively correlated with elephant habitat use. Distance to the settlement was negatively associated with elephant habitat use in a quadratic manner. The predicted habitat use map of Asian elephants in all three study areas indicates most of the study sites are suitable elephant habitats, except for a portion of Gunung Inas-Bintang Hijau Forest Complex. Nevertheless, these forest complexes should continue to be prioritised in forest management for elephant conservation. The findings confirmed factors that influence elephant habitat use in this landscape and serve to support an informed conservation effort for elephants, particularly in the northern Peninsular.

Keywords: *Asian elephants, habitat use, biophysical factors, Central Forest Spine, habitat connectivity*

4.1 INTRODUCTION

Natural habitat provides basic needs for a species to thrive, including food, shelter, breeding grounds, and water sources. In the Anthropocene, mega-herbivores are likely to face greater threats compared to other smaller species. The danger of local extinction for large mammals, such as elephants and rhinoceroses, is real if we fail to conserve these species in their natural habitats (Ripper et al., 2019; Clements et al., 2010). As the largest terrestrial mammals, elephants require large roaming areas to sustain their biological needs; therefore, the presence of large areas of suitable habitat is essential to their long-term survival. According to the IUCN Red List of Threatened Species, the distribution of Asian elephants across their range of countries has reduced in size, and their global population is showing a decreasing trend (Williams et al., 2020). Habitat loss is identified as one of the main reasons that threatens the existence of Asian elephants (Williams et al., 2020; Department of Wildlife and National Parks Peninsular Malaysia, 2022).

Malaysia is estimated to have between 1,223 and 1,667 elephants in Peninsular Malaysia (Saaban et al., 2011) and between 1,000 and 1,500 elephants in Sabah (Sabah Wildlife Department, 2020), positioning it as one of the few Asian nations with significant potential for Asian elephant conservation. However, the nation is experiencing a similar predicament to other countries, characterised by the reduction of natural habitats for its megafauna, including elephants, tigers, gaurs, and tapirs (Clements et al., 2010; Department of Wildlife and National Parks Peninsular Malaysia, 2013). Elephants in Malaysia are believed to be affected by various local threats such as habitat loss and fragmentation, poaching, landscape modifications, and human-elephant conflicts (Saaban et al., 2011; Department of Wildlife and National Parks Peninsular Malaysia, 2013), mainly due to national development.

Malaysia, in the past few decades, has experienced rapid economic development, mainly through trading natural resources (timber and non-timber forest products, and mineral resources) and commodities such as rubber and palm oil (Khan, 2012). Malaysia's rainforest has been rapidly converted into agricultural land for economic development and food supply since its independence in 1967 (Khan, 2012). From the 1970s to the 1990s, Malaysia converted large areas of land into rubber and palm oil plantations, primarily the lowland to hill dipterocarp forests, which are fertile and easier to manage (Jomo, 2004). This economic development also meant that the original habitat for megafauna, such as elephants, is no longer available in its natural shape, size, and quality. Many once-intact forests are now fragmented, isolated, and disconnected, giving way to plantations, infrastructure, and residential areas in the name of development (Jomo et al., 2004; Department of Town and Country Planning Peninsular Malaysia, 2022). Hence, the geographical distribution of elephants in Peninsular Malaysia has become increasingly restricted. Now, elephants in Peninsular Malaysia occur only in seven States namely Perak and Kedah in the northern region, Terengganu, Kelantan and Pahang in the east-cost, and Johore in the southern region, instead of 11 states and two federal territories (Saaban et al., 2011) that were once home to elephants (Khan, 2012; Olivier, 1978a). Elephants no longer occur in other States because they were translocated out from their original habitats as part of human-elephant conflict mitigation measures (Khan, 2012; Saaban et al., 2011).

A study by Tan (2017) on elephant distribution in human-occupied landscapes in Peninsular Malaysia revealed that elephant distribution has reduced by nearly 68% in the past 40 years. This suggests that the decline in elephant presence throughout Peninsular Malaysia has been ongoing for several decades, likely due to a combination of factors. In addition to habitat loss and fragmentation, increasing human-elephant conflict is a significant concern. As forests shrink, elephants are forced into closer proximity with human settlements. For instance, within a year (2016 to 2017), the Wildlife Department recorded 688 HEC cases across

Peninsular Malaysia, with the elephant ranking third among species that cause the most conflict with humans, after the long-tailed macaque and wild boar (Department of Wildlife and National Parks Peninsular Malaysia, 2017b).

Recognising that the Asian elephant is a species of national and international importance, the Malaysian government has initiated a comprehensive conservation strategy to protect the elephant. Elephants in Peninsular Malaysia were granted the highest level of protection and categorised as a Totally Protected species under the Wildlife Conservation Act 2010. Subsequently, the National Elephant Conservation Action Plan (NECAP 1.0 and NECAP 2.0) was produced to guide elephant conservation in Peninsular Malaysia and promote coexistence between humans and elephants (Department of Wildlife and National Parks Peninsular Malaysia, 2013). However, efforts to conserve elephant populations often lack fine-scale scientific evidence regarding their habitat use and distribution patterns, particularly within forest complexes designated for conservation.

Elephants require large roaming areas that can provide enough food to support their energy requirements (Wall et al., 2006), as well as other biological needs. Given that the average home range of Asian elephants is 200 km^2 for females and 250 km^2 for males (Kaliyappan, 2023; Sukumar, 2012), maintaining significant, connected habitats is crucial for their survival. The presence of natural habitats, such as protected areas (PAs) and wildlife corridors, within areas undergoing development is essential for enabling species to persist within their natural distribution ranges. However, in the absence of scientific evidence, conservation efforts often default to prioritising forested areas, assuming they are inherently suitable habitats for elephants and other wildlife, which may not always be the case.

Biophysical factors such as topography (e.g., elevation, slope steepness, terrain ruggedness), and landscape structure (e.g., fragmentation, connectivity, settlement area within forest, etc.) play crucial roles in shaping elephant habitat use. For instance, lowland dipterocarp forests provide sufficient food, water sources, and mineral licks for herbivores such as elephants. In contrast, mountainous areas may have fewer food resources for elephants due to the types of plants that are distributed in high-elevation areas and the scarcity of water sources.

In the National Elephant Conservation Action Plan (NECAP), three Managed Elephant Ranges (MERs) were proposed for elephant conservation, aligned with the existing Central Forest Spine (CFS) master plan (Department of Wildlife and National Parks Peninsular Malaysia, 2013). The CFS master plan 1.0 specified 37 ecological linkages to connect four main forest complexes from the north to the south of Peninsular Malaysia (Department of Town and Country Planning Peninsular Malaysia, 2010). It is considered the backbone of Peninsular Malaysia's environmentally sensitive area network and was created to secure mutual coexistence and benefit for development and conservation (Department of Town and Country Planning Peninsular Malaysia, 2010). Although MERs within CFS forest complexes are identified as important areas for elephant conservation, information about elephant-habitat relationships has not been established to assess the suitability of these areas as elephant habitats (e.g., lowland to montane forests), thereby proving a priority area for elephant conservation.

An assessment study by de la Torre et al. (2019) on the functionality of CFS 28 ecological linkages (17 primary linkages and 11 secondary linkages) using movement data of 53 elephants shows that 57% have high potential to be effective corridors, and 25 are with acceptable functionality, and 18% of them are weak or not functioning as ecological corridors for wildlife.

The Malaysian government highlighted challenges in managing elephant habitats within MERs and intends to strengthen its science-based management approach (Asian Elephant Range States, 2017; Department of Wildlife and National Parks Peninsular Malaysia, 2013). Reliable information on elephants' ecology (e.g., distribution and habitat suitability) is listed in NECAP as one of the primary data requirements to ensure the effective management of remaining elephant populations and their habitats in Malaysia. Existing studies using GPS-collared elephants often reflect the behaviour of individuals captured near roads or human settlements and translocated due to conflict, thereby limiting our understanding of how wild elephants occupy the deeper, less accessible parts of the forest. Consequently, there remains a critical need for science-based, non-invasive methods to better understand elephant distribution and habitat preferences across forest landscapes of varying quality. Since habitat requirements are species-specific, especially for large mammals like elephants, and have significant implications for management strategies (Krausman, 1999), assessing habitat suitability and the influence of both natural and human-driven factors is essential.

To address this knowledge gap, this study employed non-invasive surveys of elephant dung signs and spatial data analysis across three major forest complexes in northern Peninsular Malaysia. A spatial occupancy framework, also referred to as a spatial replicate survey, was used to assess elephant habitat use. This approach has been widely applied to study species distribution, abundance, and habitat use, including for Asian elephants (Lakshminarayanan et al., 2015; Jathanna et al., 2015a). Unlike conventional occupancy models that rely on repeated temporal visits to estimate detection probability, spatially replicated surveys involve single-occasion sampling across multiple spatial units, making them suitable for large, logistically challenging landscapes. Elephant dung data is a reliable indicator of the presence of elephants at a specific location during recent months (Alfred et al., 2010). This is because the organic elements in the dung can degrade over time (Karuppannan et al., 2019b; Hedges et al., 2012a). Therefore, using dung data within an occupancy framework provides a valuable, low-impact method for understanding how elephants respond to ecological and anthropogenic factors, including topography, across their habitats.

This study aimed to investigate Asian elephant habitat use in relation to key environmental and human-related factors. Specifically, I examined the effect of elephant habitat use in relation to i) ecological factors, ii) anthropogenic factors influencing elephant habitat use, and iii) developed a spatial habitat prediction model to produce a suitability map for elephants within the selected forest complexes in northern Peninsular Malaysia.

The findings of this study will provide valuable insights into understanding the effect of topography on elephant habitat use and are especially important in confirming priority areas for elephant habitat conservation efforts. The resulting habitat suitability model also produced a spatial prediction map highlighting areas of conservation priority. These findings contribute to more informed management strategies, especially within the MERs, and support efforts to ensure the long-term survival of elephants in Malaysia.

4.2 MATERIALS AND METHODS

4.2.1 Study areas

The study was conducted in three main forest complexes situated within the main-range forest complex in the northern region of Peninsular Malaysia (also known as West Malaysia). Three study sites were selected, namely the Royal Belum Forest Complex (RBSP), Temengor Forest Complex (TFC), and Gunung Inas-Bintang Hijau Forest Complex (GIBHFC). These study sites were selected based on the following criteria: i) the forest complex that has *a prio*ri knowledge of elephant occurrence within the Managed Elephant Ranges (MERs), either with or without connection to Central Forest Spine ecological linkages for wildlife (Olivier, 1978b; Khan 2012), and ii) landscape to encompass lowland to high elevation area. Peninsular Malaysia has a warm equatorial climate with two distinct wet and dry seasons, but with all-year-round precipitation. Situated in the northern region of the Peninsular, all study areas experience similar climates with the dry season usually occurring in April to October and the wet season from November to March. The dominant forest types in the study areas are lowland dipterocarp (LDF; up to 300 m a.s.l.), hill dipterocarp (HDF; 300 to 750 m), upper hill dipterocarp (UHDF; 750 to 1200 m), Oak-montane (OMF, 1200 to 1500 m), and montane-ericaceous forest (MEF; above 1500 m). The category of inland forests follows the definition of the Department of Forestry Peninsular Malaysia. Some of these forest complexes comprise a fraction of primary forest, secondary forest (regeneration forest), and disturbed forests due to past and present timber extraction activities, as well as other development projects (i.e., dam construction, telecommunication towers, and resettlement of the Indigenous community). Two of the three study areas, namely Temengor Forest Complex (TFC) and Royal Belum Complex (RBSP), are also home to Indigenous people who have lived in these forests for generations.

All three study areas are recognized as Managed Elephant Ranges (Department of Wildlife and National Parks Peninsular Malaysia, 2013) and play an important part in the Central Forest Spine (CFS) ecological connectivity of the remaining forests from north to south of Peninsular Malaysia (Department of Town and Country Planning Peninsular Malaysia, 2022). Nevertheless, these three regions possess distinct legal land designations and varying levels of protection. Out of the three research areas, only RBSP benefits from strong protection by the State of Perak, ensuring the preservation of its untouched ecosystem. The Temengor Forest Complex (TFC), comprising a few forest reserves (i.e., Amanjaya Forest Reserve, Banding Forest Reserve, Temengor Forest Reserve, and Piah Forest Reserve) is a designated area of protected forest with various levels of protection, including areas designated for timber production, water catchment regions, and areas where indigenous tribes (i.e., Temiar and Jahai) have been resettled. Gunung Inas-Bintang Hijau Forest Complex comprises three forest reserves (i.e., Gunung Inas Forest Reserve, Bintang-Hijau Forest Reserve (Larut Matang), and Bintang Hijau Forest Reserve (Hulu Perak)) and has various levels of protection (i.e., Forest Plantation and timber extractions).

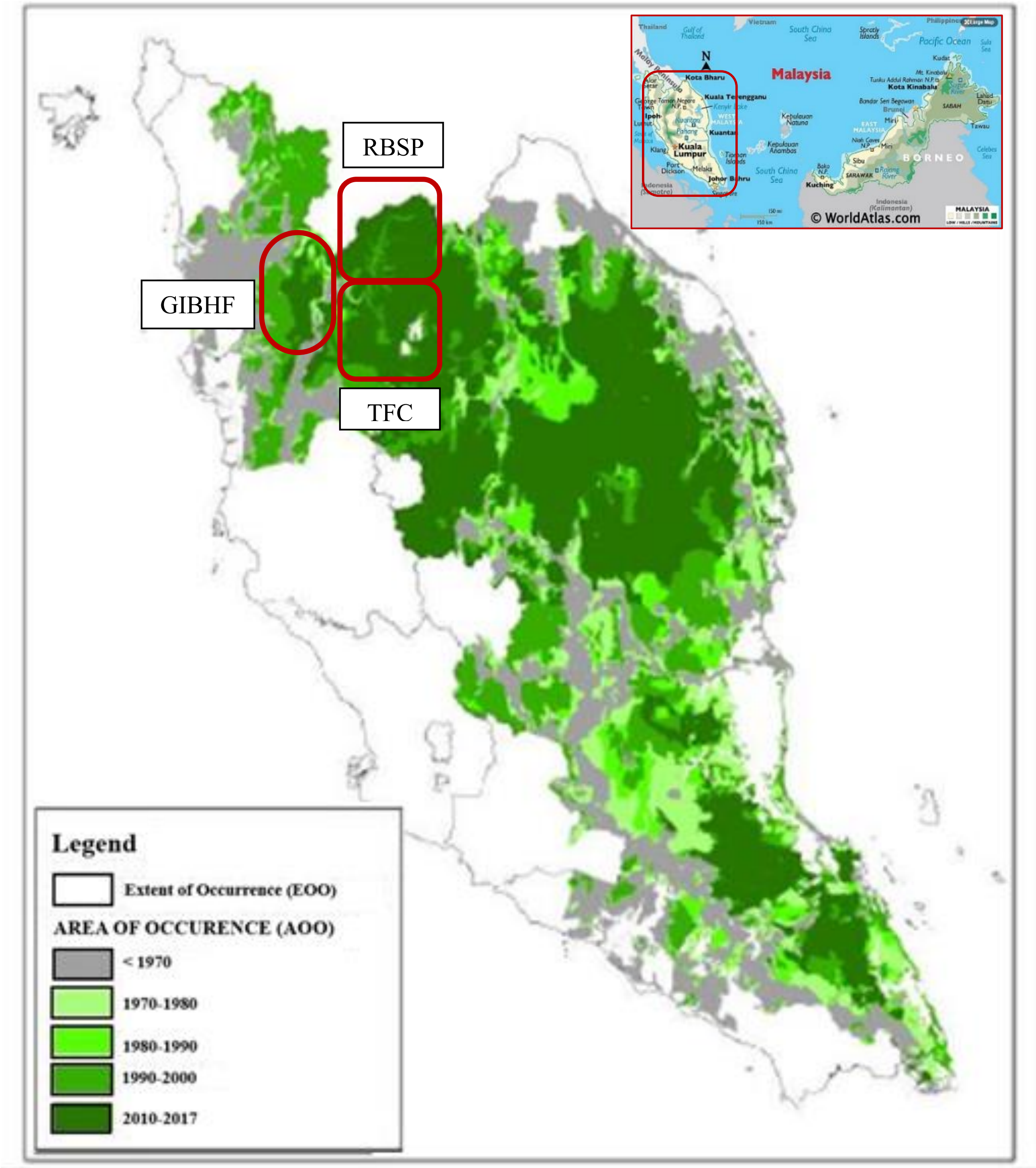


Figure 4.1 The past and present occurrence of elephant distribution in Peninsular Malaysia. The study areas (identified with the red boxes, GIBHFC- Gunung Inas-Bintang Hijau Forest Complex, RBSP-Royal Belum State Park, and TFC- Temengor Forest Complex) are located in the northern region of Peninsular Malaysia and are known to be main habitats for elephants. Map modified from the RedList of Mammals for Peninsular Malaysia 2.0 by Department of Wildlife and National Parks Peninsular Malaysia (2017).

4.2.2 Sampling design and data collection

Field sampling was conducted from September 2019 until August 2020 over a period of 11 months, with two interruptions due to the occurrence of natural events beyond my control. Fieldwork was temporarily stopped after the second trip in October 2019 due to the early arrival of the wet season and subsequent increased safety risk to the research team. The fieldwork was resumed in February 2020 when the rainy season was over, and the forest was officially reopened for research activities. Unfortunately, the arrival of the COVID-19 pandemic in Malaysia in March 2020 forced the authorities to impose a nationwide lockdown to prevent the spread of the disease, including outdoor research activities. Fieldwork was later resumed in June 2020 with special approval from the relevant authorities.

A spatial occupancy framework using an occupancy signs survey was applied in this study. The study areas (i.e., Royal Belum State Park, Temengor Forest Complex, and Gunung Inas-Bintang Hijau Forest Complex) were overlaid with grid cells of 9 km^2 (3 km x 3 km), resulting in 917 cells. Each cell is treated as a study site. This study was not intended for estimating the proportion of total area occupied by elephants; therefore, the grid size (sampling unit) is smaller than the average home range of elephants in Malaysia (~200 km^2 – 250 km^2). A smaller sampling unit was chosen considering habitat heterogeneity, as we are investigating elephants' response to ecological and anthropogenic factors. Field recce was conducted in the indigenous settlements within the study areas to assess the history of elephant presence prior to the field sampling. The accessibility into the study areas was by 4WD and foot from the roadside (Gerik-Jeli Road bisecting the study areas), a network of logging roads connecting villages located deep in the forest, as well as by boat for areas that were not accessible by vehicle. The research teams are guided by the indigenous personnel who are well- traverse in the forest environment for safety precautions.

In this study, transect replicates refer to 500 m spatial survey lines established to detect elephant presence, with each line treated as a replicate within the occupancy framework. For clarity, the terms *transect replicate*, *replicate*, and *transect* are used interchangeably throughout this thesis to refer to the 500 m survey lines described above. The sign survey was conducted using these transect replicates, with the first transect starting from a randomly selected point within each sampling site (9 km^2). Observers walked through the forested landscape by following existing elephant trails whenever such trails were visible. This approach took into account the environmental context, recognizing that elephants often share these trails with other wildlife and that not all forested areas are suitable or safe for walking. In the absence of visible elephant or wildlife trails, a new path was created to continue the survey. This was necessary under several conditions: (i) when entering a new sampling site, (ii) when accessing a newly designated site, or (iii) when avoiding physical barriers such as steep terrain or dense vegetation.

Transects were laid out in a continuous manner, with each new 500 m replicate beginning at the endpoint of the previous one, regardless of whether it remained within the same sampling site or crossed into an adjacent one. Each transect replicate was further divided into five consecutive 100 m segments, along which the presence or absence of elephant dung was recorded as binary data, '1' for detected and '0' for undetected. Recording detections at every 100 m interval was intended to ensure that no dung piles were overlooked while walking the transect. However, for the purpose of analysis, detection data were ultimately consolidated at the transect replicate level, whereby a replicate was considered as either detected ('1') or not detected ('0'), regardless of the number or location of detections along its length. This method allowed for systematic and fine-scale detection data to be collected across the landscape. Discoveries of other elephant signs, such as footprints, tusk marks, feeding marks, and rub marks on trees, were also recorded as supplementary information. Survey sites were pre-determined prior to each field trip to ensure broad spatial coverage across the three study areas.

However, not all planned sites were accessible due to unforeseen logistical constraints such as rugged terrain or safety concerns. In such instances, real-time decisions were made in the field to adjust the survey's direction while maintaining representative coverage. During each sampling trip, two research teams were deployed simultaneously to different designated sites to increase spatial coverage within a limited timeframe, across the three forest landscapes.

Transect replicates were considered independent because they were recorded on different days and initiated with random starting points and random bearings each day, an approach aligned with methods used by Sagtiasiwan (2019) to ensure data independence. For data analysis, a minimum of four transect replicates per sampling site was required; however, six to eight replicates per day were recommended to achieve better site representation (Goswami, pers. comm.). Although we aimed to follow these guidelines, various challenges were encountered during fieldwork. Consequently, not all sampling sites had an equal number of transect replicates, and the lengths of some transects varied from 100 m to the full 500 m due to various reasons (e.g., accessibility constraints, weather, timing, etc.). Figure 4.2 shows the study sites that were visited during the sampling period across the three forest complexes: Gunung Inas–Bintang Hijau Forest Complex (GIBHFC), Royal Belum State Park (RBSP), and Temengor Forest Complex (TFC).

In this study, the principles of spatially replicated surveys were followed as a foundation for the sampling design. However, due to practical field constraints including difficult terrain, limited accessibility, and unpredictable weather, modifications to the sampling protocol were occasionally unavoidable. Consequently, adjustments were made during both data collection and analysis to accommodate these challenges, while ensuring that the final dataset remained as robust and representative as possible. Every effort was made to maintain alignment with the core assumptions of the spatial occupancy modelling framework.

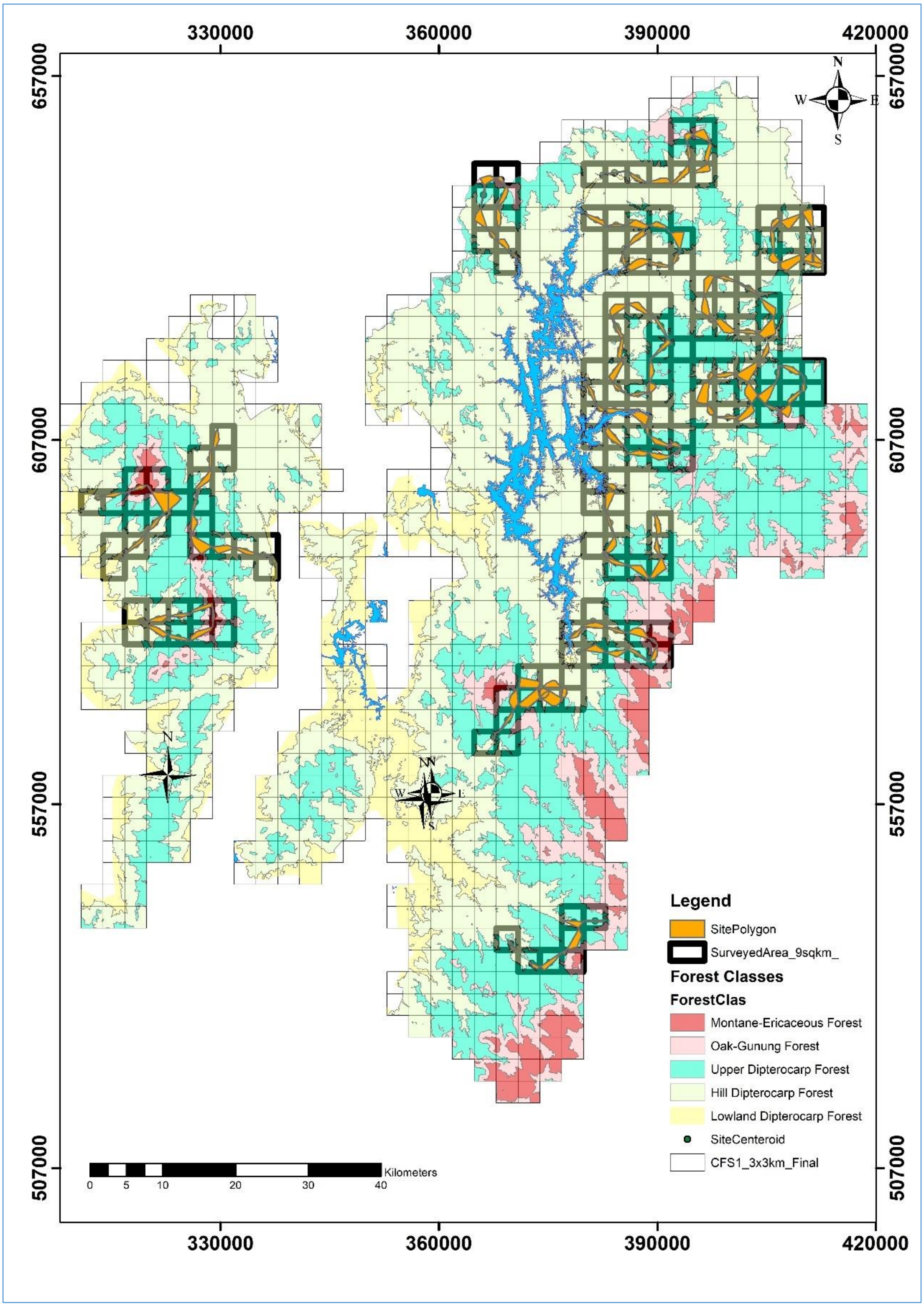


Figure 4.2 The study sites sampled were identified with black squares. Individual polygons were created to represent daily survey areas within each 9 km² study site.

4.2.3 Data analysis

4.2.3.1 Selection of site (occupancy) covariates

Site-level covariates (i.e., predictors in occupancy modes) were selected based on ecological relevance and data availability. A total of 12 site covariates were used in the analysis of elephant habitat use (Table 4.1). Some of these environmental covariates (e.g., elevation) were derived from remotely sensed data, made available by the U.S. Geological Survey (U.S. Geological Survey, n.d.); https://www.usgs.gov/tools/download-data-maps-national-map), and Google Earth Engine (GEE) (i.e., nightlights, https://earthengine.google.com) (Gorelick et al., 2017). The use of remotely sensed data is a common practice in ecological studies, as it can directly measure or serve as a proxy for factors affecting habitat suitability, hence improving the overall accuracy of the predictive models (Bradley et al., 2012).

To examine elephant distribution and habitat use, I focused on three main topographic covariates: namely, elevation (m), steepness of slope (in degrees), and Terrain Ruggedness Index (TRI) to assess their influence on elephant habitat selection. Additional covariates were included to provide a more comprehensive assessment of habitat use, incorporating both ecological and anthropogenic factors relevant to the study areas. Values for elevation, slope steepness, and TRI were derived from a Digital Elevation Model (DEM) obtained from the USGS and subsequently processed using ArcGIS 10.4 (Esri, 2023) and QGIS 3.18.3 (QGIS Development Team, 2024) software. The elevation and slope values at specific locations in the DEM raster represent the mean values of the multiple elevation points within each pixel (Mingueza, 2018). In QGIS, the (TRI) is calculated from DEM using a method developed by Riley et al. (1999). The TRI quantifies topographic heterogeneity by measuring the amount of elevation difference between a central pixel and its surrounding cells.

For the data analysis purposes, individual polygons were created to represent daily survey areas within each 9 km^2 study site (Figure 4.2). These polygons were constructed by connecting the furthest north, south, east, and west points of the transect replicates surveyed on a given day. The GPS coordinates of each were represented by the centroid of the polygon, auto-generated using the ArcGIS function of the Coordinate X, Y Averaging method, and used to represent the respective study sites. For non-surveyed sites, the coordinates of the centre point were used. It is important to note that some study sites contain more than one polygon (labelled as a, b, and c) to represent transect replicates surveyed on different days within the same site.

For covariates represented as raster layers, 50 points were randomly generated within each polygon using the ArcGIS tools, and the mean values of these points were used to represent the covariate values for each site (de la Torre, per comms.). For analysis purposes, all continuous covariates were standardised to z-scores using Microsoft Excel to facilitate the use of a numerical optimisation algorithm and prevent convergence failure during the parameter estimation (Donovan & Hines, 2007). Pearson correlation test was then used to identify collinearity between 12 continuous site (occupancy) covariates.

4.2.3.2 Selection of detection covariates

Three detection covariates were used in the initial analysis: (i) Study area (a reference site - a categorical covariate used to account for variation in detection probability across different locations), (ii) Effort (the distance walked per transect replicate), and (iii) Observation Mode (classified as a=walk, b=drive, and c=a combination of both methods). For the study area covariate, Royal Belum State Park (RBSP) was selected as the reference category in the model. This allowed detection probabilities at other study areas to be interpreted relative to RBSP. The model does not estimate a separate detection effect for the reference site (RBSP) but serves as the baseline against which other study areas are compared. The observation mode covariate was later excluded from the analysis due to persistent errors during model fitting. The software was unable to compute the values despite multiple troubleshooting attempts. All transect replicates were accounted for in the analysis, except for two specific reasons (i) any transect replicates of 100 m that were split across two adjacent study sites (i.e., located in two different grid cells), and (ii) outlier transect replicates that were shorter than 100 m (did not meet the minimum length requirement).

In this study, environmental covariates were extracted at the grid cell level (25 km^2). Each sampling site was treated as a single analytical unit in the habitat use model, even if it was visited more than once. This approach reflects the fact that the environmental variables remained constant within each grid cell and were not affected by repeated surveys. Multiple visits to the same grid cell were used to strengthen the detection data; however, the environmental variables remained constant within each grid cell across replicates, as they were derived from static spatial layers (e.g., DEM, land cover). To address the variability in effort across sites, the number of replicates and the total transect length per site were carefully accounted for in the analysis, where survey effort is known to influence detection probability. These are the criteria set in the analysis: i) each transect replicate within a sampling site was treated as a repeated detection occasion (not as a separate sampling site), ii) detection/non-detection data were recorded per replicate, and this structure was handled within a hierarchical occupancy framework using the repeated measures approach, iii) for the habitat use model, only one spatial data point per sampling site (grid cell) was used. However, where dung was recorded during repeated visits at different parts of the site (spatially apart), up to 2–3 centroids of transects were used to retrieve spatial covariates, thereby improving representation, particularly in large or heterogeneous sites. This was done cautiously and selectively.

Table 4.1 A compilation of site covariates chosen for the analysis of elephant habitat utilisation

Site covariates	Justification	Reference
Environmental factors		
Elevation	Elephants prefer the lowland due to the abundance of food and water sources, as well as energy saving.	Taher et al., 2021; Sharma et al., 2020; Bahar et al., 2018; Sagtiasiwan, 2019; de la Torre et al., 2019; Aini et al., 2015
Steepness of slope (°)	Elephants prefer a gentle slope. Due to their large body size, energy consumption increased if elephants were to climb steep hills (although at lower altitudes).	Taher et al., 2021; Sharma et al., 2020; Sagtiasiwan, 2019; de la Torre et al., 2019; Aini et al., 2015
Terrain Ruggedness Index (TRI)	Terrain ruggedness is a strong habitat use predictor. The ruggedness of the terrain may influence elephant movement in the forest.	Thapa et al., 2019; Srivathsa et al., 2014
Distance to the main river	Elephant needs a large amount of water and do not stay too far from a water source; riparian areas provide food.	Taher et al., 2021; de la Torre et al., 2021; Sagtiasiwan, 2019; Lakshminarayan et al., 2015; Aini et al., 2015
Distance to the lake	Elephants do not use large water bodies to cross, but go around them; elephants were recorded swimming across the Temengor lake.	Sukumar, 2003
Tasselled Cap Wetness	Wetness index captures important information about the vegetation (i.e., forest structure or moisture content). such as forest structure or moisture content.	de la Torre et al., 2021; de la Torre et al., 2019
Enhanced Vegetation Index (EVI)	A measure of vegetation productivity.	de la Torre et al., 2021; de la Torre et al., 2019; Sukumar, 2003
Normalised Difference Water Index (NDWI)	NDWI is known to be strongly related to the plant water content.	de la Torre et al., 2021; de la Torre et al., 2019
Anthropogenic factors		
Distance to indigenous settlement	Elephants avoid human; elephants frequent farms and plantations for food.	Sharma et al., 2020; Sagtiasiwan, 2019
Distance to main road	The impacts of linear structures on elephant habitat use.	de la Torre et al., 2021; Wadey, 2020; Sharma et al., 2020; Sagtiasiwan, 2019; de la Torre et al., 2019; Abrams et al., 2018
Distance to plantations or monocultures edge	Elephants frequent plantations for food.	de la Torre et al., 2021; de la Torre et al., 2019; Sukumar, 2003
Nightlights	Indicative of human perturbation across the landscape.	de la Torre et al., 2021; de la Torre et al., 2019

4.2.3.3 Occupancy modelling

Habitat occupancy of elephants in study areas was analysed using detection/non-detection data i) to estimate the probability of detection (p) and ii) to estimate the probability of occurrence (ψ). The challenges of imperfect detections and spatial autocorrelations of the survey design were considered in the analysis. The sampling site (i.e., a grid cell represents a sampling site) is treated as a data point (instead of transect replicates) in the analysis, as applied by Jathanna et al. (2015a) and Lakshminarayanan et al. (2015). The use of transect replicates as individual data points was initially considered, as reflected in the original study design, to capture fine-scale spatial variation. However, this level of detail was deemed unnecessary for predictive mapping of wide-ranging megafauna such as elephants, whose large home ranges (~200–250 km^2) render short distances (100–500 m) relatively insignificant (Tan, per. comms.). While transect-level data are valuable for field surveys, occupancy modelling and habitat prediction are more appropriately conducted at the scale of sampling sites (i.e., grid cells), which better reflect the spatial ecology of large-ranging species, such as elephants**.** Therefore, the sampling site is used as a data point, and this habitat use analysis incorporates spatial autocorrelation based on the coordinates of the sites.

The occupancy modelling was conducted in two phases to investigate the relationship between elephant habitat use and environmental variables (natural and anthropogenic variables). Ecological studies of mammals' habitat use usually examine the linear and quadratic relationship between the species and its environmental variables. Both linear and non-linear components could play very important roles in a species' habitat use selection. In this study, there is a theoretical reason (based on ecological and biological knowledge of elephants' behaviour and habitat use) to believe that elephant relationships in their habitat may involve linear (First-order term) and or quadratic (Second-order term) relationships. Thus, both linear and quadratic relationships were tested in the global model (Appendix IV). Quadratic relationships were tested for each variable because the habitat use may be high or low at the extreme values of the explanatory variable (i.e., U- or N-shaped curves, respectively). Although the inclusion of higher-order (quadratic) relationships may have some implications, such as contributing to a too complex model without clear ecological justification, which makes it more challenging to interpret in realistic conservation contexts. However, the environmental variables that exhibit significant quadratic patterns have been chosen for the subsequent phase of analysis. Next, multivariate modelling with and without spatial autocorrelation was conducted to get the top model with significant variables. Explanations of these analyses are described as follows:

i. Multivariate modelling without spatial autocorrelation

The multivariate occupancy modelling without autocorrelation was conducted using the single-species, single-season habitat use models in the R package 'unmarked' version 1.1.1 (Fiske and Chandler, 2011) in R version 4.1.2 (R Core Team, 2019). The 'unmarked package' allows researchers to systematically build and compare models with different subsets of predictors (covariates). It fits hierarchical models of animal occurrence and abundance to data collected on species to account for imperfect detections (Fiske and Chandler 2011). The detection probability (p) was modelled by allowing the habitat use parameter to remain constant (~1~1) or to vary with individual or additively combined detection covariates (Tan et al., 2016). The significant contributing detection covariates (i.e., study area and efforts) were retained and used to model habitat use probability with site covariates (Tan et al., 2016).

Global model construction was subsequently produced to incorporate all predictor variables (covariates) that might influence both occupancy probability and detection probabilities of elephant habitat use. Maximum Likelihood Estimation (MLE) was used in the model fitting that involved estimating the parameters of these processes to best match the observed data. The goodness-of-fit of the full model (global model) was assessed to evaluate

1) the plausibility of the model being correct (p>0.05); and 2) on how adequately the model described the observed data, determined by an over-dispersion statistic.

ii. Multivariate modelling with spatial autocorrelation

In the second phase of the analysis, the R package "stocc" version 1.31 (Johnson, 2021) was used in R4.1.3 (R Core Team, 2019) to account for spatial autocorrelation in the model. The package stocc stands for Fit a Spatial Occupancy Model via Gibbs Sampling. The posterior predictive loss criterion (Johnson et al., 2013) was used for model selection between the model without spatial autocorrelation parameter (best model from the first phase of analysis-multivariate modelling without autocorrelation) and the model with spatial autocorrelation parameters.

Both models (the model with and without an autocorrelation parameter) were fitted using a probit link instead of the logit link as it increases computational efficiency and flexibility through a data augmentation approach (Johnson et al., 2013; Tan et al., 2016). The spatial autocorrelation parameter was specified using the restricted spatial regression model (RSR), threshold=8.45 (based on the elephant home range size of 200 km^2 and 250 km^2), and moran.cut of 193 (0.1*number of study sites). The spatial random effects are constrained to be orthogonal to the fixed effects (Tan et al., 2016) in the RSR regression model, and it usually improves spatial confounding and yields a more precise estimate of the regression coefficient (Hanks et al., 2015). For each of the Bayesian models, the Gibbs sampler was run for 40,000 iterations following a burn-in of 10,000 iterations and a thinning rate of 5. In this model, the fixed effects refer to the explanatory covariates used to predict elephant habitat use. These covariates are specified as fixed effects because they are treated as constant across the study area and directly contribute to explaining variation in elephant detection probability or occupancy.

4.2.3.4 Habitat predictive mapping

The final occupancy analysis recognised the model without spatial autocorrelation to be more reliable compared to the top model that accounted for spatial autocorrelation (Table 4.5). Therefore, the prediction map (distribution model) of elephant occurrence in study areas (i.e., GIBHFC, RBSP, and TFC) was based on the top model of the combination of three site covariates (i.e., elevation (Elev), distance to plantations (Dist_Plant) and distance to settlements (Dist_Sett)).

4.3 RESULTS

4.3.1 Field results

A total of 168 (18.3%) sites (grid cells of 9 km^2) across these study areas were visited between September 2019 and August 2020. A total of 53 (31.5%) out of 168 visited sampling sites (grid cells) have recorded dung, with a total of 645 dung detections (Table 4.2). Some study sites were visited more than once, but the transects were spatially apart; therefore, a total of 193 locations were used in the analysis. The survey effort invested was 74 days, with a total of 154.9 km distance covered, and 645 detections of elephant dung were recorded. The number of replicates per site ranged from one replicate to 13 replicates. The total length of replicates per site ranged from 0.1 km to 5.8 km, regardless of whether there were detections or no detections of elephant dung.

During general observation made during the field sampling for elephant signs, such as dung, rubbing marks on trees, feeding sites, and footprints, I noticed that more signs were detected in RBSP and TFC compared to GIBHFC. The number of dung detections for each study area shows that the highest detection was recorded in TFC (360 detections), followed by RBSP (250 detections), and GIBHFC (35 detections) (Table 4.2). Although the analysis only takes into account the detection of elephant dung, it is worth noting that elephant footprints were observed in the high elevation area (~1800 m) whilst, in some areas, no signs of elephants were recorded at lowland dipterocarp forest even though the location seems to provide good habitat requirement for elephants (Or, per comms). This also refers to areas where local communities (indigenous and non-indigenous people) in the surrounding area claimed that elephants have no longer lived in the area for the past 10-20 years. The cause of this situation is unclear to them, however, in the Gunung Inas-Bintang Hijau Forest Complex (GIBHFC), there have been reports suggesting that elephants were relocated from the area owing to conflicts between humans and elephants (locals, per comms.).

Table 4.2 The detections of elephant dung across three study areas and the visited coverage of each study area.

Study areas	Total size (km^2)	Number of grid cells (study site)	Number of Sites visited	Percentage	Records of elephant dung
RBSP	1683	187	53	28.3 %	250
TFC	4608	512	82	16 %	360
GIBHFC	1962	218	33	15.1 %	35
Total	8253	917	168	18.3%	645

4.3.2 Selection of site and detection covariates

The result of the site covariate Pearson's correlation test indicates that there are covariates that were moderately correlated (Table 4.3), following the strength and significance of a correlation described by Fowler and Cohen (1995). Pairs of covariates were considered strongly correlated when $r > 0.7$, and a modest correlation was defined as $r = 0.40$ to 0.69 (Fowler and Cohen, 1995). 'Distance to roads' is moderately correlated to 'Distance to plantations' ($r = 0.641$), whilst 'Distance to settlements' is moderately correlated to 'Distance to lake' ($r = 0.594$). Although these four variables are modestly correlated, I decided not to remove any of them as they (i.e., 'distance to road' and 'distance to plantation'; 'distance to lake' and 'distance to settlements') are biologically sensible for the study areas and for the elephants.

Table 4.3 Correlation matrix of the continuous site covariates for study areas. Site covariates tested were: elevation (Elev), slope steepness (Slop), Tasseled-cap wetness index (Wet), Enhanced Vegetation Index (Evi), Normalized Difference Water Index (NDWI), Terrain Ruggedness Index (TRI), nightlights (NL), distance to plantations (DistPlant), distance to road (DistRoad), distance to lake (DistLake), distance to river (with buffer of 500m) (DistRiv), and distance to indigenous settlements (DistSett).

	Elev	Slop	Wet	Evi	NDWI	TRI	NL	DistPlant	DistRoad	DistLake	DistRiv	DistSett
Elev	1	0.338	-0.436	0.009	-0.014	0.127	-0.115	0.124	0.089	0.333	0.377	0.134
Slop	0.338	1	-0.39	-0.003	0.284	-0.03	-0.084	-0.011	0.078	0.213	0.068	0.335
Wet	-0.436	-0.39	1	-0.046	-0.335	-0.088	0.194	-0.096	-0.049	-0.354	-0.134	-0.564
Evi	0.009	-0.003	-0.046	1	0.098	0.016	0.09	0.04	-0.036	-0.054	0.026	-0.077
NDWI	-0.014	0.284	-0.335	0.098	1	-0.074	-0.141	0.06	0.065	-0.126	0.081	0.074
TRI	0.127	-0.03	-0.088	0.016	-0.074	1	-0.06	-0.067	-0.022	0.061	0.135	0.046
NL	-0.115	-0.084	0.194	0.09	-0.141	-0.06	1	-0.259	-0.236	-0.092	0.02	-0.044
DistPlant	0.124	-0.011	-0.096	0.04	0.06	-0.067	-0.259	1	0.641	-0.042	0.347	-0.097
DistRoad	0.089	0.078	-0.049	-0.036	0.065	-0.022	-0.236	0.641	1	-0.354	0.293	-0.16
DistLake	0.333	0.213	-0.354	-0.054	-0.126	0.061	-0.092	-0.042	-0.354	1	-0.153	0.594
DistRiv	0.377	0.068	-0.134	0.026	0.081	0.135	0.02	0.347	0.293	-0.153	1	-0.139
DistSett	0.134	0.335	-0.564	-0.077	0.074	0.046	-0.044	-0.097	-0.16	0.594	-0.139	1

4.3.3 Elephant habitat use and its relationship to habitat variables

Naïve occupancy recorded for elephant habitat use based on the 193 sites is 0.725 (72.5%). Naïve occupancy refers to the proportion of surveyed sites where elephant signs were detected, without accounting for imperfect detection or detection probability. It provides a basic estimate of habitat use but may over- or under-estimate true occupancy if detection is less than perfect.

The global occupancy model incorporating all 12 site covariates (Table 4.4) and two site covariates with quadratic terms (i.e., I(DistPlant^2) and I(DistSett^2)), and detection covariates shows that four site covariates namely Elevation (Elev), Terrain Ruggedness Index (TRI), Distance to Plantation (DistPlant), and Distance to Settlements (DistSett) both in linear and quadratic terms were statistically significant (*p<0.05*) (Table 4.4). Distance to Settlements shows a negative correlation in a quadratic manner. Three site covariates (i.e., Elev, DistPlant, and TRI) were negatively correlated with the probability of occupancy. It is worth noting that two other site covariates, namely Tasseled-cap wetness index (Wet) ($p=0.0843$), and Normalized Difference Water Index (NDWI) ($p=0.0539$), were marginally not significant. For the probability of detection, all detection covariates (i.e., site_tfc, site_gibh, and EFF) were statistically significant ($p<0.05$) and positively correlated with the elephant habitat use.

Table 4.4 Global Model incorporating selected site covariates (linear and quadratic terms) and detection covariates.

Occupancy (logit-scale):				
	Estimate	SE	z	P(>|z|)
(Intercept)	11.1683	3.617	3.0877	0.00202
Elev	-2.6749	1.076	-2.485	0.01295
Slop	0.1366	0.604	0.2263	0.82094
Wet	-1.4953	0.866	-1.7265	0.08426
Evi	-0.0438	0.454	-0.0965	0.92309
NDWI	-1.289	0.669	-1.9274	0.05393
TRI	-2.7391	1.02	-2.6841	0.00727
NL	-0.4475	0.395	-1.1316	0.25778
DistPlant	-2.9244	1.112	-2.6301	0.00854
I(DistPlant^2)	1.5658	1.265	1.238	0.2157
DistRoad	0.8834	0.769	1.1489	0.25061
DistLake	-0.0643	0.957	-0.0672	0.94642
DistRiv	-0.7302	0.948	-0.7705	0.44098
DistSett	9.0733	3.493	2.5973	0.0094
I(DistSett^2)	-7.777	2.602	-2.989	0.0028
Detection (logit-scale):				
	Estimate	SE	z	P(>|z|)
(Intercept)	-0.5512	0.266297	-2.07	3.85E-02
site_tfc	0.57319	0.153848	3.73	1.95E-04
site_gibh	-1.38986	0.236143	-5.89	3.96E-09
EFF	0.00249	0.000576	4.33	1.48E-05

4.3.4 Spatial autocorrelation data analysis

Analysis to account for spatial autocorrelation was conducted using two methods to confirm the differences in accounting for spatial autocorrelation in the data analysis. Based on stocc analysis, the 95% Highest Posterior Density (HPD) estimate for both top models with and without spatial autocorrelation indicated that the model is better fitted without spatial autocorrelation (Table 4.5). The variance parameter for the spatial model (tau) tested showed that the model without spatial autocorrelation (CI 95%, tau=1) is better than the model with spatial autocorrelation. The top model without spatial autocorrelation shows that elephant habitat occupancy is negatively affected by 'elevation' (-1.3879; 95% HPD -2.5555 to -0.2202) and 'distance to plantation' (-0.4786; 95% HPD -0.9093 to -0.04793). Elephant habitat use is positively affected by 'distance to settlement' (dist_sett) in linear manner (9.8777; 95% HPD 3.0807, 16.6747) and negatively affected in a quadratic manner (-11.1025; 95% HPD -18.1330, -4.0719) (Table 4.5). For the detection probabilities, both covariates, i) study sites (i.e., site_gibh, site_tfc, and RBSP (Intercept)) and ii) Effort (EFF), played important roles. Site_gibh (-0.8537) shows a relatively lower detection probability compared to RBSP (Intercept) (-0.2374), whilst the detection probability at site_tfc (0.3153) is significantly higher than RBSP (Table 4.5). For the effort (EFF), the detection probability is likely to increase with an increase in survey effort.

The final occupancy analysis of the top model without spatial autocorrelation based on the stocc results shows that elevation (Mean: -1.2025, SD: 0.7062) and distance to plantations (Mean: -0.4899, SD: 0.2232) are negatively correlated to elephant habitat use. Distance to settlement (dist_sett) is positively correlated to the elephant habitat use in a linear manner (Mean: 8.6019, SD: 4.0906) and negatively correlated in a quadratic manner (Mean: -9.6021; SD: 4.1959), a U-shaped relationship (Table 4.6). For the detection covariates, all study areas (i.e., intercept (site_RBSP), site_gibh, and site_tfc) and sampling effort (EFF) show a positive correlation to elephant habitat use (Table 4.6).

As both stocc and occupancy analysis have independently shown that the best models are models without spatial autocorrelation, therefore, it is confirmed that the modelling of the elephant occupancy is better performed without spatial autocorrelation. Hence, the prediction map and results discussed in this study will be based on the model without spatial autocorrelation.

Table 4.5 The 95% Highest Posterior Density (HPD) based on significant covariates in top models for both without spatial autocorrelation and with spatial autocorrelation. Site and detection covariates tested were: elev (Elevation), dist_plant (Distance to plantation), tri (Terrain Ruggedness Index), dist_sett^2 (Distance to settlements in quadratic term), site_gibh (Gunung Inas Bintang Hijau Forest Complex), site_tfc (Temengor Forest Complex), and EFF (effort).

Without spatial autocorrelation				With spatial autocorrelation			
The occupancy detection model				The occupancy detection model			
	Mean	SD	95% HPD*		Mean	SD	95% HPD*
(Intercept)	2.0305	9.3962	(0.7049, 3.3562)	(Intercept)	4.1014	23.1063	(0.8415, 7.3613)
elev	-1.3879	8.2762	(-2.5555, -0.2202)	dist_plant	-0.9686	9.4337	(-2.2995, 0.3624)
dist_plant	-0.4786	3.0527	(-0.9093, -0.04793)	tri	-0.4831	5.4661	(-1.25424=, 0.2881)
dist_sett	9.8777	48.1770	(3.0807, 16.6747)	dist_sett	11.0295	60.8895	(2.4389, 19.6200)
dist_sett.2	-11.1025	49.8322	(-18.1330, -4.0719)	dist_sett.2	13.3085	71.5520	(-23.4033, -3.2137)
The detection model parameters				The detection model parameters.			
	Mean	SD	95% HPD*		Mean	SD	95% HPD*
(Intercept)	-0.2374	2.3104	(-0.5634, 0.0886)	(Intercept)	-0.1958	2.2422	(-0.5121, 0.1206)
site_gibh	-0.8537	2.5256	(-1.2100, -0.4973)	site_gibh	-0.6889	2.1290	(-0.9893, -0.3885)
site_tfc	0.3153	1.2799	(0.1348, 0.4959)	site_tfc	0.2525	1.2865	(0.0710; 0.4341)
EFF	0.0013	0.0048	(0.0006, 0.0020)	EFF	0.0013	0.0047	(0.0007, 0.0020)
The variance parameter for the spatial model				The variance parameter for the spatial model			
	Mean	SD			Mean	SD	
tau	1	0		tau	0.0346	9.26E-02	

*Highest Posterior Density (HPD)

Table 4.6 The occupancy analysis without autocorrelation for prediction mapping of elephant habitat use in all study areas.

	Mean	SD
Site covariates		
(Intercept)	1.7367	0.8227
elev	-1.2025	0.7062
dist_plant	-0.4899	0.2232
dist_sett	8.6019	4.0906
dist_sett.2	-9.6021	4.1959
Detection covariates	Mean	SD
(Intercept)	-0.2323	0.1668
site_gibh	-0.8568	0.1843
site_tfc	0.3102	0.0937
EFF	0.0014	0.0003

4.3.5 Predictive mapping of suitable habitat for elephants across the study areas

The predictive mapping produced based on the probability of habitat use (occupancy values ranging from 0 to 1 (most suitable; presented as green colour) shows an interesting pattern of elephant habitat use in all three study areas (Figure 4.3). The map is produced based on three significant site covariates (i.e., elevation, distance to settlement, and distance to plantations) in the top model. The predictive map shows that almost all sites in Royal Belum State Park (RBSP) are suitable for elephants, except for some area that borders Thailand. Within the Temengor Forest Complex (TFC), the likelihood of elephants utilising their habitat varies from low to moderate to high, with values ranging from more than 0 to 1. Certain areas within the TFC, particularly in the southern portion, have noticeably lower occupancy levels (~<0.6). For the Gunung Inas-Bintang Hijau Forest Complex (GIBHFC), the predictive map shows that the Gunung Inas Forest Reserve has the lowest (~0) probability of habitat use by elephants, compared to the rest of the complex (i.e., Bintang Hijau (Larut Matang) and Bintang Hijau (Hulu Perak) Forest Reserves) that seems to be highly suitable habitat for elephants (Figure

4.3). Figure 4.4 (a, b, and c) provides a reference map that displays the study areas with various variables.

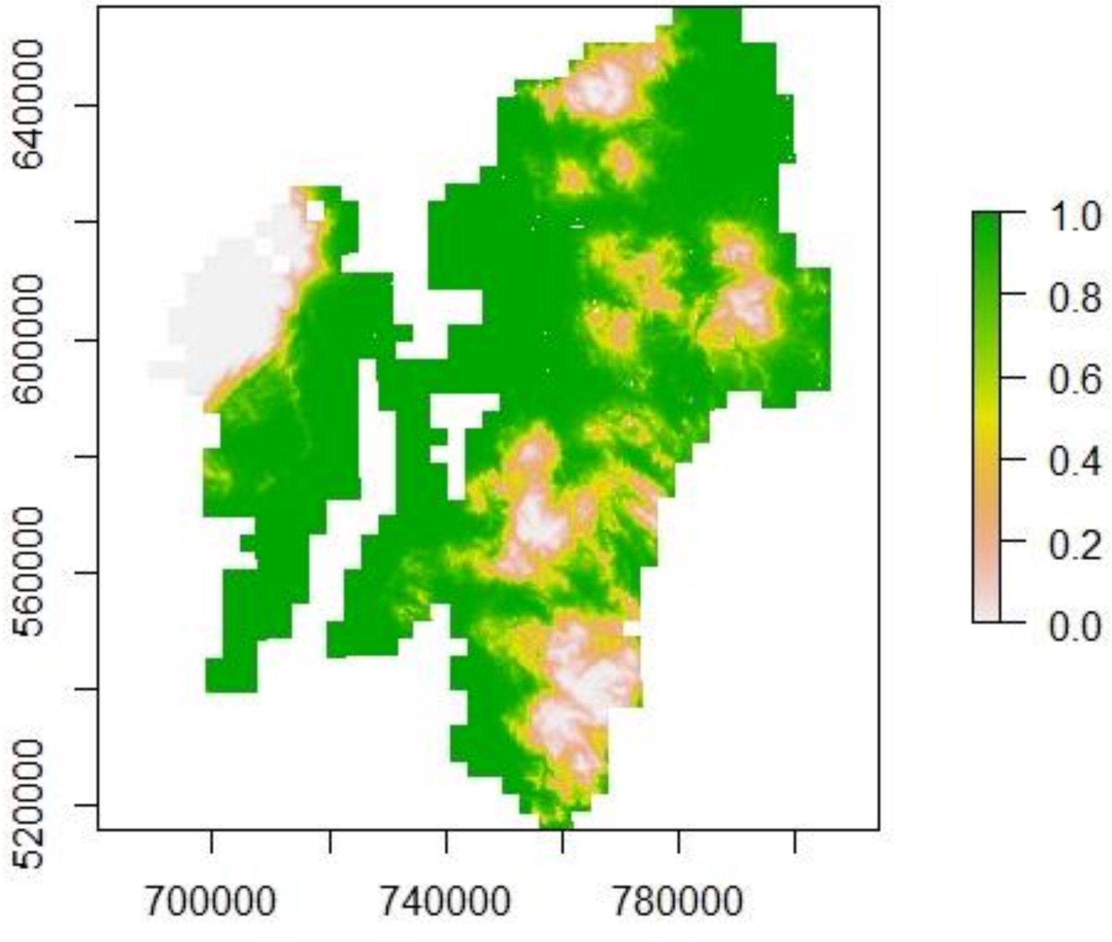
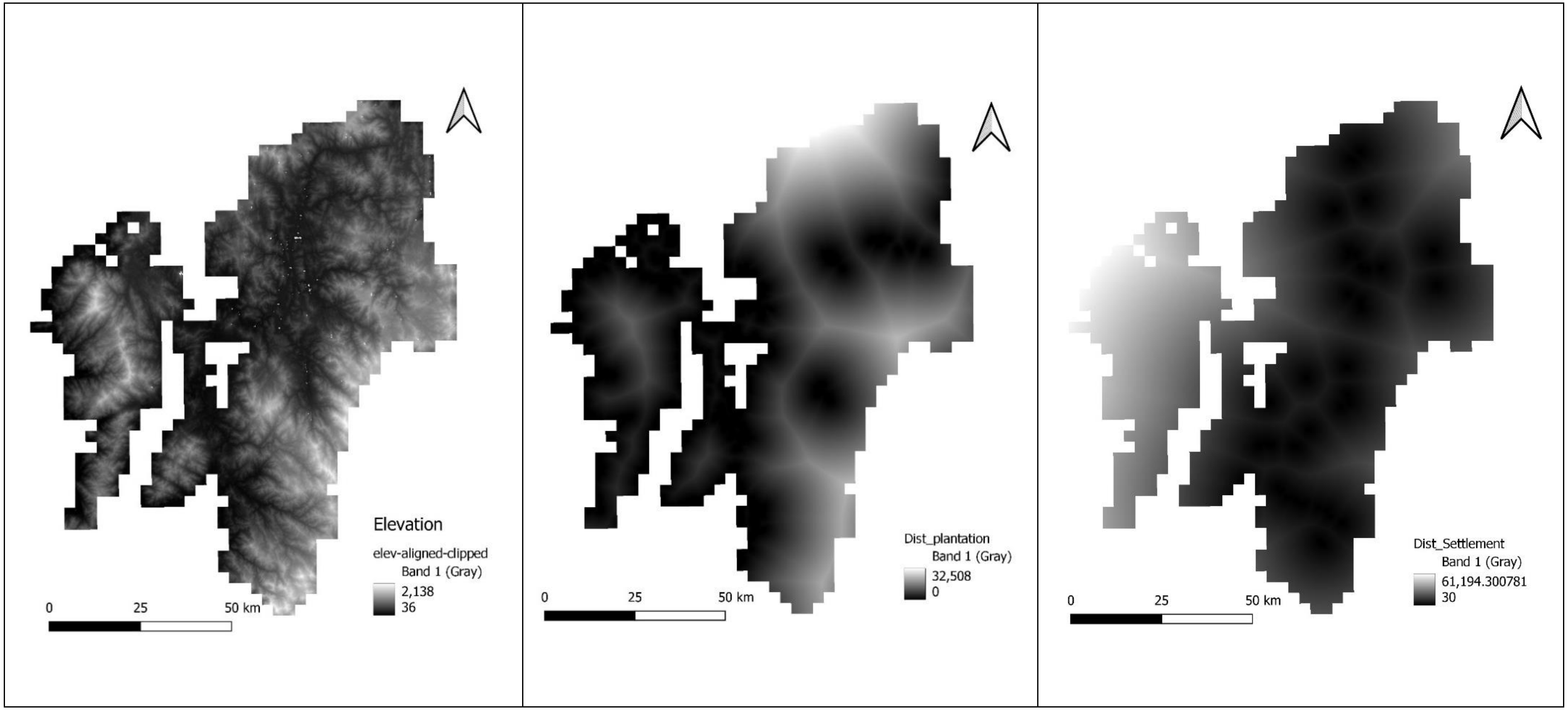


Figure 4.3 A predictive map of elephant habitat use was generated for three study areas, with the value of probability of habitat use ranging from 0 to 1. A value of 0 suggests that elephants are unlikely to utilise the habitat. In contrast, a value of 1 indicates a high likelihood that elephants will use the region, making it a suitable habitat for them.



a. Elevation b. Distance to plantations c. Distance to settlements

Figure 4.4. A reference map is provided for each significant site covariate, including a) elevation, m a.s.l., b) distance to plantation, m, and c) distance to indigenous settlement, m.

4.4 DISCUSSION AND CONCLUSION

Habitat utilization of Asian elephants in tropical rainforests is influenced by various natural and anthropogenic factors, particularly the availability of food resources, water supplies, shelter, mating opportunities, and the presence of humans in the same landscape (Williams et al., 2020; Lim et al., 2017; Sukumar, 2003). The challenge of accurately identifying specific elephant habitats throughout the Peninsular region has resulted in the simplification of designating all forested areas across Central Forest Spine as acceptable elephant habitats (Managed Elephant Ranges), based on historical knowledge. The results of this study provide vital insights into how elephants use the three main landscapes in the northern Peninsular, which include both natural and altered environments.

Findings from this study show that elephant habitat use in Royal Belum State Park (RBSP), Temengor Forest Complex (TFC) and Gunung Inas-Bintang Hijau Forest Complex (GIBHFC) are influenced by the combination of three factors namely i) elevation, ii) distance to plantations that are situated around the forest complexes, and iii) the distance to the Indigenous settlements that are located within the study areas. The influence of these individual factors is discussed in the following subheadings.

4.4.1 The effect of elevation on elephant distribution (habitat use)

The effect of higher elevation on elephant habitat use has been demonstrated in this study, suggesting that elephants may have limited use of high-elevation locations, despite these areas being known to be their natural habitat. All three study areas were previously thought to be core habitats for elephants (Khan, 2012; Department of Wildlife and National Parks Peninsular Malaysia, 2013), and high-elevation areas are usually recorded at the forest ridge and either located at the centre of the study areas or on the perimeter of the forest complexes. The findings highlighted that the habitat use of elephants in northern Peninsular Malaysia is similar to the habitat usage reported by other researchers. Elephants have been reported to avoid high-elevation areas based on the theory of food intake and energy consumption due to their large body mass (Wall et al., 2006). A study by de la Torre et al. (2019) based on the movements of 54 GPS-collared elephants in Peninsular Malaysia, including some of the study areas, indicated that elevation plays an important part in defining elephant distribution, in which elephants do prefer lowland areas. Aini et al. (2015) reported that elephant distribution in the forest is up to 1055 m asl, based on two GPS-collared elephants. In Peninsular Malaysia, this is a reasonable explanation for elephants, as the largest terrestrial mammals, which require 150 kg of food per day to sustain their body mass while foraging in the undulating terrain of our rainforest. Rainforest formations that developed over altitudinal changes are found in Peninsular Malaysia, where different forest vegetation types are found in specific altitudinal zones (Saw, 2010). Observations made in the mountainous area during sampling confirmed that the vegetation at the top of the mountain (> 1,200 m asl) may not provide the necessary habitat (in terms of food, shelter, and water) for the elephants. Thus, it is essential to acknowledge that the mountainous area of tropical rainforest provides few food supplies for elephants to fulfil their daily needs, compared to the lower elevation areas where vegetation suitable for elephants can be found in abundance (Alfred et al., 2012).

Besides limited food sources, lack of water on the mountain could be another leading factor for elephants to forage at lower elevation areas. Signs of elephants were easily found in areas with water sources such as rivers, streams, and the swampy areas (Or, per obs.). One interesting note, we observed only one elephant footprint in the mountainous area during the sampling period (at the Bintang Hijau Forest Complex, at an elevation of 1800 m a.s.l.). This observation is interesting because it highlights the rarity of elephant presence at higher elevations within the study area. The Bintang Hijau Forest Complex, located at around 1.800

m a.s.l., represents one of the highest altitudinal zones in the landscape. The detection of only a single elephant footprint at this elevation suggests that elephants may actively avoid or infrequently use these mountainous areas, possibly due to factors such as lower food availability, steeper terrain, or limited access to water sources. Additionally, it is possible that this area falls outside the core range of the local elephant population, indicating a genuine lack of elephant distribution rather than temporary avoidance. This finding, when considered alongside the more frequent signs in lowland areas, supports the broader ecological pattern that elephants tend to prefer lower elevations with more favourable foraging and movement conditions.

Another reason that could discourage elephants from using higher elevation areas is the limited availability of shelter and a suitable place to rest, especially in mountainous area. The unique morphology of the mountain vegetation means there is a lack of vegetation that can provide good shelter for elephants, especially from the heat of the sun, or any natural elements that may harm them. In Borneo, Asian elephants prefer to live in lowland forests with open areas to feed (e.g., higher food source compared to primary forest), and find secluded areas to rest, a flat or gently sloped ground up to 300-400 m of elevation, and in proximity to water sources (Alfred et al., 2010; Alfred et al., 2012). The forested area at a lower altitude in Peninsular Malaysia may offer a more suitable environment for elephants to meet their survival needs.

Furthermore, it is worth noting that the two biophysical parameters, slope steepness (Slope) and terrain roughness index (TRI), did not show statistically significant influence on elephant habitat utilization in this study. This finding contrasts with the results of Mingueza (2018) in Borneo, which indicated that elephants generally prefer slopes with inclinations up to 7.5 degrees. One possible explanation for these differences is that elephants in the study areas may not be as strongly constrained by slope or terrain ruggedness, or that other environmental factors such as elevation, water availability, or anthropogenic disturbance may play a more dominant role in shaping habitat use.

It is also important to consider that elevation, which was found to be a significant predictor, can act as a broader ecological surrogate, encompassing several gradients including terrain, vegetation type, and climate. Given the potential intercorrelation among slope, TRI, and elevation, it is possible that their individual effects are masked when modelled separately. A dimensionality reduction approach, such as Principal Component Analysis (PCA), could be employed in future studies to integrate these variables into a single synthetic terrain metric, thereby capturing the combined effect of terrain complexity while minimizing collinearity (Lin et al, 2008). Although such analysis was beyond the scope of this thesis, it offers a promising direction for further investigation and future publication.

4.4.2 The utilization of elephant habitats in proximity to human settlements

Royal Belum State Park (RBSP) and Temengor Forest Complex (TFC) are home to thousands of indigenous people who have shared the forest landscape with wildlife, including elephants, for centuries. The current locations of these settlements are primarily the result of a national resettlement initiative launched by the government in the late 1970s (Ronzi et al., 2018; Lim et al., 2017). This study offers a fascinating perspective on the cohabitation of elephants and indigenous tribes within the same landscape (i.e., RBSP and TFC), a subject that remains poorly understood in Malaysia. In the occupancy model, distance to settlement (dist_sett) exhibited both a positive linear coefficient (Mean: 8.6019; SD: 4.0906) and a negative quadratic coefficient (Mean: -9.6021; SD: 4.1959), indicating a U-shaped relationship between elephant habitat use and distance from settlements. This suggests that elephant habitat use initially declines with increasing distance from settlements (i.e., elephants use areas near settlements more), reaches a minimum point at intermediate distances, and then increases again at greater distances from settlements (as the positive linear effect overtakes the negative quadratic curvature).

This pattern may reflect the complex behaviour of elephants in response to human presence, where they may balance risk and resource availability by selecting areas that optimize safety and access to resources. One possible explanation for the higher habitat use near settlements is the availability of cultivated crops such as bananas, tapioca, and fruit trees (e.g., jackfruit, durian, rambutan, *dokong*, etc.), which are also key food sources planted by the indigenous communities for their own sustenance (Azrina et al., 2010; Lim et al., 2017). However, at intermediate distances, habitat use may decline due to increased human activity (e.g., logging, lack of food) or degraded habitat. In contrast, elephants appear to reoccupy areas further away from settlements, which may be attributed to higher habitat quality and reduced human disturbance. The relationship between humans and elephants in these two study areas is discussed in greater detail in the following paragraphs.

The indigenous people's way of life involves planting crops that can provide food for their families, alongside other daily activities such as collecting non-timber forest products, hunting wild animals, and fishing for food (Azrina et al., 2010; Lim et al., 2017). Some villagers have small plots of rubber trees that provide a steady income for their families. Over time, elephants may develop crop-raiding behaviour as they come to associate human settlements with easy foraging opportunities (Wong, per comms.), especially since many of the crops grown by local communities are also highly favoured by elephants, even if they are not naturally found in the forest. The repeated visits by elephants to villages for food (Department of Wildlife and National Parks Peninsular Malaysia, 2021a; Azrina et al., 2010) suggest that they have learned to associate settlements with reliable food sources. For instance, during the fruiting season, elephants are known to enter settlement areas in search of fruits such as durian, chempedak, jackfruit, and *dokong*. They often remain in close proximity to these villages for an extended period of time (Chairman of JPKKOA RPS Kemar - Kamel, per. comms). In some cases, the indigenous communities find themselves competing with elephants to protect their crops and harvest fruits for sale. These encounters can result in injuries or psychological stress for both humans and elephants (Or, per. obs.). In the present study, the sampling areas appeared to offer ample natural food sources for elephants, but this factor was not directly examined in the analysis.

Forest management practices could be another factor influencing elephant habitat use in response to human settlements. The Temengor Forest Complex (TFC) comprises several forest reserves, some of which are designated for timber production. Within this complex, a network of logging roads, ongoing logging activities, and areas previously logged as part of a rotational logging cycle are present. Some of these areas are in close proximity to indigenous settlements, which may indirectly expose settlements (and their crops) to elephant activity, while also altering natural elephant habitats in the vicinity. A study by de la Torre (2021a) found that elephant movements were more likely in areas of disturbed vegetation such as regrowth, secondary forest, and forest gaps. These vegetation types are commonly found in actively logged forests like the Temengor Forest Complex (TFC). In contrast, no logging activities occur in Royal Belum State Park (RBSP). However, the expansion of indigenous settlements driven by population growth, internal community dynamics, or the depletion of local food sources has been observed in both TFC and RBSP (Department of Wildlife and National Parks Peninsular Malaysia, 2021a; Lim et al., 2017). These practices may further increase the human-elephant encounters, as elephants continue to forage through the broader forest landscape.

On the other hand, the quadratic relationship suggests that the distribution of elephants in the forest is not affected by their proximity to indigenous populations. This is because these vast landscapes still offer an ample supply of high-quality food and other necessary resources for the elephants' survival (Department of Wildlife and National Parks Peninsular Malaysia, 2013). Even if elephants enter human settlement areas for food, they would retreat to their preferred habitat for relaxation and socializing once they have finished eating the crops. In TFC and RBSP, visiting elephants will be driven away by villagers to safeguard their crops by creating loud noises, using fire, and setting off firecrackers. The recurrence of these behaviours may indirectly account for the presence of elephants in locations that are more distant from the settlement areas.

Given the insights into how elephant habitat use is influenced by the distance to settlement, it is crucial for the conservation effort for elephants in TFC and RBSP to incorporate human-elephant conflict (HEC) mitigation measures that could promote a win-win situation for the indigenous communities and the elephants who continue to share the same landscape. The government's effort to encourage coexistence with elephants requires a comprehensive plan that can guarantee the communities do not perceive the presence of elephants as a threat.

4.4.3 The correlation between elephant habitat utilization and proximity to plantations

Elephant crop depredation is not uncommon in Peninsular Malaysia, where elephants encroach into plantations such as oil palm and rubber plantations in search of food (de la Torre et al., 2021a; Khan, 2012). In recent years, many such incidents have occurred, especially when the locations of these plantations are at the forest edge or near the elephant's natural habitat. This could explain why the occurrence of elephants is higher in areas closer to plantations. Elephants stay close to plantation areas as they feed on the crops (e.g., the young shoots of palm oil trees and the bark of rubber trees), but return to the forest for shelter (Khan, 2012). Another study by de la Torre et al. (2021b) reported that human-dominated landscapes can serve as prime habitats for elephants, even when sufficient natural resources are available elsewhere (e.g., in forested areas). A study by Kaliyappan (2023) of elephant foraging behaviour in landscapes with palm oil plantations adjacent to forests shows that elephants living in areas close to plantations have a smaller home range and spend time inside the oil palm plantations, presumably for feeding.

In the study areas, plantations are found surrounding the study sites, particularly the Gunung Inas-Bintang Hijau Forest Complex (GIBHFC). The land use management of this forest complex includes Forest Plantation (*Hutan Ladang*) (i.e., Gunung Inas Forest Reserve). It was reported that 600 ha of the Gunung Inas Forest Reserve were approved for a durian plantation (*Musang King*, a famous variety of highly valued durian) in 2019 (Zulkefli, 2022). Young durian trees were observed during the 2020 sampling period. The significant correlation between commodity production and elephant habitat utilization necessitates a serious approach towards managing elephant habitats. Elephant habitat management must take into account the presence of commodity plantations (crops that are preferred by elephants) surrounding the forest reserves that are home to elephants. According to the Department of Wildlife and National Parks Peninsular Malaysia (2022), Asian elephants have been identified as the third most frequently encountered species in human-wildlife conflicts. A significant number of these conflicts arise from encounters with elephants in plantations or orchards.

4.5 Prediction of elephant habitat utilization in northern Peninsular Malaysia

The study areas are considered the primary habitats for elephants in northern Peninsular Malaysia (Department of Town and Country Planning Peninsular Malaysia, 2022; Department of Wildlife and National Parks Peninsular Malaysia, 2013; Khan, 2012). The visual representation of the predicted elephant habitat use in TFC, RBSP, and GIBHFC provides a clear indication that not all study sites across these landscapes are suitable for elephants (Figure 4.3). Suitable habitat for elephants could be much smaller in size for each of the study areas compared to what has been presumed in the past that all forested areas are suitable habitats for elephants. Forested areas across the Central Forest Spine have been identified as Managed Elephant Ranges (MERs) with the assumption that forested area is a natural home to elephants. The low or no use of Gunung Inas Forest Reserve by elephants (occupancy value ~ 0) might be due to various factors, such as constant disturbance from human activities (during the time of the survey) and the fact that a large proportion of this forest reserve consists of higher-elevation ground. Massive clearings of that forest reserve for durian plantation were observed in 2020, during the sampling period. The heavy disturbance in the area could have disturbed the foraging behaviour of the elephants. Nevertheless, the adjacent Bintang-Hijau Forest Reserve (BHFR) (i.e., BHFR Larut Matang and BHFR Hulu Perak) seems to provide a suitable habitat for elephants (Figure 4.3, signified by the green colour). During the sampling period, few detections of elephant dung were recorded in GIBHFC, and were limited to a few sites within BHFRs. The are possibly no more elephants in GIFR (i.e., Sungai Sedim Forest Eco-park that is located within GIFR, and leading to the peak of BHFR) for the past 10 years due to the removal (assumed to be translocated out) of the elephants from the forest. A study by Tan (2017) on elephant distribution in a human-dominated landscape also indicated that there was a past presence of elephants in the GIBHFC.

Some of the sites within GIBHFC have become popular recreational spots for the public, which could be the reason that elephants were moved away from the landscape. Similar circumstances were observed in the south of TFC, where elephants that encroached into areas for public recreational activities were immediately translocated out to a new landscape, for public safety. Nevertheless, in 2022, a research group on Asian Elephants, Management and Ecology of Elephants (MEME) managed to deploy a GPS collar on a male elephant in the BHFR, and the transmitted GPS locations in the past two years indicated that this elephant had been roaming between GIFR and BHFR (Lim, per comms.). In understanding the likelihood of habitat use by elephants in these three study areas, it is important to recognize that although data collected are limited to areas visited for each study area and further extrapolated to all three study areas based on the top occupancy model, it met the minimal requirements and provides the necessary scientific evidence to help with the elephant habitat conservation in the northern region. According to MacKenzie (2017), an occupancy survey necessitates visiting at least 10% of the research area.

With the above ecological and anthropogenic reasons that could explain the elephant habitat use, all three study areas, except GIFR can be considered to still serve as a good habitat for elephant conservation, but require in-depth investigation of other factors that could lead to the disappearance of the elephants from these habitats without notice (e.g., continue removal of elephants, unsustainable land use management and prioritization of eco-tourism, etc.). The presence of elephants in these three landscapes also signifies the importance of the CFS ecological linkages that connect to these forest complexes to allow the movement of elephants. In conclusion, habitat-based conservation efforts for Asian elephants in northern Peninsular Malaysia require serious consideration of the natural and anthropogenic factors found within and, or surrounding of these three forest complexes, in particular its relationship to Indigenous community settlement areas, the presence of plantation areas that can be controlled by human, and the natural topographic features of the landscape. Conservation with assumptions could lead to an unjust use of limited resources (e.g., time, funds, and human resources) to save the endangered Asian elephant. Given the diminishing elephant habitats in Peninsular Malaysia, it is crucial to have an informed conservation strategy that could support the overall conservation of elephants, as well as set a good fundamental framework for the management of human-elephant conflicts. This evidence-based prediction of elephant distribution would provide useful information to support elephant habitat management.

CHAPTER 5: POPULATION VIABILITY ANALYSIS OF ASIAN ELEPHANTS IN NORTHERN PENINSULAR MALAYSIA: A CASE STUDY OF THE GREATER ULU MUDA FOREST COMPLEX

ABSTRACT

Malaysia, being one of the range countries for the Asian elephant (*Elephas maximus*), possesses significant potential to safeguard this endangered species from the threat of extinction. Asian elephants are distributed across seven states in Peninsular Malaysia, including the northern region in the Greater Ulu Muda Forest Complex (GUMFC). Given the average population size of 279 elephants in an area of 1,629.31 km^2, it is essential to forecast the viability of this isolated elephant population in response to environmental changes caused by both natural and anthropogenic factors. A population viability analysis (PVA) was conducted using Vortex 10 to simulate 52 scenarios evaluating the current and projected impacts of environmental and anthropogenic changes on the Asian elephant population in the Greater Ulu Muda Forest Complex (GUMFC) over a 500-year period. The Baseline (Control) scenario showed no risk of extinction (PE = 0), indicating long-term persistence in the absence of significant stressors. In contrast, several scenarios involving key threats—particularly those simulating continued removal of elephants ('Harvest') and declining habitat availability ('Trends in Carrying Capacity')—resulted in a 100% probability of extinction (PE = 1), despite some showing a positive stochastic growth rate. These high-risk scenarios had average extinction times (TE) ranging from 20 to 433 years, underscoring the urgency of intervention. The findings underscore the urgent need for conservation actions that prioritise halting the extraction or translocation of elephants and maintaining or enhancing habitat quality and availability. Without such measures, the GUMFC elephant population faces a serious risk of local extinction.

Immediate, coordinated efforts from relevant stakeholders are essential to reverse these projected declines and ensure the population's long-term viability.

Keywords: Asian elephants, Greater Ulu Muda Forest Complex, population viability analysis, harvest, carrying capacity, conservation strategies, extinction risk.

5.1 INTRODUCTION

The biodiversity crisis across the globe during the Anthropocene is an undeniable fact, with up to one million plant and animal species facing extinction according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2009), which analysed findings from over 15,000 studies and government reports. Fauna with large body mass, like elephants, will go extinct first compared to species of smaller body mass (Ripple et al., 2019). The Asian Elephant may be the next megafauna to face the risk of extinction if conservation efforts to protect the species fail to address the threats (Clements et al., 2010). The IUCN Red List reported that the global population size of Asian elephants continued to show a decreasing trend (Williams et al., 2020). Megafauna extinction in Malaysia is occurring, with the record of the extinction of two rhinoceros species: the Javan Rhinoceros, which went extinct in Malaysia in 1932 (Clements et al., 2010), and the Sumatran Rhinoceros, which went extinct in Malaysia in 2019.

Asian elephant in Malaysia is listed as a Vulnerable (VU) species in the Redlist of Mammals for Peninsular Malaysia 2.0 despite its global conservation status (Endangered) (Department of Wildlife and National Parks Peninsular Malaysia, 2017a). The estimated elephant population for Peninsular Malaysia ranges from 1,223 to 1,677 elephants (Saaban et al., 2011). However, these approximate calculations may have been affected by additional factors that pose a risk to elephants. Habitat loss, habitat fragmentation, human-elephant conflicts and retaliation killings, and wildlife poaching across the species' range could put elephants in danger of facing extinction (Department of Wildlife and National Parks Peninsular Malaysia, 2023; Williams et al., 2020; Saaban et al., 2011; Clements et al., 2010). For instance, the extent of elephant occurrence in Peninsular Malaysia has declined by approximately 48.5% from 6,568,122 hectares in 1980 to 3,380,588 hectares in 2017 (Department of Wildlife and

National Parks Peninsular Malaysia, 2017a). However, there is a shortage of research on the feasibility of elephant populations in Peninsular Malaysia, which might offer valuable information on the well-being of elephants and the factors that pose risks to them. One study was by Saaban et al. (2020) that investigated the viability of elephants in the southern region of Peninsular and the findings shed light on the possibility of local extinctions under certain scenarios.

Little is known about elephants in the northern region of Peninsular Malaysia, particularly in the Greater Ulu Muda Forest Complex (GUMFC) (1,629 km^2), one of the most important forest complexes in the north. A baseline study of their density (in Chapter 2) indicates a population size ranging from 185 (density of $0.11/km^2$) to 420 (density of $0.25/km^2$) elephants. Because of the significant disconnection of GUMFC from other elephant habitats, they are thought to be isolated from the rest of the elephant populations in the Peninsula. Although there are CFS's secondary linkages being identified to connect the forests of GUMFC to other forest complexes, it is not proven effective for the elephants. Another theory is that the elephant population in the GUMFC may not be straying from their native habitat unnecessarily. Wadey (2020) study shows that even translocated elephants will find their way home to their native habitat. Evaluating the viability of this lone elephant population for the GUMFC is therefore imperative to understand their population status in the future, given that this landscape continues to face changes due to human activities (i.e., logging, sand mining, forest exploration into private orchards, etc.). A better understanding of risk factors could provide a good foundation to support elephant conservation in Malaysia.

Assessing the viability of elephants in Peninsular Malaysia in response to ongoing national developments and changes in land use management, as well as the increase of human-elephant conflicts, is fundamental. If there were no clear insights to guide the conservation initiatives, the current plans for elephant conservation may fail to prioritise the conservation efforts effectively. Population viability assessment (PVA) is a crucial ecological tool that informs decision-makers about species' status, aiding researchers and conservation planners in predicting extinction and improving species management plans (Akcakaya and Sjögren-Gulve, 2000; Saaban et al., 2020). The PVA is one of the main criteria being used in assessing the viability of the species in terms of extinction risk (i.e., IUCN Redlist for Endangered Species). Identifying threats facing a taxon via a comprehensive PVA is essential for conservation planning, especially for species that have a small population size or are isolated (Lacy et al., 2021). Combinations of stochastic (or random, or probabilities) and deterministic features of a PVA allow an explicit model of the extinction process and the quantification of threats to extinction for a species, especially that of an isolated and single population (Lacy et al., 2021). In addition to anthropogenic causes, it is crucial to consider natural phenomena such as drought, flood, and diseases that are beyond our control while conducting a population viability evaluation. Quaternary Megafauna Extinction theories recognize that a combination of both extreme climate change and anthropogenic factors (e.g., increase in human impacts such as hunting) is the reason and predict a biomass crash in the future (Barnosky, 2008). IPBES (2019) reports confirmed an inseparable link between biodiversity loss and climate change, with a prediction that a 2°C increase in warming above pre-industrial levels may threaten an estimated 5% of all species with extinction (Jeff 2019). Therefore, it is important to assess the viability of the isolated elephant population in GUMFC, based on the above-mentioned factors.

Given the availability of a robust estimate of elephant population size for GUMFC, this study aims to evaluate the long-term viability of an elephant population in this landscape. I investigate the probability of extinction or population declines for an Asian elephant population over 500 years incorporating different scenarios of habitat availability, based on available information about the landscape (e.g., changes in forest cover, including increase, decline, and business-as-usual scenario), elephant removal by any means (e.g., translocation, poaching, retaliation killing due to human-elephant conflicts, and roadkill), and catastrophic events (e.g., history of drought, flood, and epidemic disease). The results of this study could provide vital information on the factors that should be considered while monitoring elephant numbers and evaluating the likelihood of their extinction. Gaining this knowledge is essential for informed elephant conservation efforts, as it can help avoid unintentionally overlooking concerning factors during the planning and execution phase. This research has the potential to improve the strategic planning of elephant conservation initiatives in Malaysia.

5.2 MATERIALS AND METHODS

5.2.1 Study areas

The population viability analysis was conducted for the single elephant population in the Greater Ulu Muda Forest Complex (GUMFC), in the State of Kedah, Peninsular Malaysia (Figure 5.1). The GUMFC borders the Thailand provinces of Yala and Songkla. The study area comprised seven forest reserves, spanning a total of 162,931 ha (1,629.31 km^2). These reserves consisted of lowland dipterocarp forest, hill dipterocarp forests, upper dipterocarp forest, as well as riparian and limestone vegetation (Department of Forestry Kedah, 2020; Ramasamy, 2017; Suksuwan, 2008). The forest complex comprises pristine primary forest, previously logged secondary forest, and currently logged areas. GUMFC is mainly composed of the Ulu Muda Forest Complex, which accounts for 65.31% of the total area, followed by Pedu Forest Reserve (9.39%), Padang Terap Forest Reserve (7.85%), and another four forest reserves (Table 5.1). In 2018, the state government of Kedah gazetted 26,275 ha of the area from three forest reserves as Ulu Muda State Park (Government of Kedah Darul Aman Gazette, Gazette No. 341, dated 10th May 2018). Besides forested area, three man-made dams (i.e., Pedu Lake, Ahning Lake, and Muda Lake) totalling 79.5 km^2 were created in GUMFC to supply water for agriculture (mainly paddy fields), industries, and domestic usage for three States in the northern region (Lembaga Sumber Air Negeri Kedah, 2021) (Table 5.2). This forest complex experiences two distinct seasons, a wet season (May and October) and a dry season (between December to March) (Suksuwan, 2008).

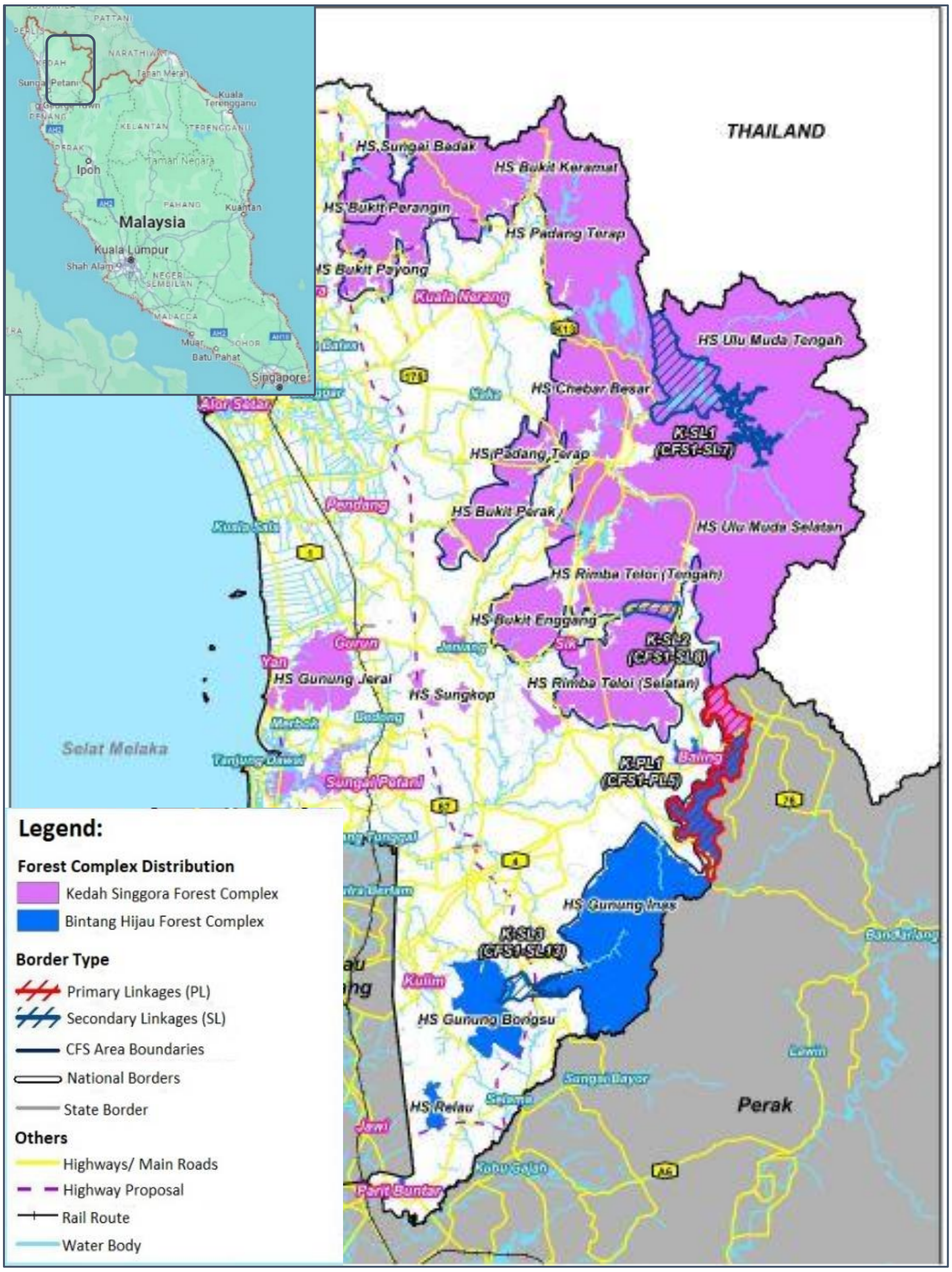


Figure 5.1 The location of the Greater Ulu Muda Forest Complex in the state of Kedah, and its connectivity to CFS ecological corridors. GUMFC (162,900 ha) forms a significant part of the Kedah Singgora Forest Complex. Map modified from Central Forest Spine Master Plan (Department of Town and Country Planning Peninsular Malaysia, 2022).

Table 5.1 The list of forest reserves that were considered as part of the Greater Ulu Muda Forest Complex (GUMFC)

Name	Size (ha)	Gazettement (Year)	Forestry Data (Year)	Legal Protection Status	Percentage of GUMFC
Ulu Muda Forest Reserve*	105,060	1932	2014	Permanent Forest Reserve	64.48
Ulu Muda Forest Reserve (addition)	1,359	2013	2014	Permanent Forest Reserve	0.83
Pedu Forest Reserve*	15,299	1952	2014	Permanent Forest Reserve	9.39
Chebar Besar Forest Reserve*	8,827	1951	2014	Permanent Forest Reserve	5.42
Chebar Kecil Forest Reserve	1,184	1951	2014	Permanent Forest Reserve	0.73
Padang Terap Forest Reserve	12,785	1949	2014	Permanent Forest Reserve	7.85
Bukit Keramat Forest Reserve	10,226	2013	2014	Permanent Forest Reserve	6.28
Bukit Saiong Forest Reserve	8,191	2013	2014	Permanent Forest Reserve	5.03
Total area (ha)	162,931				

Note: *Three forest reserves were gazetted as the Ulu Muda State Park in 2018: Ulu Muda Forest Reserve (11,118 ha), Pedu Forest Reserve (13,715 ha), and Chabar Besar Forest Reserve (1,442 ha).

Table 5.2: A list of man-made lakes (dams) in GUMFC.

Name	Size (ha)	Built (Year)	Purpose
Ahning Dam (Reservoir area)	1,200	1989	Water supply
Pedu Dam (Reservoir area)	5,200	1969	Irrigation
Muda Dam (Reservoir area)	1,550	1969	Irrigation
Total area (ha)	7,950		

5.2.2 Population viability analysis

Population viability analysis (PVA) was conducted by using VORTEX 10 (version 10.5.6.0) (Lacy and Pollak, 2015), a free software designed for a stochastic simulation of the extinction process. This software has been extensively used to study extinction risks and elephant management scenarios (Saaban et al., 2020; Sukumar et al., 2009). In this analysis, I used demographic parameters established for Asian elephants and obtained from the literature with specific information, except for the elephant population size (Table 5.3). The population data is based on the results obtained in Chapter 2 of this thesis, following a robust faecal-based DNA capture-recapture method to estimate elephant density. The population size was calculated for GUMFC based on the mean density value (0.17 elephants/ km^2). The purpose of using the accurate population size of elephants determined for GUMFC was to accurately represent the current population of elephants in this specific landscape (279 elephants in 1,629.31 km^2; approximately 19.2% of the current mean population estimates for Peninsular Malaysia at 1450 elephants). As a result of their lack of connectedness with other elephant habitats in Peninsular Malaysia, I assumed elephants reported from GUMFC could be from a single population. A standard iteration of 1000 cycles and a timeframe of 500 years were used based on the literature (Armbruster et al., 1999; Leimgruber et al., 2008; Saaban et al., 2020; He et al., 2020). A projection of 500 years instead of a commonly used 100 years was selected for this study with recent findings (Armbruster et al., 1999) showing that long-lived animals such as elephants (25 years of generation time) will require a longer time frame. This is because a lag period before an extinction usually occurs after 200 years (Armbruster et al., 1999). It is, however, worth noting that the IUCN Red List of Threatened Species still uses a 100-year time frame as their criteria in assessing the short-term viability analysis for animals with generation years between 20-33 years including elephants.

The PVA analysis in this study focuses on two main challenges threatening the elephants in GUMFC, namely Harvest (the removal of elephants by any means), and changes in Carrying Capacity, K. The scenarios for both categories were determined based on the information we had acquired about this forest complex. Carrying capacity, K is the maximum number of animals of a given population that can be supported by the available resources (McCullough, 1992). In this study, variations in carrying capacity are closely correlated with alterations in forest cover, as the presence of forests determines the availability of habitat for elephants. The analysis for this study utilised published data on the extent of forest cover and logging activity in GUMFC, particularly the Ulu Muda Forest Complex. Only 12% (~12,720 ha) of the UMFC (106,419 ha) is categorized as Protection Forest, in which no timber production is allowed (Berita Harian, 2019). According to the state government of Kedah, a total of 75,000 ha of forest in Kedah have been allocated for timber production, of which 25,000 ha of this area is from Ulu Muda Forest Reserve (Anon., 2021). The logging is said to comply with the Annual Cutting Quota that has been set in the 12th Malaysia Plan by the National Land Council, which is 4,200 hectares per year (Anon., 2021). It is reasonable to use this information as a benchmark in estimating the changes to forest cover for GUMFC (percentage of annual forest loss as [4,200 ha/ 162,900 ha of GUMFC] x 100% = 2.57%). We projected three scenarios to reflect the present condition (CCapacityB = -2.57), a further decrease in forest cover due to logging (CCapacityC = -5.14%), or a reduction in the loss of forest cover due to the slowing down of the logging industry, forest regeneration and/ or the increased of protection from the government (CCapacityD = -1.29%). CCapacity A is set for a scenario where there are no changes to the carrying capacity.

In addition to habitat loss, removing elephants from GUMFC through any method can result in the unforeseen local extinction of elephants in the surrounding area. Removal of elephants in the form of poaching activities, retaliation killing due to human-elephant conflict, translocation of elephants out of their original habitat, and legal or illegal killing of elephants were considered based on published information and past experiences. Evidence of active poaching activities was observed in this landscape, in which we discovered elephant skulls with suspected bullet holes, active wire snares, and an active poachers' camp (Or. per. Obs.). In 2017, the Department of Wildlife and National Parks Peninsular Malaysia arrested seven men who were involved in the hunting of at least 15 elephants from forest complexes in Peninsular Malaysia (Illah, 2017). In 2023, a wildlife poaching and trade syndicate in the Ulu Muda area was revealed with the arrest of six local men who had been involved in such activities for the past 10 years (Wan, 2023). Besides that, in recent years, elephants have been removed from this forest complex due to HEC, and in some incidents, elephants were found poisoned, either intentionally or unintentionally (Noorazura, 2022). In 2022, 30 elephants across Peninsular Malaysia were translocated out of their original habitat due to human-elephant conflict (Mohd, 2022). Please refer to Table 5.5 and Table 5.6 for the list of scenarios reflected in the analysis concerning carrying capacity (trend in K) and harvest, respectively.

In the catastrophic events such as extreme climate change (e.g., flood and drought), I tested the event of drought as it is more likely to occur in GUMFC compared to flood. While catastrophic floods can cause temporary destruction to the habitat of elephants, the impact of drought can be even more harmful to them. The study area is known to be a hotspot for extreme drought. For instance, severe droughts have been observed in this forest complex, which is measured by the water levels of the above three dams, in particular the Pedu dam, which received water from the Muda dam and the Ahning dam. The current water level of Pedu dam stands at 37.02% as of August 2024, which is within the typical capacity range (Anon., 2024). However, over the period from 1974 to 2023, there was a time in April 1982 when the water level dropped below a crucial level of 15%, reaching a low of 11.21% (Anon., 2024). Extreme heat is likely to affect elephants more severely than flooding, as they are particularly susceptible to high temperatures. Elephants face thermoregulation challenges because they lack sweat glands and do not pant, two standard mechanisms for heat dissipation in mammals (Weissenböck et al., 2012). They rely on behaviours such as bathing in water or mud to cool down, seeking shade under trees, and flapping their ears to reduce body temperature (Lefebvre et al., 2023; Weissenbock et al., 2012). Wild forest fires induced by extreme heat are not uncommon in Malaysia, and that could further threaten the survival of elephants during drought.

Table 5.3: Summary of the parameters used in the simulation of the Baseline (Control) scenario in Vortex 10 (version 10.5.6.0).

Input parameters	Values	Source/ Justification
Scenario Settings	Baseline scenario	
Number of iterations	1000	Leimgruber et al., 2008
Number of years	500	Leimgruber et al., 2008; Saaban et al. 2020; He et al., 2020
Extinction definition	Only 1 sex remains	Tilson et al., 1994; Leimgruber et al., 2008; Saaban et al., 2020
Species Description		
Inbreeding depression	Yes	
Lethal equivalent	3.14	Tilson et al., 1994; He et al., 2020
Percent due to recessive lethal alleles	50	Tilson et al., 1994
EV correlation between reproduction and survival	0.5	Default value
Number of populations	1	
State Variables	na	
Reproductive System (Polygynous)		
Age of first offspring for females	20	Sukumar, 1993; Tilson et al., 1994; Armbruste 1999
Maximum age of female reproduction	60	Tilson et al., 1994; Sukumar, 2003; Leimgruber et al., 2008; Saaban et al., 2020
Age of first offspring for males	15	Sukumar, 1993; Leimgruber et al., 2008; Armbruster, 1999
Maximum age of male reproduction	60	Sukumar et al., 2003; He et al. 2020
Maximum lifespan	70	He et al., 2020
Maximum number of broods per year	1	He et al., 2020
Maximum number of progeny per brood	1	Tilson et al., 1994; Sukumar, 2003; Leimgruber et al., 2008; Saaban et al., 2020
Sex ratio at birth- in % males	50%	Tilson et al., 1994; Leimgruber et al., 2008; Saaban et al., 2020
Density-dependent reproduction	N0	Tilson et al., 1994; Leimgruber et al., 2008; Saaban et al., 2020

Reproductive rates		
Percentage of adult females breeding	18	Leimgruber et al., 2008
Input parameters	Values	Source/ Justification
SD in % breeding due to EV	3.2	Tilson et al., 1994; Leimgruber et al., 2008; Saaban et al., 2020;
Distribution of Broods per year (%)	na	
Mortality Rates		Tilson et al., 1994; Leimgruber et al., 2008; Saaban et al., 2020; 20% SD in mortality due to EV
Mortality rates for females (years)		
0-1	15:00%	
>1-5	4.00%	
>5-15	2.00%	
>15	2.50%	
Mortality rates for males (years)		Tilson et al., 1994; Leimgruber et al., 2008; Saaban et al., 2020; 20% SD in mortality due to EV
0-1	15:00%	
>1-5	5.00%	
>5-15	3.00%	
>15	3.00%	
Mate Monopolization		
Percentage of males in breeding pool	80.00%	Tilson et al., 1994; Leimgruber et al., 2008; Saaban et al., 2020
Initial Population Size	279	The mean population size calculated based on density of 0.17 animals per km^2, and size of study areas (GUMFC, 1629 km^2), Or, 2024, Chapter 3
Start with age distribution	Stable	Tilson et al., 1994; Leimgruber et al., 2008; Saaban et al., 2020
Carrying capacity	335	added 20% of the current mean population for K
SD in K due to environmental variation	5	Leimgruber et al., 2008; Saaban et al., 2020; Sukumar, 2003
*Future change in K? (Trend in K?)	No	Saaban et al., 2020
Catastrophes	No	
Harvest	No	

Table 5.4 A list of scenarios used in the PVA simulation. Different values were used for Harvest and Carrying Capacity parameters to reflect the conservation challenges in the GUMFC.

Scenario ID	Scenario name	No. of catastrophe	Carrying capacity (Trend in K)	Harvest
S1	Baseline	0	No	No
S2	Disease	1	No	No
S3	Drought	1	No	No
S4	CCapacityA (**0%)	0	No	No
S5	CCapacityB (**-2.57%)	0	Yes	No
S6	CCapacityC (**-5.14%)	0	Yes	No
S7	CCapacityD (**-1.29%)	0	Yes	No
S8	HarvestA (*1, 1)	0	No	Yes
S9	HarvestB (*2, 2)	0	No	Yes
S10	HarvestC (*3, 3)	0	No	Yes
S11	Disease + Drought	2	No	No
S12	Disease + HarvestA	1	No	Yes
S13	Disease + HarvestB	1	No	Yes
S14	Disease + HarvestC	1	No	Yes
S15	Disease + Drought + HarvestA	2	No	Yes
S16	Disease + Drought + HarvestB	2	No	Yes
S17	Disease + Drought + HarvestC	2	No	Yes
S18	Disease + CCapacityA	1	No	No
S19	Disease + CCapacityB	1	Yes	No
S20	Disease + CCapacityC	1	Yes	No
S21	Disease + CCapacityD	1	Yes	No
S22	Drought + HarvestA	1	No	Yes
S23	Drought + HarvestB	1	No	Yes
S24	Drought + HarvestC	1	No	Yes
S25	Drought + CCapacityA	1	No	No
S26	Drought + CCapacityB	1	Yes	No
S27	Drought + CCapacityC	1	Yes	No
S28	Drought + CCapacityD	1	Yes	No
S29	Drought + HarvestA + CCapacityA	1	Yes	Yes
S30	Drought + HarvestB + CCapacityA	1	Yes	Yes
S31	Drought + HarvestC + CCapacityA	1	Yes	Yes
S32	Drought + HarvestA + CCapacityB	1	Yes	Yes
S33	Drought + HarvestB + CCapacityB	1	Yes	Yes
S34	Drought + HarvestC + CCapacityB	1	Yes	Yes
S35	Drought + HarvestA + CCapacityC	1	Yes	Yes
S36	Drought + HarvestB + CCapacityC	1	Yes	Yes

Table 5.4 (continued)				
Scenario ID	Scenario name	No. of catastrophe	Carrying capacity (Trend in K)	Harvest
S37	Drought + HarvestC + CCapacityC	1	Yes	Yes
S38	Drought + HarvestA + CCapacityD	1	Yes	Yes
S39	Drought + HarvestB + CCapacityD	1	Yes	Yes
S40	Drought + HarvestC + CCapacityD	1	Yes	Yes
S41	Disease + Drought + HarvestA + CCapacityA	2	Yes	Yes
S42	Disease + Drought + HarvestB + CCapacityA	2	Yes	Yes
S43	Disease + Drought + HarvestC + CCapacityA	2	Yes	Yes
S44	Disease + Drought + HarvestA + CCapacityB	2	Yes	Yes
S45	Disease + Drought + HarvestB + CCapacityB	2	Yes	Yes
S46	Disease + Drought + HarvestC + CCapacityB	2	Yes	Yes
S47	Disease + Drought + HarvestA + CCapacityC	2	Yes	Yes
S48	Disease + Drought + HarvestB + CCapacityC	2	Yes	Yes
S49	Disease + Drought + HarvestC + CCapacityC	2	Yes	Yes
S50	Disease + Drought + HarvestA + CCapacityD	2	Yes	Yes
S51	Disease + Drought + HarvestB + CCapacityD	2	Yes	Yes
S52	Disease + Drought + HarvestC + CCapacityD	2	Yes	Yes

Table 5.5 Four scenarios are set for Carrying Capacity that reflect the annual forest cover in GUMFC.

Carrying Capacity	Future change in K	% of increase or decrease	Description
CCapacityA	No	0	No forest loss
CCapacityB	Yes	-2.57	Current rate of forest loss
CCapacityC	Yes	-5.14	Increased rate of forest loss
CCapacityD	Yes	-1.29	Decreased rate of forest loss (e.g., forest regeneration, reduced timber production)

Note: The PVA approach used in this study does not account for the spatial aspect of individual elephants within their distribution landscape. The method used to quantify the impact of forest reduction on population size in the PVA was based on proportional changes in forest cover, which were translated into reductions in carrying capacity (K).

Table 5.6 Three scenarios are set for the annual Harvest (removal of elephants) for GUMFC.

Harvest Scenario	Input values		Description
	Female	Male	
before the age of 20 (Females), 15 (Males)			
	0	0	No removal of elephants
after the age of 20 (Females), 15 (Males)			
HarvestA	1	1	The minimum rate of removal (e.g., controlled unlawful removal of elephants, restricted translocation)
HarvestB	2	2	The average rate of removal (e.g., increased in unlawful and lawful removal of elephants)
HarvestC	3	3	The maximum rate of removal (e.g., rampant poaching, increased in escalated killing of elephants due to human-elephant conflicts, ongoing translocation of elephants)

5.3 RESULTS

5.3.1 Probability of Extinction

A total of 52 scenarios were analysed, comprising independent stressors (single scenario) or combinations of stressors (multiple scenarios) (Table 5.7). The population viability analysis (PVA) results show a variation in the probability of extinction (PE) ranging from no extinction (PE=0) to possible extinction possibility (PE=1 (100%)) over 500 years, depending on the stressors. Table 5.7 and Figure 5.2 show the summarized results for all scenarios and the mean stochastic growth rates for each of the scenarios, respectively. For the Baseline (Control) scenario, the deterministic growth rate (det-r) is at 0.0320, and the stochastic growth rate (stoch-r) is 0.0306, indicating a stable population under normal conditions, and the probability of population extinction is 0%, with all extant populations surviving through the projected 500 years. All the other independent stressors (i.e., disease, drought, harvest (A, B, C), and CCapacity (A, B, C, and D)) show variability in their effects on the mean growth rate (stoch-r) and PE of elephants in GUMFC (Table 5.7, Figure 5.2).

The impact of "Disease" shows a slight decrease in the growth rate (stoch-r = 0.0291) compared to the Baseline, but the population remains stable with no extinction (PE=0). For "Drought", a further reduction in growth rate is observed (stoch-r = 0.0259) with increased variability (combined with other stressors). However, no extinction at the end of 500 years, but a reduction in population size (N-extant = 325.59) (Table 5.7). In comparison between these two catastrophic events, a combination of HarvestB or HarvestC in the respective scenario shows a higher PE for Drought. For instance, S24 (Drought + HarvestC) resulted in 98.3% extinction risk compared to S14 (Disease + HarvestC) of 70.2 %. However, in general, the combination of two catastrophic events alone (S11, Drought + Disease) will not lead to extinction but shows a smaller population size (N-extant = 322.45) compared to the Baseline scenario (N-extent = 332.48). The growth rate decreases slightly (det-r of 0.0265), but the population remains generally stable. Some scenarios incorporating "Harvest" and "Carrying Capacity" show a considerably concerning trend leading to extinction in less than a generation for elephants (of 25 years) (Table 5.7, Figure 5.3).

For the harvesting impact (S8 to S10), the result shows increasing levels of harvesting (annual removal of 2, 4, and 6 individual elephants) lead to reduced growth rates and higher extinction risks (Figure 5.4). HarvestC (representing the worst scenario for removal of elephants), where the stochastic growth rate (stoch-r) drops significantly to 0.0075, compared to HarvestA (stoch-r = 0.0235) and HarvestB (stoch-r = 0.0162). The scenario of removing 3 males and 3 females annually shows a 7% probability of extinction (PE=0.070) with population numbers reduced (N-extant = 316.7). However, a significant effect was observed when

HarvestC was combined with each of the catastrophe events. For instance, elephant extinction risk is greater for Drought + HarvestC (PE=0.9830) compared to Disease + HarvestC (PE=0.7020). Nevertheless, the extinction risk is 100% when both catastrophe events are combined with HarvestC (Disease + Drought + HarvestC), with a mean TE of 126.1 years to come.

For the Carrying Capacity (S5 to S7) where the scenario reflected the changes in the forest cover (trend in K, based on % of increased or decreased in forest cover) shows there is an absolute risk for a population collapse, in which any reduction in the forest cover (CCapacityB = -2.57, CCapacityC = -5.14, and CCapacityD = -1.29) would lead to population extinction with populations eventually declining to zero at different time frame (Table 5.7; Figure 5.5). In a scenario where there are no changes to forest cover (CCapacityA = 0), the population remains stable at 332.7 elephants, and PE=0. For scenario implicating mitigation measures to increase forest cover (CCapacityD), even under stress shows some resilience (e.g., reduced forest loss, and forest regenerations), although the risk of extinction remains high and could lead to extinction in 78 years to come (Tabe 5.7). In terms of population growth rate (stoch-r), even though some scenarios (e.g., S5, S6, and S7) reflecting changes in forest cover show a positive stochastic growth rate but the probability of extinction remains high (Table 5.7, Figure 5.2). These findings indicate that the elephant population in GUMFC is at significant risk of becoming extinct due to the decline in forest area in this forest complex.

Overall, the PVA result indicates that any combination of scenarios (stressors) such as disease, drought, and harvesting, especially under reduced forest cover (CCapacity B, C, D) leads to a near-certain probability of extinction exceeding 90%, and drastically reduced population sizes compared to the baseline scenario (Figure 5.5). A similar effect was observed for any scenarios that incorporate HarvestC, in which it increased the probability of extinction (Figure 5.4). For instance, S41 (Disease + Drought + HarvestA + CCapacityA) shows PE at

1.3% compared to S46 (Disease + Drought + HarvestC + CCapacityB) shows PE at 100%. In terms of growth rate, the scenarios implicating HarvestC mostly show a negative growth rate compared to a reduction in forest cover, but still project a growth. On its own, HarvestC shows a low extinction risk (PE=0.07) and meanTE at 237.8 years to come. Figure 5.2 provides a visual summary of how different scenarios impact the elephant population's viability over 500 years in the GUMFC. The stoch-r value observed across 52 models ranges from a maximum of 0.0308 to a minimum of -0.0485, reflecting the varying impacts caused by a single stressor (scenario) or a combination of multiple stressors on the elephant population growth in GUMFC (Table 5.7). The positive scenarios suggest that the population is expected to increase over time and, hence, represent more favourable environmental conditions or effective management strategies on the ground by the stakeholders. On the other hand, the negative scenario indicates scenarios where the population is expected to decline and, hence, are less favourable in elephant conservation efforts. The deterministic growth rates (det-r) represent the average rate of population growth under each scenario, assuming the conditions are stable and predictable.

Table 5.7 Results of the population viability analysis of the elephant population in the Greater Ulu Muda Forest Complex. (See Table 5.5 & 5.6 for the input parameters for carrying capacity and harvest).

Scenario ID	Scenario Name	det-r	stoch-r	SD(r)	SE(r)	PE	N-extant	SD(N-ext)	N-all	SD(N-all)	median TE	mean TE
S1	Baseline	0.0320	0.0306	0.0280	0.0009	0.0000	332.48	6.49	332.48	6.49	0	0.0
S2	Disease	0.0308	0.0291	0.0350	0.0011	0.0000	330.01	13.86	330.01	13.86	0	0.0
S3	Drought	0.0278	0.0259	0.0447	0.0014	0.0000	325.59	19.69	325.59	19.69	0	0.0
S4	CCapacityA	0.0320	0.0307	0.0281	0.0009	0.0000	332.70	6.03	332.70	6.03	0	0.0
S5	CCapacityB	0.0320	0.0307	0.0500	0.0016	1.0000	0.00	0.00	0.00	0.00	40	40.1
S6	CCapacityC	0.0320	0.0305	0.0488	0.0015	1.0000	0.00	0.00	0.00	0.00	21	20.8
S7	CCapacityD	0.0320	0.0308	0.0500	0.0016	1.0000	0.00	0.00	0.00	0.00	78	78.0
S8	HarvestA	0.0320	0.0235	0.0279	0.0009	0.0000	331.54	6.87	331.54	6.87	0	0.0
S9	HarvestB	0.0320	0.0162	0.0279	0.0009	0.0000	328.75	8.82	328.75	8.82	0	0.0
S10	HarvestC	0.0320	0.0075	0.0299	0.0009	0.0700	316.70	27.46	294.53	85.07	0	237.8
S11	Disease+Drought	0.0265	0.0244	0.0496	0.0016	0.0000	322.45	24.88	322.45	24.88	0	0.0
S12	Disease+HarvestA	0.0308	0.0219	0.0351	0.0011	0.0000	328.36	15.38	328.36	15.38	0	0.0
S13	Disease+HarvestB	0.0308	0.0139	0.0359	0.0011	0.0430	321.16	29.29	307.35	71.20	0	260.3
S14	Disease+HarvestC	0.0308	-0.0023	0.0506	0.0016	0.7020	283.10	74.07	84.38	135.69	335	239.7
S15	Disease+Drought+HarvestA	0.0265	0.0167	0.0497	0.0016	0.0060	312.13	38.55	310.26	45.37	0	323.7
S16	Disease+Drought+HarvestB	0.0265	0.0029	0.0582	0.0018	0.5260	269.90	83.02	127.96	146.41	477	271.1
S17	Disease+Drought+HarvestC	0.0265	-0.0268	0.0819	0.0026	0.9980	280.50	20.51	0.56	12.55	103	126.1
S18	Disease+CCapacityA	0.0308	0.0292	0.0347	0.0011	0.0000	331.01	12.08	331.01	12.08	0	0.0
S19	Disease+CCapacityB	0.0308	0.0292	0.0539	0.0017	1.0000	0.00	0.00	0.00	0.00	40	40.0
S20	Disease+CCapacityC	0.0308	0.0297	0.0520	0.0016	1.0000	0.00	0.00	0.00	0.00	21	20.8
S21	Disease+CCapacityD	0.0308	0.0286	0.0529	0.0017	1.0000	0.00	0.00	0.00	0.00	78	78.1
S22	Drought+HarvestA	0.0278	0.0185	0.0451	0.0014	0.0010	318.81	30.77	318.49	32.37	0	433.0
S23	Drought+HarvestB	0.0278	0.0079	0.0492	0.0016	0.2460	293.89	61.37	221.62	137.35	0	297.3
S24	Drought+HarvestC	0.0278	-0.0192	0.0734	0.0023	0.9830	260.06	71.42	4.42	34.83	127	156.8
S25	Drought+CCapacityA	0.0278	0.0259	0.0451	0.0014	0.0000	325.75	20.78	325.75	20.78	0	0.0

Table 5.7 (Continued)

Scenario ID	Scenario Name	det-r	stoch-r	SD(r)	SE(r)	PE	N-extant	SD(N-ext)	N-all	SD(N-all)	median TE	mean TE
S26	Drought+CCapacityB	0.0278	0.0256	0.0603	0.0019	1.0000	0.00	0.00	0.00	0.00	40	40.0
S27	Drought+CCapacityC	0.0278	0.0260	0.0606	0.0019	1.0000	0.00	0.00	0.00	0.00	21	20.8
S28	Drought+CCapacityD	0.0278	0.0257	0.0613	0.0019	1.0000	0.00	0.00	0.00	0.00	78	78.0
S29	Drought+HarvestA+CCapacityA	0.0278	0.0185	0.0451	0.0014	0.0020	320.18	27.40	319.54	30.89	0	313.0
S30	Drought+HarvestB+CCapacityA	0.0278	0.0077	0.0495	0.0016	0.2790	297.61	59.35	214.59	142.73	0	289.5
S31	Drought+HarvestC+CCapacityA	0.0278	-0.0188	0.0722	0.0023	0.9780	201.18	108.73	4.43	33.47	130	156.7
S32	Drought+HarvestA+CCapacityB	0.0278	-0.0032	0.0712	0.0023	1.0000	0.00	0.00	0.00	0.00	40	40.0
S33	Drought+HarvestB+CCapacityB	0.0278	-0.0245	0.0745	0.0024	1.0000	0.00	0.00	0.00	0.00	40	40.0
S34	Drought+HarvestC+CCapacityB	0.0278	-0.0445	0.0790	0.0025	1.0000	0.00	0.00	0.00	0.00	40	40.0
S35	Drought+HarvestA+CCapacityC	0.0278	-0.0029	0.0733	0.0023	1.0000	0.00	0.00	0.00	0.00	21	20.8
S36	Drought+HarvestB+CCapacityC	0.0278	-0.0254	0.0811	0.0026	1.0000	0.00	0.00	0.00	0.00	21	20.8
S37	Drought+HarvestC+CCapacityC	0.0278	-0.0436	0.0810	0.0026	1.0000	0.00	0.00	0.00	0.00	21	20.8
S38	Drought+HarvestA+CCapacityD	0.0278	-0.0039	0.0700	0.0022	1.0000	0.00	0.00	0.00	0.00	78	77.9
S39	Drought+HarvestB+CCapacityD	0.0278	-0.0290	0.0826	0.0026	1.0000	0.00	0.00	0.00	0.00	77	76.6
S40	Drought+HarvestC+CCapacityD	0.0278	-0.0485	0.0927	0.0029	1.0000	0.00	0.00	0.00	0.00	69	66.9
S41	Disease+Drought+HarvestA+CCapacityA	0.0265	0.0167	0.0497	0.0016	0.0130	314.15	36.45	310.07	50.78	0	317.2
S42	Disease+Drought+HarvestB+CCapacityA	0.0265	0.0034	0.0574	0.0018	0.4880	273.14	83.37	139.86	149.03	0	267.5
S43	Disease+Drought+HarvestC+CCapacityA	0.0265	-0.0261	0.0807	0.0026	0.9980	205.50	27.58	0.41	9.23	104	128.7
S44	Disease+Drought+HarvestA+CCapacityB	0.0265	0.0153	0.0507	0.0016	0.0210	269.62	36.81	263.96	53.13	0	277.6
S45	Disease+Drought+HarvestB+CCapacityB	0.0265	-0.0040	0.0648	0.0020	0.7830	217.71	77.20	47.25	96.69	274	237.7
S46	Disease+Drought+HarvestC+CCapacityB	0.0265	-0.0351	0.0858	0.0027	1.0000	0.00	0.00	0.00	0.00	87	99.5

Table 5.7 (Continued)												
Scenario ID	Scenario Name	det-r	stoch-r	SD(r)	SE(r)	PE	N-extant	SD(N-ext)	N-all	SD(N-all)	median TE	mean TE
S47	Disease+Drought+HarvestA+CCapacityC	0.0265	0.0128	0.0529	0.0017	0.0740	223.15	39.17	206.65	69.53	0	331.1
S48	Disease+Drought+HarvestB+CCapacityC	0.0265	-0.0141	0.0736	0.0023	0.9750	188.88	72.92	4.73	31.59	164	186.1
S49	Disease+Drought+HarvestC+CCapacityC	0.0265	-0.0484	0.0931	0.0029	1.0000	0.00	0.00	0.00	0.00	66	72.1
S50	Disease+Drought+HarvestA+CCapacityD	0.0265	0.0160	0.0503	0.0016	0.0110	292.30	35.56	289.08	46.70	0	265.5
S51	Disease+Drought+HarvestB+CCapacityD	0.0265	-0.0010	0.0623	0.0020	0.6920	238.94	83.40	73.60	119.65	349	259.4
S52	Disease+Drought+HarvestC+CCapacityD	0.0265	-0.0305	0.0841	0.0027	0.9980	240.50	91.22	0.48	11.13	95	112.3

Note:

det-r: Deterministic growth rate, indicating the population's growth rate without considering random events.

stoch-r: The mean stochastic growth rate, which includes the effects of random events.

SD (r): Standard deviation of the stochastic population growth rate, showing the variability in growth rates.

PE: Probability of extinction, indicating the likelihood of the population going extinct.

N-extant: Number of extant populations at the end of the simulations.

SD(N-ext): Standard deviation of the number of extant populations.

N-all: Total number of populations, including extinct ones, at the end of the simulations.

SD(N-all): Standard deviation of the total number of populations.

medianTE: Median time to extinction in years, if applicable.

meanTE: Mean time to extinction in years, if applicable.

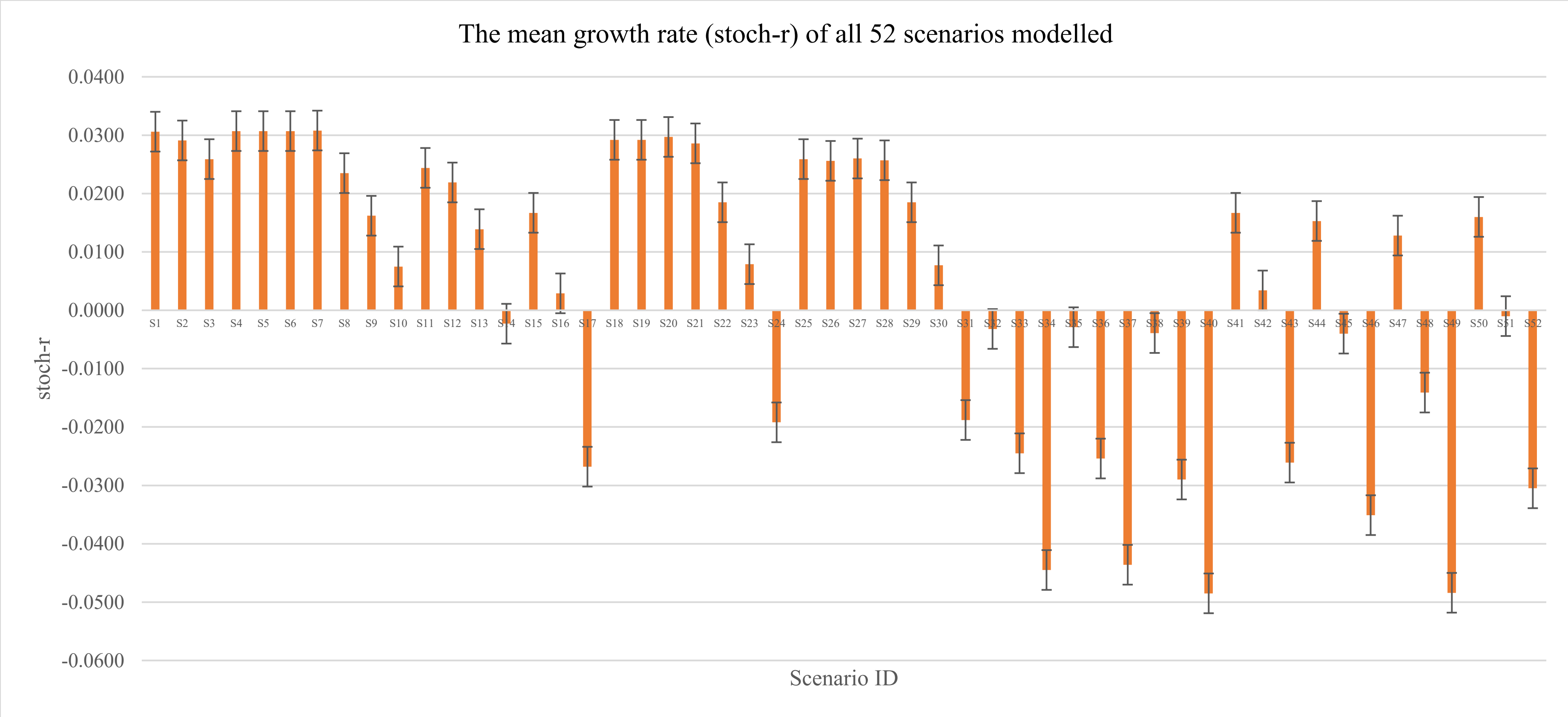


Figure 5.2 The average growth rate (stoch-r) and the minimum and maximum standard errors for all 52 scenarios simulated in the population viability analysis. The positive stoch-r values signify situations in which the population is anticipated to increase on average, while the negative values suggest circumstances where the population is predicted to decrease over time.

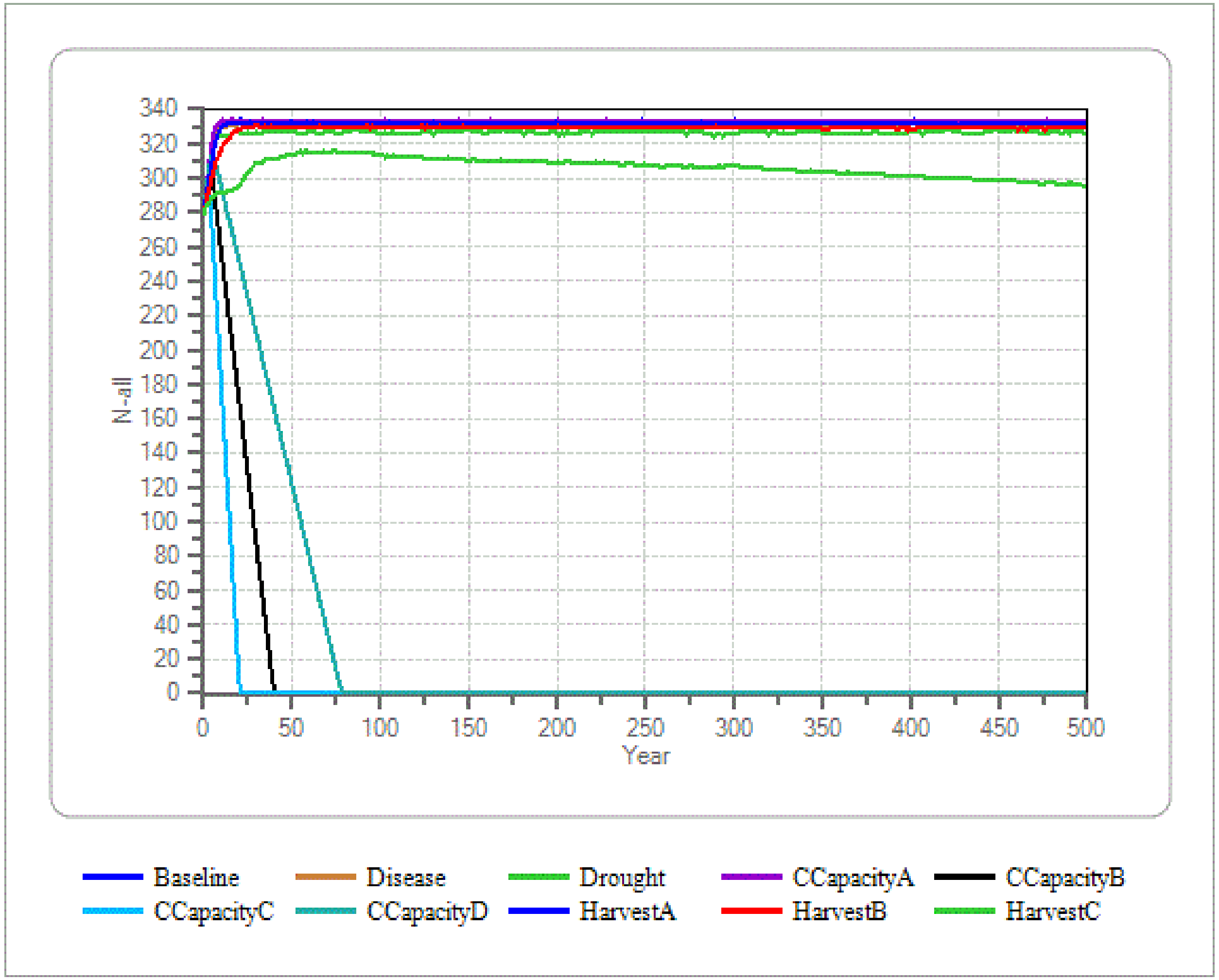


Figure 5.3 The probability of population extinction (PE) with the Time of Extinction (TE) for the individual stressors.

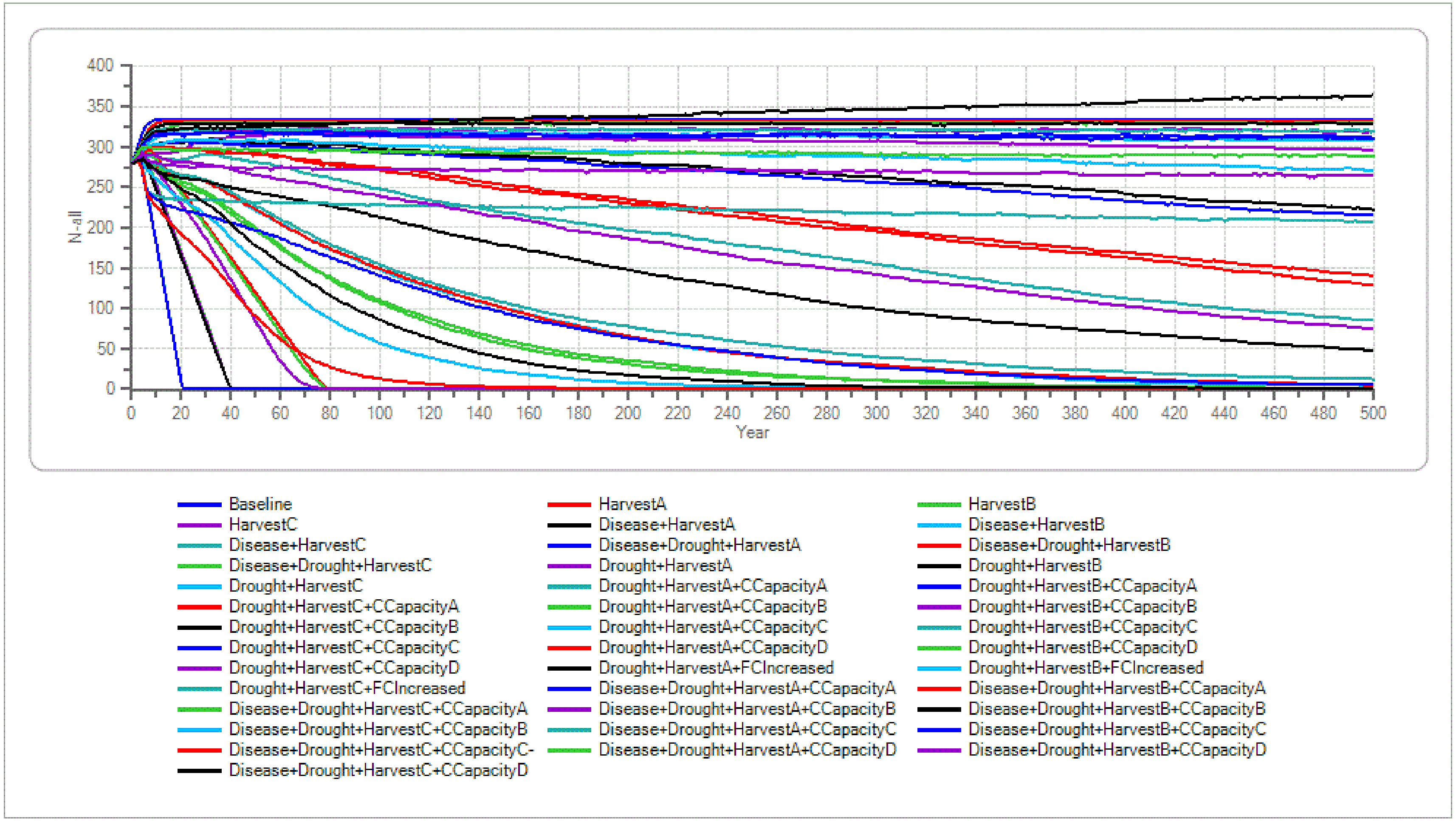


Figure 5.4 The population viability of elephants in GUMFC based on Harvest as the stressor. Annual removal of elephants: HarvestA = 2, HarvestB = 4, and HarvestC = 6 elephant

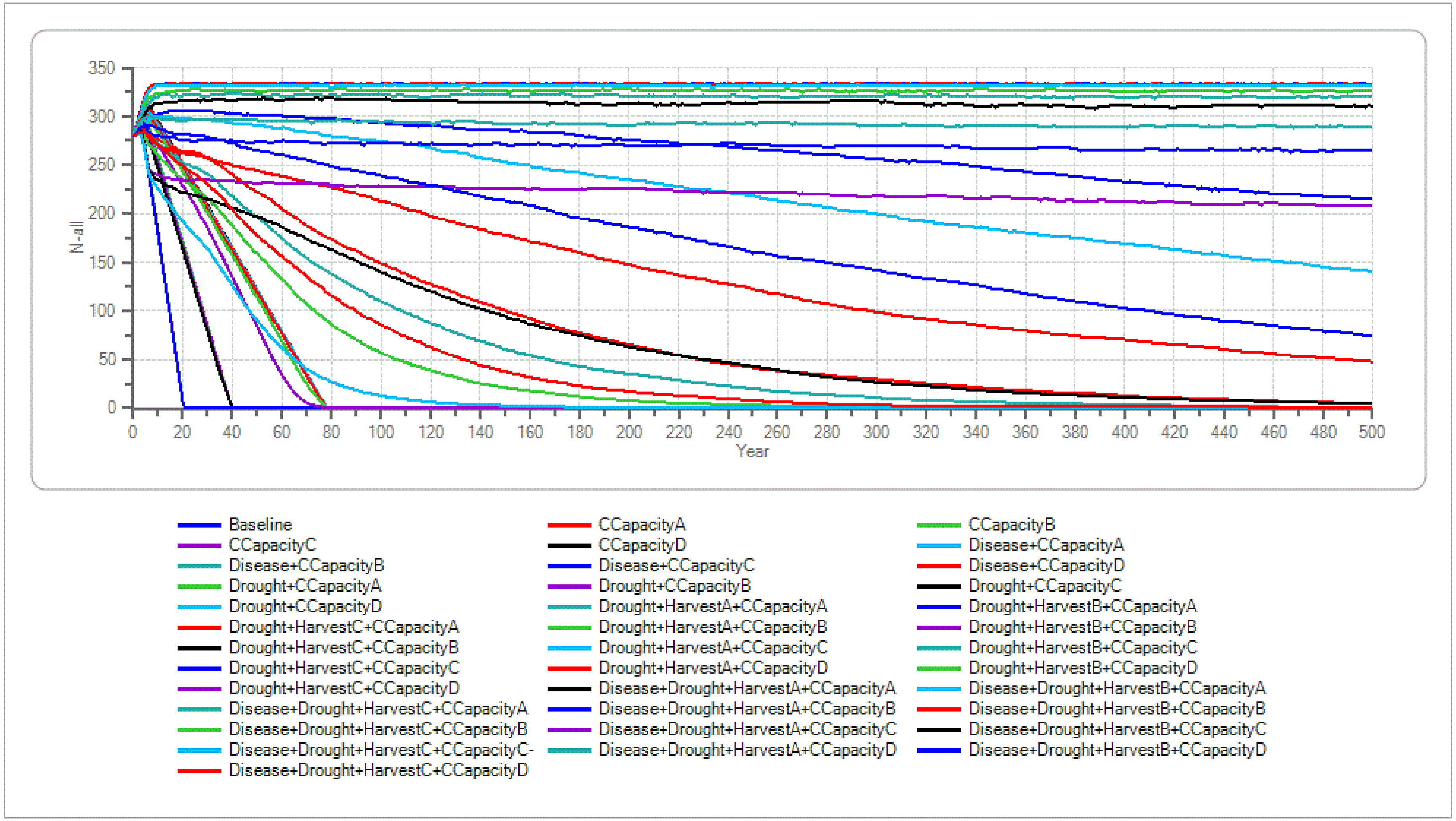


Figure 5.5 The population viability of elephants in GUMFC based on Carrying Capacity - Trend in K (% of increased or decreased) as the stressor.

Trend in K: CCapacityA = No changes in K, CCapacityB = -2.57, CCapacityC = -5.14, CCapacityD = -1.29.

5.4 DISCUSSION AND CONCLUSION

5.4.1 Factors affecting the viability of the elephant population in GUMFC

This is the first assessment of elephant population viability for this forest complex, based on the first robust population size estimation that was obtained from my research, and described in Chapter 2 of this thesis. The PVA results provide valuable insights into the future of the elephant population in GUMFC, which is much needed to aid conservation planning and prioritising interventions. Based on the PVA results, I speculate that the elephant population in GUMFC is susceptible to extinction unless measures are taken to mitigate the threats. In general, the PVA results suggest that while the elephant population may remain stable under baseline conditions, the introduction of additional stressors such as catastrophe events (i.e., disease and drought), harvesting, and carrying capacity (the effect of forest cover) significantly increases the risk of extinction, as well as a reduction in the size of the population. The results indicate a concerning trend leading to possible local population extinction, especially in scenarios featuring the impact of i) changes in carrying capacity based on forest cover as a means of habitat availability for elephants, and ii) Harvest (the removal of elephants) from this forest complex, and its implication to the overall health of elephant population in GUMFC. Although one can argue that the viability of a species population is influenced by natural events such as birth, death, and unfortunate natural disasters that are beyond human control, it is important to pay attention to these two significant stressors (Carrying Capacity and Harvest) to manage the risk of population extinction before it is too late. This is because scenarios modelled in PVA were carefully designed to reflect the environmental factors (stochastic events) that could affect the viability of the elephant population in GUMFC.

A species' population growth depends on birth, death, immigration, and emigration, and how the species interacts with resource availability (Krausman, 2002). Extinction risks associated with the stressors that incorporate variability in forest cover (i.e., current forest cover (S5), reduced in forest cover (S6), as well as increased forest cover (S7)) indicate the significant roles played by forest cover (as the availability of habitat) in sustaining the elephant population in GUMFC for centuries to come. Elephants, as the largest terrestrial mammals, will require a large area to live with their home range in Malaysia recorded at around 250 km^2 (Department of Wildlife and National Parks Peninsular Malaysia, 2023). A better elephant habitat management that includes the reduction of logging areas, reforestation, or natural regeneration of the logged-over areas could reduce the extinction risk. For instance, S7 (CCapacityD), a scenario depicting a better protection of forest cover (forest loss is at a lower rate: -1.29), shows a delay in meanTE to 78 years, compared to CCapacityB (S5, current rate of forest loss: -2.57, meanTE at 20.8 years), and CCapacityC (S6, increased rate of forest loss: -5.14, meanTE at 40.1 years). This emphasises that the long-term survival of the elephant population in GUMFC is subject to the availability of forest as their ultimate habitat. Large bodies and energetic wildlife such as elephants will require more energy, and therefore more land area to provide an adequate source of energy (Fuller et al., 2016). Adult elephants have been documented to require 150 kg of food and consume up to 200 litres of water per day, and these needs can only be met by undisturbed or well-maintained natural habitats. Therefore, habitat preservation and restoration should be prioritised in managing the elephant population in GUMFC. Besides that, in a natural habitat, the forest provides favourable conditions for elephants to mate, as the elephants continue to thrive within the ecosystem, which is another aspect that contributes to the expansion of their population.

Although the results obtained here demonstrate the impact of forest cover changes on elephant survival, a key limitation of this study lies in how forest loss was incorporated into the population viability analysis. The model used was not spatially explicit, and changes in forest cover were represented as proportional reductions in carrying capacity (K), serving as a simplified representation of habitat loss. This approach does not account for the spatial distribution, configuration, or fragmentation of forest habitats, which are known to have a critical influence on elephant movement, dispersal, and long-term viability. The assumption that habitat loss uniformly affects population capacity overlooks the ecological complexity of elephant landscape use, particularly in fragmented environments. Furthermore, the use of carrying capacity (K) as a fixed value tied to habitat extent assumes a form of population equilibrium that may not accurately reflect real-world dynamics, especially for wide-ranging megafauna in changing environments. While this method offers a practical approximation within the Vortex platform, it lacks the spatial resolution needed to capture landscape-level changes and their impacts on population processes. Future research aiming to explore the impacts of forest cover on animal viability should consider incorporating spatially explicit population models that integrate habitat configuration, movement barriers, and functional connectivity. These models can better reflect how species respond to habitat fragmentation and loss across the landscape and can produce more ecologically realistic outcomes to guide conservation planning.

Besides the forest cover, the lawful or unlawful removal of elephants from GUMFC may have a detrimental long-term effect, which becomes the second important factor that will lead to an increase in population extinction risk. Results proved that when the Harvest level is increased from two to six elephants per year, the extinction risks increase even though the growth rate may remain positive in some scenarios. Historically, removal of elephants from their habitat in a lawful manner (e.g., translocation of elephants due to human-elephant conflicts and construction of dams in the forested area, culling of elephants due to HEC (before 1974), and killing of elephants as an act of self-defence by authorities during monitoring/ translocation operations) or unlawful practices (e.g., hunting for elephant body parts such as tusks, retaliation killing due to HEC, etc.) have been reported (Saaban et al., 2011). In

Peninsular Malaysia, it was reported that around 600 elephants (~40% of the current population) have been translocated since 1974, mainly due to conflict with humans (Saaban et al., 2011). The translocation of elephants is the last solution for the wildlife department in dealing with HEC issue, which often occurs in the periphery of forests (Department of Wildlife and National Parks Peninsular Malaysia, 2023).

Unlawful removal of elephants, such as poaching and poisoning of elephants, has happened in Peninsular Malaysia, including in GUMFC. For instance, at least two elephants were dead and believed to have been poisoned (intentionally or unintentionally) between 2021 and 2022 within the study area (i.e., Pedu Forest Reserve) (Noorazura, 2022). In GUMFC, poaching signs were observed across the landscape. The study team discovered the skull of an elephant with presumed bullet holes, removed a total of 48 wire snares in a single encounter, and discovered an active poacher camp (Or, per. obs.). The effect of HarvestC increased significantly when combined with other stressors, further proving that any removal of elephants from the landscape could potentially lead to extinction, even when one catastrophe stressor was modelled together. Therefore, the elephants must remain in their original landscape and avoid any unnecessary removal from their natural habitat. HEC management will require new intervention without any elephants being relocated to new habitats, while concurrently enhancing enforcement measures to suppress unlawful killings of elephants. If prompt measures were not implemented, the ongoing removal of elephants from their native habitat could ultimately result in the local extinction of the population in its historical range, such as in GUMFC. Evidently, in Peninsular Malaysia, only 7 states still have elephants (Saaban et al., 2011), whilst it was once reported that elephants were distributed across Peninsular Malaysia Khan, 2012; Olivier, 1978a).

Besides that, it is crucial to model catastrophic events to anticipate possible natural disasters, as they cannot be disregarded in species conservation. The outbreak of zoonotic disease that is detrimental to elephants should be taken into consideration. The current known disease associated with elephants, such as Elephant Endotheliotropic Herpesvirus (EEHV), usually affects young captive elephants in Asia, North America, and Europe, and has a high mortality rate (Lee et al., 2021; Bucko and Gieger, 2019). Lee et al. (2021) reported that for the first time in Malaysia, EEHV haemorrhagic disease (EEHV HD) cases have been observed in the wild elephant population in the state of Sabah, east Malaysia. In the captive environment with human care, the infected young elephants' mortality rate is approximately 65%; thus, one can assume that in a natural environment, the mortality rate could be higher and may pose a significant threat to the wild elephant population (Lee et al., 2021). Besides EEHV, the presence of chronic infectious disease -tuberculosis (TB) has been reported globally in both wild and captive elephants (Rajbhandari et al., 2022) and has become a concern in maintaining healthy wild elephant populations (Department of Wildlife and National Parks Peninsular Malaysia, 2023). In addition to these known diseases, there is a potential for a future occurrence of unfamiliar zoonotic diseases that may pose harm to elephants. In recent findings by Foggins et al. (2023), death in African elephants (*Loxodonta africana*) has been confirmed to be due to bacteria (*Pasteurella sp*.) infections that led to fatal septicaemia in the wild elephants in Botswana and Zimbabwe in 2020. The study further confirmed that African elephants are susceptible to opportunistically pathogenic *Pasteurella* species (Foggins et al., 2023). Although such bacterial infection was not reported in Asian elephants, it warrants attention to potential disease outbreaks that could pose future conservation concerns for the remaining populations of endangered Asian elephants.

Another catastrophic event that was projected is the scenario of extreme drought in the study areas. Flood was not considered in this study, given the consideration that elephants in GUMFC have a higher chance of being affected by drought compared to flood. This is because, under normal circumstances, elephants in this forest complex are mainly affected by the drought, in which detection of their presence (detection of signs such as food prints and dung) during the dry season was primarily found in areas with water supply (Or., per obs.). There is no historical record of significant floods in this landscape that could jeopardize the elephant population, but severe droughts have been recorded in recent years. While the PVA results indicate a minimal impact of catastrophic events on elephant extinction, the risk becomes more significant when these events are combined with additional stressors such as HarvestC and CCapacity (B, C, and D). These combined factors demand our immediate attention. A study that explored the life history traits of large terrestrial mammals including elephants found that various factors (e.g., low reproduction rate, delayed sexual maturity, long gestation period, small litter size, long generation time, etc.) will prevent these animals from adapting genetically at a sufficient pace to keep track with changing environments such as climate change and habitat fragmentations (Fuller et al., 2016). Therefore, even if elephants can disperse at a wider geographical range during catastrophic events, the combined effect of their life history may place them at a greater risk of extinction (Fuller et al., 2016), and this could be the case for elephants in GUMFC if we continue with business as usual.

On top of all the stressors that have been modelled in PVA, the extinction risks observed could be influenced by other factors that have not been explored in this study. Factors such as the size of an elephant population, the effectiveness of ecological corridors that connect GUMFC to other forest complexes, and the influence of genetic factors were beyond the initial objective of this study. Despite the exclusion of these factors from the analysis, it is essential to acknowledge that a species' population size plays a crucial role in the vulnerability of a population to sustain for a long time (Akcakaya and Sjogren-Gulve, 2000). Even with a positive mean growth rate, the elephant population in GUMFC is vulnerable to demographic stochasticity (DS) (e.g., fluctuations in natural birth rate and death rate, changes in natural environmental variability (EV), as well as human-induced circumstances that could lead to unfavourable outcomes after some time. In PVA using Vortex, the size of demographic stochasticity is a consequence of the population size (Lacy and Pollak, 2021). For this study, it is worth explaining that the population size of elephants in GUMFC is based on faecal DNA that was produced based on the density estimate of 0.17 animals per km^2, which is higher when compared to the generally cited estimate of 0.1 animal per km^2 (Sukumar, 2003). Besides that, it is essential to recognize that even though one may have the necessary technical ability to reduce errors in estimating the population size of a species using DNA genotyping techniques, it is possible to overestimate the size due to factors like inevitable genotyping errors (Lampa et al., 2013).

Another factor that could affect the population growth and extinction risk is the genetic variability of the elephant population. This is especially true given that elephants in GUMFC are technically isolated from other forest complexes that have elephants (Or, per comms.). Although this factor was not explored in this study, generally in isolated populations over a long time, the species tends to have a lower genetic diversity due to inbreeding and lack of genetic drift that can enhance the genetic diversity and overall health of the population genetic to withstands challenges in their environment (Ortega and Maldonado, 2020; Fuller et al., 2016). A recent study of elephant genetic diversity of the elephant population (n = 220) in the Taman Negara National Park (TNNP) (central Peninsular Malaysia) indicates a high level of genetic diversity, and no evidence of inbreeding (Karuppannan et al., 2023). This may be attributed to the national park's connectivity with bigger forest complexes, which facilitates a robust genetic exchange among elephants. Elephants in TNNP are believed to have an increased likelihood of survival and a greater ability to adapt to changes in their habitat (Karuppannan et al., 2023).

5.4.2 Conservation considerations for elephants in Peninsular Malaysia

This study highlights two main focuses needed to reduce extinction risks for Asian elephants in Peninsular Malaysia, in particular for GUMFC. Although input parameters were based on the case of GUMFC, it is believed to provide valuable insights about the species' viability for other elephant populations across the country. The conservation of elephants in Malaysia is governed and supported by various national and international master/ action plans, and policies (Saaban et al, 2011), but the execution of these plans sometimes faces various shortcomings as it involves a network of different parties with different goals. A multifaceted approach is needed to handle challenges in elephant protection, which includes habitat protection, HEC management, anti-poaching efforts, community engagements, evidence-based research, as well as genuine political will by the decision-makers.

In-situ conservation for elephants needs to focus on the habitat-specific challenges faced by the elephant populations across their distributed geographical range. In Peninsular Malaysia, the Central Forest Spine master plan was launched by the federal government in 2010 to allow the movement of elephants and other wildlife across forest complexes (Department of Town and Country Planning Peninsular Malaysia, 2010; Department of Town and Country Planning Peninsular Malaysia, 2022; Department of Wildlife and National Parks Peninsular Malaysia, 2013). However, a study by de la Torre et al. (2019) found that only 58% of 39 ecological corridors/linkages are realistically effective in allowing wildlife movements. In the case of GUMFC, although there are attempts to connect the Ulu Muda Forest Complex to another forest complex (i.e., Gunung Inas Forest Reserve) through the ecological corridors (K-PL1), but the potential of this corridor (~100 m in width) (Department of Town and Country Planning Peninsular Malaysia, 2022) being used by elephants remains unknown. In addition, the reduction and fragmentation of natural forest habitat would pose a threat to the population through the erosion or loss of heritable genetic diversity, which is required for evolutionary change and adaptation, and its loss impedes the long-term survival of species (Ortega and Maldonado, 2020). Therefore, it is important to carefully design and maintain these wildlife corridors to ensure they serve the intended purpose of reconnecting fragmented habitats and supporting the possible gene flow of the elephants. Unfortunately, this process typically involves a lengthy duration and necessitates the dedication of the respective authorities, who may occasionally face conflicts owing to their obligations to generate revenue and promote development for their states. The lack of obligation for the state to follow the federal government's conservation plan (concerning land matters) from a legal standpoint is a disadvantage for species protection in Malaysia (Or, per. comms.).

Conservation of elephant habitat necessitates the authorities to implement stringent enforcement actions in closely managing the resource extraction practices carried out by permitted companies to prevent additional loss of forest cover and unnecessary damage to the elephant habitat. For instance, illegal timber extractions by licensed or unlicensed parties in multiple forest complexes that are home to elephants, including Ulu Muda Forest Reserve, were reported in the past (Mohd, 2021; Noorazura, 2018; Anon., 2018; Jalal et al., 2015). Despite the authorities' efforts to address these incidents, they persist and require diverse forms of support, such as financial, manpower, technical, and expertise support, to sustain enforcement measures aimed at halting these illegal activities. This includes engaging local communities as vigilant informants and implementing stringent measures to combat corruption related to forestry. Besides illegal timber extraction, strict monitoring of pre- and post-logging activity should be implemented to prevent loopholes in forest management. The National Forestry Act 1984, and its amendments, mandate sustainable forest management practices including reforestation and rehabilitation of logged areas (Ministry of Energy and Natural Resources, 2021). Nevertheless, field observation made during the study period discovered that the loggers did not properly carry out the replanting obligations. The tree saplings, enclosed in polybags, were simply deposited into the deforested region without any measures taken to guarantee their survival. The majority of these purported "replanting" efforts were ultimately futile and did not contribute to the restoration of the forest (Or, per. obs.). Authorities should consider the possibility of transitioning to sustainable forest management practices, such as utilizing forest carbon credits, as a potential alternative to traditional timber extraction methods. This might be a viable source of revenue (Lau et al., 2024; Siew, 2024).

The protection of habitat for elephants should come hand in hand with efforts to reduce the unlawful removal of elephants from the landscape. All seven forest reserves of GUMFC are gazetted as a no-hunting zone by the government (Attorney General's Chambers, 2020), but signs of poaching were observed across this forest complex (Or, per obs.). Poaching activities targeting elephants or other animals pose the same risks to the survival of elephants in the forest. The snares set for other animals could potentially injure the elephants and subsequently kill them. Besides killing for profit, the retaliation killing of elephants, usually through poisoning, is increasing in Peninsular Malaysia and poses a detrimental effect on the elephant populations (Department of Wildlife and National Parks Peninsular Malaysia, 2022; Department of Wildlife and National Parks Peninsular Malaysia, 2023). This could be due to an increase in HEC cases, which see the diminishing tolerance towards elephant encroachments into plantation areas, as well as settlement areas. HEC cases have rapidly increased in recent years, from 448 reported cases in 2018 to 835 reported cases in 2021 (Department of Wildlife and National Parks Peninsular Malaysia, 2018; Department of Wildlife and National Parks Peninsular Malaysia, 2021b). In 2018, the wildlife department conducted a total of 8 forensic investigations into the death of elephants; however, the results of the inquiry were not disclosed (Department of Wildlife and National Parks Peninsular Malaysia, 2018). Such unlawful killings of elephants pose an immediate threat to the wild population of elephants. Strong enforcement strategies have to be in place and strictly implemented to prevent the intentional unlawful removal of elephants.

Human-elephant conflict issues must be addressed with great care, as they directly impact the well-being of communities affected by elephants, as well as the safety of the elephants. The current policy in wildlife-human conflict management places greater importance on the well-being of humans rather than animals, which permits the lawful killing of elephants when necessary (Saaban et al., 2011). Promoting coexistence between humans and elephants as intended by the government (Department of Wildlife and National Parks Peninsular Malaysia, 2023) could be a viable solution, but it requires comprehensive study and meticulous planning to ensure its success. This approach involves understanding the complexities of human-elephant interactions, ensuring safety, assessing habitat availability, and understanding how elephants are responding to their environmental changes. It also demands the commitment of various stakeholders, including local communities, to champion the protection of elephants. For instance, the common practice of translocating elephants from a conflict area to a new landscape has proven to be less effective (Wadey, 2020); thus, revising or reassessing such a strategy to mitigate the impacts of the lawful removal of elephants from their habitats should be considered. Innovative HEC mitigation measures, such as providing non-lethal deterrent technologies to local communities, could be explored and developed to prevent the killing of elephants. At the same time, it is essential to involve communities in elephant conservation projects to promote the coexistence of humans and elephants. This approach is critical for enhancing their comprehension of HEC concerns and ultimately raising their acceptance of elephant encroachments (in a controlled manner). By doing so, we can cultivate a harmonious and sustainable connection between humans and elephants in the long run. The implementation of a coexistence relationship, in conjunction with other conservation initiatives mentioned earlier, has the potential to mitigate the threat of extinction faced by elephant populations in Malaysia and facilitate their population growth.

In conclusion, the preservation and conservation of elephant populations in Peninsular Malaysia should pay attention to the immediate threats highlighted in this study. In the case of GUMFC, preserving its natural habitat with minimal removal of elephants is essential for the viability of its elephant population and numerous other species that rely on this keystone species. This study offers significant insights for the planning of elephant conservation, aiding in the prioritization and execution of efficient strategies to guarantee the viability of elephant populations throughout Peninsular Malaysia. This would require cooperation among researchers, conservationists, local communities, governmental agencies, organisations, and companies to tackle the diverse obstacles encountered in the conservation strategies.

CHAPTER 6: GENERAL DISCUSSION AND CONCLUSION

6.1 GENERAL DISCUSSION

6.1.1 Synthesis: Elephant population status in northern Peninsular Malaysia

The study evaluated the wild elephant population in Peninsular Malaysia's northern region, focusing on the Greater Ulu Muda Forest Complex (GUMFC), Gunung Inas-Bintang Hijau Forest Complex (GIBHFC), Royal Belum State Park (RBSP), and Temengor Forest Complex (TFC). This study examines three ecological aspects of elephants and provides an overview of the elephant population status in this region. The combination of elephant population density estimation (Chapter 2), habitat use and prediction (Chapter 3), and viability analysis (Chapter 4) provides crucial insights about elephants in these forest complexes, which are vulnerable mainly due to habitat loss and fragmentation, human-wildlife conflict, and removal of elephants from the habitats. It also provides insights into the vulnerability of current elephant populations to varying levels of resource management (e.g., forest and wildlife management scenarios) and catastrophic events. Such information is essential to complement the ongoing elephant conservation efforts in Malaysia.

The estimated elephant population size in GUMFC proves that it sustains nearly 20% of the elephant populations reported for Peninsular Malaysia, and this forest complex, amongst the few intact forest complexes in Peninsular Malaysia, should be better protected and prioritised for elephant conservation. Although this forest complex seems to have a respectable number of elephants, the population viability assessment shows that elephants in GUMFC pose a great risk of future extinction from this landscape if the current threats (e.g., influence of forest cover and removal of elephants) toward elephants are not eliminated or significantly reduced (see Chapter 4 for more details). Findings from this study should be treated seriously, as they indicate a few scenarios that induced the high 'local' extinction risks. Besides that, the conservation of elephants in GUMFC should also take into account other factors that could jeopardize the survival of elephants in this landscape, such as its loss of connectivity to other elephant habitats, and its long-term effects (possible weakening of genetic conditions) on the viability of the current population in adapting to environmental changes.

One critical factor affecting the elephant's number, distribution, and viability is the availability of suitable habitats for their current and future survival. This topic was explored and discussed in Chapter 3, in which elephants' habitat uses predictions show that not all areas previously known to be home to elephants are suitable for elephants, after accounting for selected natural and anthropogenic ecological variables. Topographical characteristics (i.e., elevation) and anthropogenic factors (i.e., proximity to indigenous settlement and proximity to plantation) significantly influence elephant habitat utilization. This emphasises the need to understand elephant habitat requirements and the alterations (both historical and anticipated) in their environment to determine the areas that should be given higher priority for elephant habitat. Nonetheless, preserving the overall areas of GIBHFC, TFC, and RBSP is critical for the sustenance of elephants in the northern region.

In addition to the above findings, another important factor that has not been thoroughly studied but is believed to play a significant role in defining the distribution and vitality of elephants in Peninsular Malaysia would be the interactions between humans and elephants. Human-elephant interactions have become an issue that has induced retaliation killings towards elephants, where elephants are considered pests instead of a species that the nation should cherish. A study by Lim (2018) on the interaction between humans and elephants, focusing on the indigenous community, offers valuable insights into these interactions. A similar study should be explored to cover other stakeholders such as farmers, plantation companies, and local communities living close to elephant habitats. The information generated from such a study could complement the assessment of the elephant population in Peninsular Malaysia.

In summary, all study locations encompassed in this research can be regarded as primary landscapes for facilitating elephant conservation in the northern region and enhancing the overall sustainability of the species. Findings from this study provide valuable insights to improve elephant conservation initiatives in Peninsular Malaysia, especially in the specified study areas. It is important to note that the preservation of elephants is complex and requires the collaboration of multiple stakeholders for sustainable and successful conservation efforts. The next part examines the dynamics of elephant conservation in Peninsular Malaysia, pertinent to the scope of this study, and briefly discusses the roles and interrelations of each component.

6.1.2 Dynamics of elephant conservation in Peninsular Malaysia

The protection of elephants in Malaysia has numerous challenges at various management levels, compounded by conflicting interests among stakeholders and limited resources. Nonetheless, the preservation of this largest terrestrial mammal remains a priority on the national agenda. In a recent development, the government of Malaysia launched the second National Elephant Conservation Action Plan (2023 to 2030; NECAP 2.0), which consists of five objectives, 11 strategies, and 30 actions to guide elephant conservation efforts (Department of Wildlife and National Parks Peninsular Malaysia, 2023). This action plan was produced with the support of local researchers, Non-Governmental Organisations, and the IUCN SSC Asian Elephant Specialist Group (AsESG) (Department of Wildlife and National Parks Peninsular Malaysia, 2023).

The complex dynamics of elephant conservation in Peninsular Malaysia are illustrated in Figure 6.1. The conservation strategies for elephants are driven by three key components, namely the government (decision-makers in the management of natural resources and national development), scientific research (provides advice on the conservation efforts based on

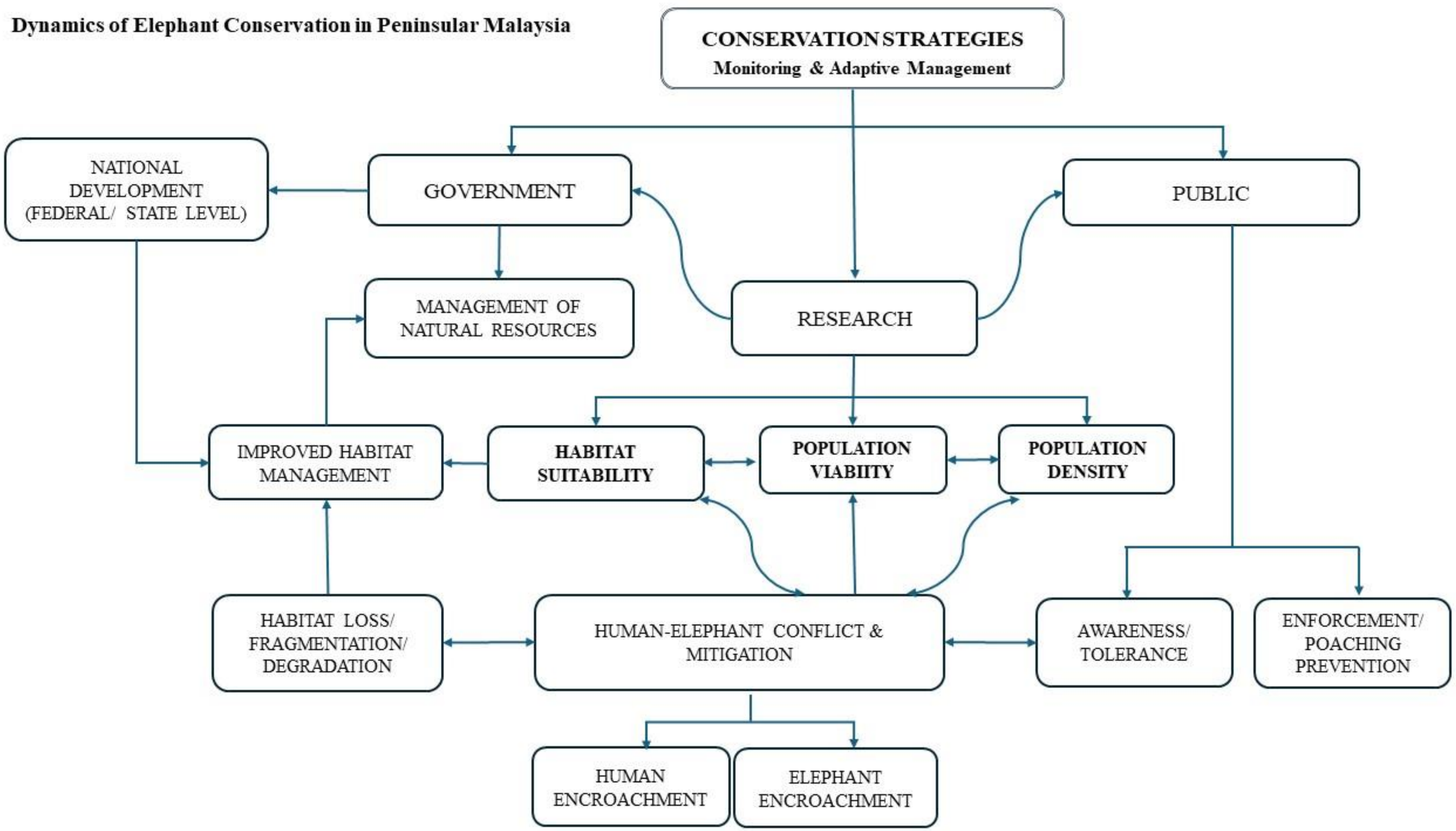


Figure 6.1 The dynamics of elephant conservation in Peninsular Malaysia necessitate attention and collaboration among various stakeholders.

evidence), and the public that is inclusive of the general public and local communities that share the same landscape with elephants (an essential player in supporting conservation). This study provides a timely assessment of elephants in the northern Peninsular, based on three components (density, habitat utilization, and population viability), to strengthen conservation initiatives, emphasizing the need to disseminate information to decision-makers and share knowledge with the public. The flow chart uses arrows to show how these components and strategies influence each other, highlighting the interdependency nature of elephant conservation efforts. It emphasises both the positive actions needed and the challenges that must be addressed to ensure the survival of elephants in Malaysia.

The population density and viability of wild elephants are closely linked to the availability of suitable habitats that can support the growth of the elephant population (Alfred et al., 2012; Sukumar, 2003), which in turn plays a crucial factor in determining the sustainability of the elephant population. However, the conservation of elephants in Malaysia is confronted by the alteration and shrinking of natural forests that serve as their habitats (Department of Wildlife and National Parks Peninsular Malaysia, 2023). The preservation of suitable habitats for elephants is a complex topic on its own, especially when the conservation of respective forested landscapes conflicts with the nation's development projects. This is due to the necessity for the state government to earn income and foster development within its authority. For instance, at the writing of this manuscript, the federal government initiative of the Central Forest Spine (CFS) was only adopted by six out of seven state governments that have elephants (Or, per. comms.), with news of one state plans to remove protections for vast areas of forest identified as CFS areas (Reklev, 2023). In this context, the protection of the elephant habitats (forests) needs a political will from the governing body.

On a positive note, in recent years, information about wildlife and its ecological habitats has started to be integrated into the nation's development plan, compared to the previous practices where wildlife components were often left out in the planning stage (Or, per. comms.). This facilitates the identification of critical areas to be excluded from the development plan or the implementation of mitigation measures to reduce the impact on wildlife habitats. For instance, the East Coast Rail Link (ECRL) in Peninsular Malaysia has implemented measures to mitigate the impact of construction on wildlife and its habitat (Choong, 2022; Anon., 2023). The initiatives include tunnelling through forest reserve areas that enabled a 90% reduction of forest loss from 2,000 ha to 276 ha, establishing viaducts and wildlife crossings (e.g., wildlife box culverts for large animals such as elephants), and providing at least MYR 9 million to support wildlife management (e.g., conflict control, habitat enrichment), and public awareness (Choong, 2022; Anon., 2023). Such initiative by the government safeguards the natural habitat of elephants in the respective areas, which is essential for environmental stability and ensuring their long-term survival.

This study also briefly examines the impact of human-elephant conflicts on elephant habitat utilization and population viability. Human-elephant conflicts can arise from two scenarios, either human activity encroaching upon forested areas (elephant habitats) or elephant ventures into human settlements, plantations, or farms (usually by the periphery of the forest). Humans are inherently unable to control large elephants due to their size and considerable strength, and when human-elephant conflicts arise, humans often perceive themselves as the disadvantaged party and view the situation negatively. Actions taken to mitigate HEC issues, as well as factors contributing to HEC such as habitat loss, land use changes, and an increase in human populations, should be examined to provide a thorough understanding of the HEC.

Having an in-depth understanding of elephants' habitat use, population size, natural behaviours (in the forest and human-associated landscape), and other ecological aspects will help in developing more effective HEC mitigation measures that would not jeopardize the existence of elephants in the area. For instance, one of the HEC mitigation strategies is to translocate elephants in conflict from their original habitat to a different location when other mitigation techniques (e.g., discharging firearms to generate noise to force elephants back into the forest) are deemed futile. The translocation of elephants is not entirely conflict-proof, as translocated elephants have been observed returning to their original habitat (up to 80 km) (Wadey, 2020), and their presence in the new area may create conflicts at the release sites (as asserted by the indigenous communities living in the study areas (TFC, RBSP)). Today, the translocation of elephants is one of the reasons that explains the absence of these animals in some forested areas, with their distribution now limited to seven states (Department of Wildlife and National Parks Peninsular Malaysia, 2017a; Khan, 2012). Regrettably, this technique remains in use as we have yet to identify a viable alternative to address the HEC concerns, especially when it threatens the safety of the people.

The cultivation of tolerance through understanding elephants is a crucial element in HEC mitigation strategies, and hence overall conservation success. The public, especially communities affected by HEC, must be equipped with correct information about HEC, its contributing factors, and safety measures for handling interactions with elephants. Enhancing public understanding of the vital role elephants play in sustaining the forest ecosystem, upon which humans rely, and their conservation status is another element that must be encouraged to deter unlawful actions (e.g., poaching, retaliation killing) that could harm the survival of this endangered species. Therefore, regular public engagements by stakeholders are vital for cultivating a comprehensive awareness about elephants, a key element that may increase tolerance and promote their protection. This step is essential to achieve the NECAP aim of managing and protecting a healthy elephant population through shared responsibility at all community levels, hence the vision to coexist.

In addition to this study, the integration of field data collected by other stakeholders (e.g., researchers, government or non-government entities, plantation companies, etc.) who conduct research in the forest, or areas with elephant encroachments (e.g., plantations, orchards, settlement areas) should be encouraged. For instance, information gathered for the National Tiger Survey that covers the whole of Peninsular Malaysia was used to support NECAP (Department of Wildlife and National Parks Peninsular Malaysia, 2023). Wildlife monitoring data from various organisations (e.g., SMART patrolling data from WWF-Malaysia, RIMAU, and Perak State Park Corporations) operating inside elephant habitats could offer significant insights to address existing knowledge gaps if well-utilised. Generally, the wildlife monitoring procedure entails recording indicators of poaching, mortality, wildlife or human activity, and other unusual discoveries (e.g., snares, camps, etc.) (Or, per. comms.). This knowledge may be crucial for enhancing the research and comprehension of elephants in their natural habitat, such as the threats and dangers presented by poaching. However, the challenges associated with utilizing such information may arise from the lack of standardized methodologies and skills required for data analysis and the willingness of data sharing amongst these parties.

In summary, effective elephant conservation efforts in Peninsular Malaysia require the participation of all stakeholders, as illustrated in Figure 5.1. Scientific research findings served as crucial tools for promoting improved protection of species and their habitats, forming the basis for conservation efforts. The integration of population density assessments, habitat utilization studies, and viability analyses establishes a robust framework for the management and conservation of Asian elephants. Further exploration of several academic areas on elephants may yield a more comprehensive understanding of their status in Malaysia.

6.1.3 Future research

Long-term field studies of wild elephants are necessary for a better understanding of the ecology and conservation of elephants, a keystone species that has a long lifespan (60-70 years)

(Fritz, 2017). This document highlights four critical research aspects essential for promoting the sustainability of elephants in Malaysia.

Firstly, the status of elephant populations in various forested landscapes in Peninsular Malaysia requires a timely update, as the last methodical assessments at selected sites (i.e., Endau Rompin Landscape in the south, and Taman Negara National Park in the central region) were conducted in 2008, nearly 16 years ago. Updated population surveys and monitoring are essential to understand current population dynamics, distribution, and trends, which are lacking in Malaysia. This information will help identify areas where conservation efforts are most needed and evaluate the effectiveness of existing conservation measures. Advanced technologies such as satellite tracking, camera traps, and genetic studies can provide valuable insights into elephant populations in Malaysia. At the writing of this manuscript, it is believed that the government of Malaysia has been formulating a plan to conduct a National Elephant Survey across elephant habitats in Peninsular Malaysia (Department of Wildlife and National Parks Peninsular Malaysia, 2023).

Secondly, the elephant distribution in forested areas across Peninsular Malaysia will need to be further assessed to gain a thorough understanding of site-specific population dynamics. This is due to the high variability in land use, forest conservation and management, human-wildlife interactions, and the geographical differences of the forests across different states. A potential aspect of the study is to investigate the impact of forest and land use alterations on elephants (e.g., deforestation, agricultural expansion, and urbanization), considering both short-term and long-term effects. This is a piece of crucial information given that significant land use changes in Peninsular Malaysia over the years could have undocumented effects on the elephant populations. Understanding these impacts (e.g., impacts on elephants such as behavioural changes, population density and viability, and effects on the environment such as habitat quality, etc.) can inform targeted conservation strategies.

Third, a thorough comprehension of elephant behaviour in their native habitats and in regions where human-elephant interactions take place, such as plantations and settlement areas, is needed. Nonetheless, we recognize that observing the behaviour of wild elephants in tropical rainforest environments may be unfeasible, in contrast to the open areas where elephants are consistently visible. However, a focused examination of elephant behaviour and their association with human presence (e.g., adaptation characteristics, encroachment motivations, etc.) can guide mitigation efforts in HEC. This will allow a reduction in unnecessary removal of elephants from the landscape, a risk factor that could jeopardize the elephant population in a particular landscape. Besides that, a thorough systematic analysis of human-elephant conflict management strategies, customized for Peninsular Malaysia by many stakeholders, is crucial for assessing and determining practical solutions to facilitate cohabitation between humans and elephants. The utilization of advanced technologies such as Artificial Intelligence (AI) and machine learning (ML) may prove beneficial for elephant conservation (e.g., HEC, etc.) (Brickson et al., 2023). and warrants exploration to enhance research and conservation initiatives. Such technologies have been tested to manage and extract vital information from vast data gathered from a variety of conservation tools such as cameras, microphones, drones, and satellite information (Brickson et. al., 2023).

Finally, a comprehensive examination of elephant population genetics (e.g., genetic variation, population heterogeneity, genetic evolution, etc.) by using non-invasive techniques will significantly enhance our understanding of elephants in Malaysia and contribute to their conservation efforts. A recent study by Karuppannan et al. (2023) investigated the genetic aspects of elephants in Peninsular Malaysia, thereby enhancing the nation's understanding of the genetic characteristics of our elephant population. Previous research on Bornean elephants by Fernando et al. (2003b) and Sharma et al. (2018) explains the origins of Bornean elephants, a subspecies of Asian elephants. This shows the potential of genetic study in the overall conservation of elephants in Malaysia.

By addressing the above research areas, conservation efforts can be more targeted, practical, and effective, ensuring the long-term survival of elephants in Peninsular Malaysia.

6.2 BROADER CONSERVATION IMPLICATIONS

This thesis, which integrates dung-based DNA analysis, habitat use assessment, and population viability analysis (PVA), offers valuable insights not only for the conservation of Asian elephants in Malaysia but also for broader applications in landscape ecology, conservation planning, and tropical wildlife management. While the study is grounded in forested landscapes of northern Peninsular Malaysia, the tools, data, and conceptual frameworks developed here have relevance that extends across species, regions, and disciplines.

At the national level, the study addresses critical knowledge gaps outlined in both the National Elephant Conservation Action Plan (NECAP 1.0 and 2.0). It delivers foundational baseline data on elephant density, habitat use, and population viability in the Greater Ulu Muda Forest Complex (GUMFC), a key conservation area and one of the last remaining strongholds for elephants in the region. These findings are particularly timely as Malaysia moves forward with NECAP 2.0 (2024–2034) and implements the National Elephant Survey (NES), to which this study can contribute valuable empirical support.

The habitat uses findings further identify high-priority zones for conservation and restoration within the Central Forest Spine (CFS), supporting more effective land-use planning, ecological corridor design, and mitigation of human-elephant conflict issues. Understanding elephants' spatial ecology and responses to human activities is crucial for developing habitat-based conservation strategies, particularly in forest-agriculture mosaics that are increasingly prevalent in Southeast Asia's landscapes.

Though focused on elephants, the methods used, such as dung-based genetic sampling, occupancy modelling, and viability simulation, are highly transferable to other wide-ranging or elusive species. The non-invasive techniques used in this study can be applied to species such as the Malayan tapir (*Tapirus indicus*) and the gaur (*Bos gaurus*), as well as large carnivores, particularly in contexts where direct observation is limited by terrain or logistical constraints. The genetic component, while elephant-specific in this case, underscores the rising importance of molecular ecology in conservation science. Future research across taxa should further integrate genetic tools to assess health, connectivity, and resilience, thereby strengthening both species-level management and landscape-scale biodiversity planning.

Additionally, the spatial and habitat modelling conducted in this study reveals how large mammals interact with tropical forest ecosystems under varying human pressures. These patterns have broader conservation implications, as they can help identify biodiversity hotspots that support co-occurring taxa such as smaller mammals, birds, and amphibians. In this way, elephant-centred conservation efforts serve as effective proxies for safeguarding broader ecosystem integrity.

The PVA analysis provides a practical framework for assessing extinction risks and testing management outcomes under diverse future scenarios. By using realistic demographic inputs, the study offers insights into how elephants in GUMFC may respond to landscape changes and anthropogenic pressures. While the model employed was streamlined to match available data, future research could build on this foundation by using complementary tools, such as RAMAS, for more complex or spatially explicit assessments. Notably, the viability modelling approach demonstrated here can be adapted to support conservation planning for other long-lived, threatened, or data-deficient species facing similar ecological challenges.

From a policy perspective, this thesis strengthens the scientific foundation for evidence-based decision-making. Its findings on population trends, critical habitats, and conflict-prone zones can inform the development of targeted conservation actions, land-use regulations, and funding priorities. While elephants often serve as flagship species, their conservation, if guided by rigorous data, can produce cascading benefits for broader biodiversity and ecosystem services. Furthermore, this study reinforces the importance of integrated conservation approaches that account for the socio-ecological complexity of human-wildlife interactions. Insights into land use, crop distributions, and community dynamics provide guidance for managing wildlife in human-dominated landscapes, where conservation efforts must be aligned with development, agriculture, and the livelihoods of indigenous and local communities.

Ultimately, this research bridges species-specific science with landscape-level conservation. By combining robust fieldwork, spatial modelling, and predictive analysis, it produces actionable insights with far-reaching relevance. The frameworks, methods, and data developed here provide a strong foundation for addressing the complex and interconnected challenges of biodiversity conservation, both within Malaysia and across tropical forest ecosystems in the Anthropocene.

6.3 LIMITATIONS OF THE STUDY

This study faced several methodological and logistical limitations that may have influenced its scope and execution.

A significant limitation in estimating elephant density through faecal DNA analysis was the difficulty in obtaining fresh dung samples containing high-quality DNA, particularly within the limited timeframe and under the challenging conditions of the tropical rainforest. Environmental exposure often led to rapid DNA degradation, rendering some samples unusable. Moreover, the volume of collected samples exceeded initial expectations, resulting in underestimated costs and extended processing time, which posed logistical and financial challenges during laboratory work.

Fieldwork was also constrained by significant logistical challenges, particularly in the ecological and habitat use components. The remote and rugged terrain, coupled with unpredictable weather and safety risks, made field access demanding. In some areas, access was further limited due to resistance from local indigenous communities, despite the study having received the necessary research approvals. These constraints reduced the spatial extent of the surveys, especially in the habitat use analysis (Chapter 4).

Nevertheless, every effort was made to follow the study design and make the most effective use of the data collected. Field teams were committed to achieving broad site coverage, and the final dataset met the minimum standards required for reliable occupancy and genetic analyses. The data analysis was conducted with careful attention to the dataset's limitations and variability, using appropriate statistical and spatial modelling techniques to ensure robust and meaningful results.

In conclusion, while the study was not without its challenges, rigorous field protocols and analytical diligence helped mitigate the impacts of these limitations, allowing the research to produce valuable insights into elephant population density, habitat use, and long-term viability.

6.4 GENERAL RECOMMENDATIONS

Based on the findings of this study, several key recommendations are proposed to guide future research and enhance conservation strategies for Asian elephants in Peninsular Malaysia, particularly within the Greater Ulu Muda Forest Complex (GUMFC):

1. **Strengthen Non-Invasive Genetic and Health Monitoring**

   Future research should incorporate genetic and physiological analyses using non-invasive faecal samples to assess the health, genetic diversity, and population structure of elephants. These studies will enable long-term monitoring of population viability and help reveal how elephants adapt to environmental and anthropogenic changes over time.

2. **Integrate Movement, Habitat Use, and Anthropogenic Factors in Monitoring**

   A deeper understanding of elephant movement patterns and habitat utilization within the Greater Ulu Muda Forest Complex (GUMFC) is essential for developing effective conservation strategies. Future efforts should integrate data on population density, habitat preferences, movement ecology, and human-related pressures (e.g., poaching and human-elephant conflict) to create comprehensive monitoring and management frameworks that can be applied across Peninsular Malaysia.

3. **Promote landscape-level habitat viability assessments**

   Habitat-based analyses that incorporate landscape biophysical features and spatial environmental data should be undertaken to evaluate the long-term viability of elephants. Conducting these assessments at site-specific levels would be particularly valuable, as different ecological and anthropogenic factors may uniquely influence how elephants use various habitats. Although this study provides preliminary insights into how elephants interact with their environment, more detailed and spatially targeted assessments would support a more comprehensive understanding of habitat suitability and enhance landscape-level conservation planning.

4. **Address human-elephant conflict through adaptive land management**

   In landscapes where elephants coexist with agricultural areas and human settlements, further research is needed to understand how elephants adapt to human presence and activities. The presence of people within or surrounding these landscapes and associated activities such as farming, infrastructure development, and land-use change can significantly affect elephant movement and behaviour. Land-use modifications, such as cultivating crops that are less attractive to elephants and implementing adaptive management strategies, should be thoroughly explored to reduce crop raiding and other forms of human-elephant conflict. These strategies should be grounded in scientific evidence and developed in consideration of local ecological conditions and the socio-economic realities of surrounding communities

5. **Align community support with conservation goals**

   When providing assistance to indigenous and local communities residing within or adjacent to elephant habitats, stakeholders, including government agencies, NGOs, and researchers, should ensure that such support is guided by ecological understanding and aligned with broader conservation priorities. Human settlements, land-use practices, and ongoing development activities in and around these landscapes can significantly influence elephant movement, behaviour, and conflict dynamics. For example, Corporate Social Responsibility (CSR) initiatives that promote the distribution of crops such as rubber or durian trees should be carefully assessed and accompanied by appropriate mitigation measures to reduce the risk of human-elephant conflict. Without such integrated planning, well-intentioned livelihood support programs may inadvertently heighten tensions between communities and wildlife, ultimately compromising both human well-being and long-term conservation outcomes.

6. **Establish a long-term, standardized monitoring program**

   A consistent and well-designed long-term monitoring framework should be established to systematically collect demographic, ecological, and genetic data on elephant populations. Such a framework will enable timely assessments of population health, trends, and viability in response to environmental changes, emerging threats, or shifting conservation priorities. Advances in genetic research, particularly through non-invasive methods, should be actively incorporated, as they can provide critical insights into population structure, genetic diversity, relatedness, and inbreeding levels, all of which are vital indicators of the long-term resilience of elephant populations. The success of this monitoring effort will depend on strong collaboration among government agencies, conservation agencies, academic institutions, local communities, and other stakeholders committed to evidence-based and adaptive elephant conservation.

7. **Reevaluate population viability under future stressors**

   Population Viability Analyses (PVA) should be periodically revisited, especially as new stressors such as habitat loss, climate change, or genetic concerns emerge. Ideally, PVAs should be tailored to specific habitat types, as elephants in different regions may face distinct ecological and anthropogenic challenges. While this study applied a more simplified or individual-based modelling approach, future research should consider alternative tools such as the RAMAS software, which offers a structured, stage- or age-based matrix modelling framework well suited for long-lived species like elephants. Unlike individual-based models, RAMAS can incorporate spatially explicit metapopulation dynamics and handle environmental variability more flexibly. Employing such tools would enhance the robustness and adaptability of conservation planning by allowing more nuanced scenario testing and risk assessments under a range of future conditions.

6.5 CONCLUSION

The tropical rainforest in Malaysia and its key inhabitants, such as elephants, are an important national treasure and will continue to play essential roles in ensuring the stability of the ecosystem, that are closely linked to the socioeconomic development of the country and the well-being of the people (Rome, 2020). This study confirmed that the northern region of Peninsular Malaysia is still home to a substantial number of elephants and generally provides a suitable habitat for elephants. These forested complexes (i.e., GUMFC, TFC, RBSP, and GIBHFC) play critical roles in sustaining elephant populations, highlighting the need to be recognized as high-priority areas for elephant conservation. Nevertheless, the viability assessment concludes that the elephant population in GUMFC may be at risk of extinction and warrants additional measures to mitigate the predicted risks.

As long-lived species with extensive habitat needs, elephants will continue to be impacted by the nation's development, demanding the implementation of various conservation strategies that cover various ecological aspects and anthropogenic factors. The application of adaptive management backed by evidence-based information is needed to accommodate the evolving circumstances in the conservation of elephants over the years. Key strategies for elephant conservation in Peninsular Malaysia should focus on i) habitat preservation and management, ii) monitoring and preservation of remaining elephant populations, iii) human-elephant conflict management, iv) evidence-based advocacy (for decision makers), and v) public participation in conservation.

Continuous monitoring of elephant populations and preservation of their conservation areas, along with appropriate natural resource management, must be implemented for both the short and long term. Besides that, a long-term study of elephant population dynamics, habitat utilization, and behaviour may provide significant insights into their life histories and how they respond to environmental changes, which would benefit the long-term conservation of this species.

Ultimately, this study advocates for the incorporation of conservation measures with national development at various levels to preserve the remaining elephant populations in Malaysia.

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8.0 APPENDICES

Appendix I (Chapter 3)

List of microsatellite markers that were tested in the process of selecting suitable primers for the samples.

Loci	Size range (bp)	Amplification success (Yes/ No)	Temperature range (°C)	Optimum Temperature (°C)
EMU1	78-82	No	56-58	56-58
EMU2	108-116	No	56-58	56-58
EMU3	137-147	Yes	56-57	56
EMU4	97-107	Yes	56-57	57
EMU5	114	Yes	56-57	56
EMU6	146-158	Yes	56-58	56
EMU7	102-122	Yes	57-58	57
EMU8	115-127	Yes	56-59	56
EMU9	463-169	Yes	56-57	57
EMU10	94-104	Yes	56-57	56
EMU12	120-152	Yes	56-58	56
EMU13	100-110	Yes	59-63	59
EMU14	130-138	Yes	56-58	56-58
EMU15	142-154	Yes	56-58	56-57
EMU17	119-137	Yes	56-59	56-58
EMX1	137-152	Yes	56-58	56
EMX2	217-223	Yes	58	58
EMX4	351-387	No	56-58	56-58
FH60	198-162	Yes	56-57	57
FH94	241-228	Yes	57-58	58
LaFSM02	133-141	Yes	56-57	57
LaFSM03	137-155	No	56-58	56-58
LaFSM05	144-156	Yes	56-58	56-57

Appendix II (Chapter 3)

The initial findings were obtained for different sample categories (based on missing loci), according to different 'alleleMismatch' variables.

alleleMismatch	matchThreshold	cutHeight	samples	unique	unclassified	multiple Match	guess Optimum	missing DataLoad	allelic Diversity
No. of sample: 37, Missing values: 0									
0	1	0	37	33	0	0	FALSE	0.005	3.5
1	0.9375	0.0625	37	32	0	4	TRUE	0.005	3.5
2	0.875	0.125	37	29	0	12	FALSE	0.005	3.5
3	0.8125	0.1875	37	22	1	15	FALSE	0.005	3.5
4	0.75	0.25	37	15	0	21	FALSE	0.005	3.5
5	0.6875	0.3125	37	10	3	21	FALSE	0.005	3.5
6	0.625	0.375	37	6	2	6	FALSE	0.005	3.5
No. of sample: 77, Missing values: 1									
0	1	0	77	73	0	0	FALSE	0.071	4.9
1	0.9375	0.0625	77	72	0	12	FALSE	0.071	4.9
2	0.875	0.125	77	65	0	28	FALSE	0.071	4.9
3	0.8125	0.1875	77	46	1	25	TRUE	0.071	4.9
4	0.75	0.25	77	30	1	47	FALSE	0.071	4.9
5	0.6875	0.3125	77	19	4	44	FALSE	0.071	4.9
6	0.625	0.375	77	12	3	45	FALSE	0.071	4.9
No. of sample: 101, Missing values: 2									
0	1	0	101	97	0	0	FALSE	0.115	6
1	0.9375	0.0625	101	96	0	12	TRUE	0.115	6
2	0.875	0.125	101	89	0	33	FALSE	0.115	6
3	0.8125	0.1875	101	66	2	45	FALSE	0.115	6
4	0.75	0.25	101	38	3	66	FALSE	0.115	6
5	0.6875	0.3125	101	24	8	56	FALSE	0.115	6
6	0.625	0.375	101	17	4	54	FALSE	0.115	6

Appendix II continued

No. of sample: 118, Missing values: 3									
0	1	0	118	114	0	0	FALSE	0.153	6.6
1	0.9375	0.0625	118	113	0	16	FALSE	0.153	6.6
2	0.875	0.125	118	104	0	37	FALSE	0.153	6.6
3	0.8125	0.1875	118	76	2	55	FALSE	0.153	6.6
4	0.75	0.25	118	49	2	76	FALSE	0.153	6.6
5	0.6875	0.3125	118	31	8	70	TRUE	0.153	6.6
6	0.625	0.375	118	21	3	74	FALSE	0.153	6.6
No. of sample: 128, Missing values: 4									
0	1	0	128	124	0	0	FALSE	0.18	6.5
1	0.9375	0.0625	128	123	0	17	FALSE	0.18	6.5
2	0.875	0.125	128	113	0	37	FALSE	0.18	6.5
3	0.8125	0.1875	128	85	1	60	FALSE	0.18	6.5
4	0.75	0.25	128	54	3	83	FALSE	0.18	6.5
5	0.6875	0.3125	128	33	8	80	TRUE	0.18	6.5
6	0.625	0.375	128	20	3	80	FALSE	0.18	6.5

Appendix III (Chapter 3)

No.	Elephant ID	focal Index	Dung size	LafMS02 A	LafMS0 2B	LafMS05 A	LafMS0 5B	EMX2 A	EMX2B	EMU7A	EMU7B	EMU10A	EMU10 B	EMU13A	EMU13B	EMU15A	EMU15B	EMU17 A	EMU17 B
1	**U1-T2S20**	T2S20	32	131	133	151	151	222	222	101	113	89	89	98	104	151	151	115	119
	RU1	T2S22	38	131	131	151	151	222	222	101	113	89	89	98	104	151	151	119	119
	RU1	T2S31	41	131	133	151	151	222	222	101	101	89	89	100	104	151	151	115	119
	RU1	T3S31	41	131	133	151	151	222	222	101	113	89	89	98	104	151	151	117	121
	RU1	T3S48	43	131	131	151	151	222	222	101	113	89	89	98	104	151	151	119	119
	RU1	T5S107	39	-99	-99	151	151	222	222	101	113	-99	-99	98	104	151	151	117	121
2	**U2-T2S24**	T2S24	40	131	131	151	151	222	222	103	103	89	89	98	104	-99	-99	119	119
	RU2	T8S10	46	131	131	151	151	222	222	101	101	89	89	98	104	149	149	119	119
3	**U3-T2S28**	T2S28	39	131	131	151	151	222	222	113	113	89	89	98	104	-99	-99	119	119
4	**U4-T2S29**	T2S29	29	131	133	151	151	222	222	113	113	89	99	100	104	151	151	115	115
	RU4	T2S34	38	131	133	151	151	222	222	113	113	-99	-99	100	104	151	151	115	115
5	**U5-T2S30**	T2S30	35	131	131	151	151	222	222	-99	-99	89	89	100	104	151	151	115	135
6	**U7-T2S32**	T2S32	33	131	133	151	151	222	222	101	107	89	89	-99	-99	151	151	115	119
7	**U8-T2S33**	T2S33	38	131	131	151	151	222	222	-99	-99	89	89	98	104	151	151	115	115
	RU8	T2S36	38	131	131	151	151	222	222	-99	-99	89	89	98	100	151	151	115	115
	RU8	T8S01	41	131	131	151	151	222	222	101	101	89	89	98	98	151	151	115	115
	RU8	T8S50	37	131	133	151	151	222	222	101	101	89	89	98	100	151	151	115	115
	RU8	T5S81	41	131	131	153	153	222	222	101	101	89	89	100	100	-99	-99	115	125
	RU8	T5S74	44	131	131	151	151	222	222	101	101	89	89	100	100	-99	-99	115	125
	RU8	T8S16	47	131	133	151	151	222	222	101	101	89	89	98	100	151	151	115	125
	RU8	T7S20	42	-99	-99	151	151	222	222	101	101	89	89	98	98	151	151	115	115
8	**U10-T2S35**	T2S35	39	131	131	151	151	222	222	-99	-99	89	89	104	104	-99	-99	121	121
9	**U11-T2S37**	T2S37	42	131	133	149	149	222	222	-99	-99	89	89	98	100	149	149	117	119
10	**U12-T3S04**	T3S04	32	123	123	151	151	222	222	-99	-99	89	89	-99	-99	-99	-99	119	119
11	**U13-T3S08**	T3S08	36	131	131	151	151	222	222	101	113	89	89	104	104	-99	-99	-99	-99
12	**U14-T3S30**	T3S30	48	131	133	149	151	222	222	101	123	89	99	98	104	-99	-99	121	121
13	**U15-T3S34**	T3S34	29	131	131	151	151	222	222	101	101	89	89	98	104	151	151	117	119
	RU15	T3S76	28	131	131	151	151	222	222	101	101	89	89	98	104	151	151	117	119
	RU15	T5S79	37	131	131	151	151	222	222	101	101	89	89	98	104	151	151	115	119
14	**U16-T3S46**	T3S46	38	131	133	143	153	222	222	101	101	89	99	98	104	143	153	117	135
	RU16	T3S47	44	131	133	143	153	222	222	101	101	89	99	98	104	143	153	117	135
15	**U17-T3S58**	T3S58	43	131	137	151	151	222	222	101	113	89	89	100	104	-99	-99	119	125
16	**U18-T3S74**	T3S74	49	131	131	151	151	222	222	101	113	89	89	98	98	151	151	117	117

Appendix III continued

No.	Elephant ID	focal Index	Dung size	LafMS02 A	LafMS0 2B	LafMS05 A	LafMS0 5B	EMX2 A	EMX2B	EMU7A	EMU7B	EMU10A	EMU10 B	EMU13A	EMU13B	EMU15A	EMU15B	EMU17 A	EMU17 B
17	**U19-T4S05**	T4S05	52	133	133	-99	-99	222	222	101	103	89	89	100	104	-99	-99	119	135
18	**U20-T4S07**	T4S07	44	133	133	151	151	216	222	101	101	89	89	98	98	151	151	115	119
	RU20	T4S08	36	133	133	151	151	216	222	101	101	89	89	98	100	151	151	119	119
	RU20	T10S08	37	133	133	151	151	216	222	101	101	89	89	-99	-99	151	151	115	115
19	**U21-T5S02**	T5S02	42	131	131	151	151	216	216	101	119	89	89	98	98	147	147	115	115
20	**U22-T5S03**	T5S03	36	131	131	151	151	222	222	113	113	89	89	108	108	151	151	115	125
21	**U23-T5S05**	T5S05	45	133	133	151	151	216	222	-99	-99	89	89	98	108	-99	-99	119	119
22	**U24-T5S10**	T5S10	50	129	131	-99	-99	207	207	101	101	101	103	104	104	-99	-99	-99	-99
23	**U25-T5S13**	T5S13	35	137	137	151	151	222	222	-99	-99	89	89	98	98	151	151	-99	-99
24	**U26-T5S14**	T5S14	43	131	131	151	151	222	222	113	113	89	89	98	98	151	151	115	125
25	**U27-T5S15**	T5S15	48	133	133	153	153	216	222	101	101	89	89	98	98	151	151	119	121
26	**U28-T5S17**	T5S17	46	131	131	151	151	222	219	-99	-99	101	101	98	98	131	131	119	119
27	**U29-T5S19**	T5S19	49	129	129	151	151	207	207	119	119	93	111	-99	-99	-99	-99	123	123
28	**U30-T5S20**	T5S20	52	-99	-99	151	151	219	222	113	113	89	89	98	98	151	151	115	125
29	**U31-T5S21**	T5S21	42	131	131	151	151	222	222	101	101	89	89	98	98	-99	-99	-99	-99
	RU31	T5S43	40	131	131	151	151	219	219	101	101	89	89	98	98	-99	-99	-99	-99
30	**U32-T5S22**	T5S22	40	129	129	151	151	222	222	-99	-99	89	89	98	98	-99	-99	119	119
31	**U33-T5S23**	T5S23	46	-99	-99	151	151	222	222	101	101	89	89	-99	-99	-99	-99	121	121
32	**U34-T5S24**	T5S24	32	131	131	151	151	222	222	101	101	-99	-99	-99	-99	151	151	115	115
33	**U35-T5S26**	T5S26	38	133	133	151	151	216	222	101	101	89	89	98	98	153	153	119	121
34	**U36-T5S29**	T5S29	28	131	131	151	151	-99	-99	-99	-99	-99	-99	100	100	151	151	123	135
35	**U37-T5S30**	T5S30	36	129	129	-99	-99	222	222	101	107	89	89	104	104	-99	-99	115	115
36	**U38-T5S31**	T5S31	35	131	133	151	151	222	222	-99	-99	89	89	98	98	153	153	115	115
37	**U39-T5S32**	T5S32	39	131	133	151	151	222	222	-99	-99	89	89	98	98	149	149	117	117
38	**U40-T5S33**	T5S33	44	131	131	151	151	222	222	101	101	89	89	-99	-99	-99	-99	-99	-99
39	**U41-T5S35**	T5S35	45	131	133	151	151	222	222	107	113	89	89	104	104	151	151	-99	-99
40	**U42-T5S36**	T5S36	36	129	131	149	151	222	222	101	115	89	89	100	100	149	151	117	117
41	**U43-T5S37**	T5S37	37	-99	-99	151	151	222	222	101	115	89	89	-99	-99	151	151	115	115
42	**U44-T5S38**	T5S38	27	129	131	151	151	222	222	101	113	89	99	-99	-99	151	151	115	115
43	**U45-T5S39**	T5S39	37	129	129	151	151	222	222	101	101	89	89	-99	-99	-99	-99	115	115
	RU45	T5S80	36	-99	-99	151	151	222	222	101	101	89	89	-99	-99	-99	-99	115	115
44	**U46-T5S40**	T5S40	37	129	137	151	151	222	222	-99	-99	89	89	104	104	-99	-99	117	117
45	**U47-T5S42**	T5S42	33	129	137	149	149	222	222	101	101	-99	-99	98	104	-99	-99	-99	-99

Appendix III continued

No.	Elephant ID	focal Index	Dung size	LafMS02A	LafMS02B	LafMS05A	LafMS05B	EMX2A	EMX2B	EMU7A	EMU7B	EMU10A	EMU10B	EMU13A	EMU13B	EMU15A	EMU15B	EMU17A	EMU17B
46	**U48-T5S44**	T5S44	22	-99	-99	151	151	-99	-99	-99	-99	89	89	98	98	151	151	115	121
47	**U49-T5S45**	T5S45	40	129	129	151	151	222	222	101	101	89	89	104	104	151	151	119	119
48	**U50-T5S46**	T5S46	46	-99	-99	151	151	222	222	101	101	89	89	100	100	149	149	-99	-99
49	**U51-T5S49**	T5S49	46	131	131	151	151	222	222	-99	-99	89	89	100	100	149	149	117	119
50	**U52-T5S51**	T5S51	33	-99	-99	151	151	-99	-99	101	101	91	107	108	108	-99	-99	119	125
51	**U53-T5S53**	T5S53	38	-99	-99	151	151	207	207	101	101	-99	-99	108	108	-99	-99	119	119
52	**U54-T5S54**	T5S54	28	-99	-99	151	151	222	222	101	101	-99	-99	100	100	-99	-99	115	119
53	**U55-T5S55**	T5S55	38	-99	-99	153	153	216	216	101	101	-99	-99	98	98	-99	-99	127	127
54	**U56-T5S59**	T5S59	35	131	131	151	151	-99	-99	101	101	91	91	114	114	-99	-99	115	115
55	**U57-T5S61**	T5S61	39	-99	-99	151	151	228	228	101	101	95	105	108	108	-99	-99	115	115
56	**U58-T5S62**	T5S62	40	-99	-99	151	151	228	228	101	101	-99	-99	114	114	139	149	121	121
57	**U59-T5S77**	T5S77	46	-99	-99	151	151	222	222	-99	-99	89	89	-99	-99	151	151	117	119
58	**U60-T5S82**	T5S82	37	-99	-99	151	151	216	222	101	113	89	89	98	98	151	151	115	115
59	**U61-T5S83**	T5S83	25	129	129	151	151	-99	-99	101	101	99	99	106	106	-99	-99	-99	-99
60	**U62-T5S84**	T5S84	29	131	131	151	151	225	225	101	101	99	99	108	108	-99	-99	-99	-99
61	**U63-T5S91**	T5S91	42	129	137	151	151	222	222	101	107	89	89	98	104	-99	-99	115	135
62	**U64-T5S93**	T5S93	36	131	131	151	151	222	222	101	101	91	91	98	98	151	151	-99	-99
63	**U65-T5S94**	T5S94	39	133	137	151	151	222	222	101	107	89	89	98	98	151	151	121	121
64	**U66-T5S95**	T5S95	40	131	133	151	151	216	222	101	101	89	89	98	98	149	151	123	135
65	**U67-T5S96**	T5S96	44	131	133	149	149	216	222	101	113	89	89	104	104	149	151	115	115
66	**U68-T5S97**	T5S97	28	131	131	151	151	216	222	101	101	89	89	98	104	151	151	115	115
67	**U69-T5S98**	T5S98	51	131	133	149	151	216	222	101	113	89	89	98	104	149	151	117	117
68	**U70-T5S99**	T5S99	39	-99	-99	151	151	216	216	101	101	89	89	-99	-99	151	151	-99	-99
69	**U71-T5S100**	T5S100	31	-99	-99	151	151	-99	-99	101	101	91	91	104	104	-99	-99	119	119
70	**U72-T5S101**	T5S101	48	131	133	151	151	222	222	101	107	89	89	104	104	151	151	117	125
71	**U73-T5S102**	T5S102	28	131	131	149	149	216	222	101	101	91	91	104	104	-99	-99	-99	-99
72	**U74-T5S108**	T5S108	28	131	131	151	153	216	222	101	113	89	89	104	104	153	153	117	123
73	**U75-T5S109**	T5S109	39	-99	-99	151	151	213	219	109	109	89	89	98	98	149	149	117	123
74	**U76-T5S126**	T5S126	35	131	133	-99	-99	222	222	107	107	89	89	104	104	151	151	115	119
75	**U77-T5S131**	T5S131	48	131	133	151	151	216	222	113	113	89	99	-99	-99	151	151	115	123
	RU77	T5S132	48	131	133	151	151	216	216	113	113	89	99	-99	-99	151	151	115	123
	RU77	T8S15	45	131	133	151	151	216	222	-99	-99	89	99	100	104	151	151	115	123
76	**U78-T5S138**	T5S138	49	133	133	151	151	222	222	101	113	89	89	98	98	-99	-99	115	125

Appendix III continued

No.	Elephant ID	focal Index	Dung size	LafMS02 A	LafMS0 2B	LafMS05 A	LafMS0 5B	EMX2 A	EMX2B	EMU7A	EMU7B	EMU10A	EMU10 B	EMU13A	EMU13B	EMU15A	EMU15B	EMU17 A	EMU17 B
77	**U79-T5S144**	T5S144	45	133	133	151	153	216	222	-99	-99	-99	-99	98	98	151	151	119	121
78	**U80-T6S01**	T6S01	25	131	133	151	151	216	222	101	109	91	91	-99	-99	151	151	125	125
79	**U81-T6S02**	T6S02	44	131	133	-99	-99	216	222	101	103	89	89	100	100	151	155	121	125
	RU81	T6S03	40	131	133	155	155	216	222	101	103	89	89	98	98	-99	-99	121	125
	RU81	T6S04	42	131	133	155	155	216	222	101	103	89	89	-99	-99	151	155	121	125
80	**U82-T6S07**	T6S07	44	131	133	151	151	-99	-99	-99	-99	89	89	-99	-99	151	151	121	125
81	**U83-T7S11**	T7S11	44	131	131	151	151	216	222	101	101	89	89	-99	-99	151	151	121	121
82	**U84-T7S12**	T7S12	27	131	131	151	151	222	222	123	123	89	89	98	104	151	151	121	121
83	**U85-T7S13**	T7S13	42	131	131	149	151	222	222	113	123	89	89	98	104	151	151	117	121
84	**U86-T7S16**	T7S16	39	131	131	151	151	222	222	113	117	89	89	104	104	151	151	125	125
	RU86	T7S17	44	131	131	151	151	222	222	113	117	89	89	104	104	151	151	125	125
85	**U87-T7S32**	T7S32	32	131	133	151	151	222	222	113	113	89	89	-99	-99	151	151	117	121
86	**U88-T7S35**	T7S35	39	131	133	151	151	216	222	-99	-99	89	89	100	104	151	151	121	125
87	**U89-T8S02**	T8S02	35	127	127	151	151	120	204	-99	-99	89	89	90	90	-99	-99	-99	-99
88	**U90-T8S14**	T8S14	49	131	131	151	151	222	222	109	111	89	89	100	104	149	149	-99	-99
89	**U91-T8S25**	T8S25	45	-99	-99	151	151	222	222	101	101	89	89	98	104	143	143	115	115
90	**U92-T10S26**	T10S26	52	131	133	151	151	216	222	113	113	89	89	98	104	-99	-99	-99	-99
91	**U93-T11S02**	T11S02	26	131	133	151	151	222	222	101	101	89	89	100	104	151	151	115	125
92	**U94-T11S07**	T11S07	49	131	133	151	151	216	222	101	113	89	89	-99	-99	151	151	115	119

Note: U1 refers to the unique genotype number 1, and RU1 refers to the recaptured genotype of U1.

Appendix IV (Chapter 4)

Comparison of AICc values for each of the variables tested for their significance in the model.

Variables	Linear & Quadratic	AICc
Steepness of slope	m.Slop	1267.475
	m.Slop2	1269.365
Elevation	m.Elev	1263.545
	m.Elev2	1265.751
Tasseled Cap Wetness	m.Wet	1267.061
	m.Wet2	1269.632
Enhanced Vegetation Index	m.Evi	1264.764
	m.Evi2	1269.18
Normalised Difference Water Index	m.NDWI	1264.967
	m.NDWI2	1266.597
Terrain Ruggedness Index	m.TRI	1253.416
	m.TRI2	1254.982
Nightlights	m.NL	1252.007
	m.NL2	1251.568
Distance to plantation	m.DistPlant	1266.82
	m.DistPlant2	1266.174
Distance to the main road	m.DistRoad	1262.023
	m.DistRoad2	1287.882
Distance to lake	m.DistLake	1241.394
	m.DistLake2	1243.52
Distance to Indigenous settlement	m.DistSett	1243.674
	m.DistSett2	1221.642
Distance to river	m.DistRiv	1267.198
	m.DistRiv2	1268.103

Note: m.slop2 refers to the quadratic model.