Assessing the impacts of sustainable forest management on wildlife in Sabah, Malaysia

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DECLARATION OF AUTHORSHIP

I hereby declare that I alone am responsible for the content of my doctoral dissertation and that I have only used the sources or references cited in the dissertation.

This dissertation is based on the following manuscripts:

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CHAPTER 2

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CHAPTER 3

Roshan Guharajan, Azlan Mohamed, Seth T. Wong, Jürgen Niedballa, Azrie Petrus, Jaffly Jubili, Wai-Ming Wong and Andreas Wilting conceived the study as well as refined and implemented the methodology. Roshan Guharajan and Jürgen Niedballa performed the analysis and visualizations. Roshan Guharajan, Jürgen Niedballa, Gopalasamy Reuben Clements and Andreas Wilting wrote the manuscript. Roshan Guharajan, Azlan Mohamed, Seth T. Wong, Johny Kissing, Peter Lagan and Andreas Wilting supplied resources and secured funding.

CHAPTER 4

Roshan Guharajan, Jürgen Niedballa, Seth T. Wong, Gopalasamy Reuben Clements, Wai-Ming Wong and Andreas Wilting conceived the study. Roshan Guharajan, Seth T. Wong, Azrie Petrus, Jaffly Jubili, Jasrin Kuntagil, Enn Lakim, Haostin Jineh, Victor Vitalis, Fido Dido Mansur, Indra Buana, Bendi Marinson, Daryl Chong and Robin Lietz collected the data. Roshan Guharajan and Jürgen Niedballa conducted the analysis. Roshan Guharajan, Jürgen Niedballa and Andreas Wilting wrote the manuscript. Johny Kissing, Peter Lagan and Robert C. Ong provided resources for the study.

OUTLINE

SUMMARY

There are a number of threats to the biodiversity of Southeast Asia. This global biodiversity hotspot has experienced surges in commercial poaching, particularly in mainland Southeast Asia, extirpating large mammals like tigers and rhinoceros from prime habitat in some locations. In maritime Southeast Asia, large-scale habitat degradation and loss has been driven by selective logging and industrial commodity plantations. With many ongoing initiatives to improve land-use management and protect biodiversity led by regional governments, it is useful to measure the impacts of these initiatives on biodiversity in a quantifiable way. The first aim of this dissertation was to examine the impacts of forest management at multiple scales on one particular species of high conservation value, while the second aim was to test how spatial modelling can improve protection for biodiversity. The location for this study was Sabah, a Malaysian state on the island of Borneo.

The overall distribution of sun bears *Helarctos malayanus* across the forested landscapes of Sabah was previously not quantified. We used the large amount of sun bear data available from the many camera trap studies across the state and applied occupancy models to assess and predict the current and future suitability of habitats for the species (**chapter 2**). We found that all large forested areas of Sabah were predicted to be suitable, with almost half of the area predicted to be suitable within forests where logging and plantation development is occurring or will occur in the future. Forests of higher aboveground carbon density (i.e. more intact forests) were predicted to be more suitable than forests of lower aboveground carbon density. We conclude that future conversions of forests into plantations will have an impact on sun bears. In addition, enough resources should continue to be channeled towards anti-poaching activities to protect the large forested landscapes where bears currently live.

Sabah's sustainable forest management, in particular reduced impact logging, has been practiced for almost 20 years. In two particular sites certified by the Forest Stewardship Council, Deramakot and FMU 17A, we used sun bear data from two successive survey periods four years apart with occupancy models to investigate how sun bear habitat suitability has changed (**chapter 3**). Our findings revealed that overall sun bear habitat suitability increased, but not significantly, over a 4 year period throughout Deramakot and FMU 17A. There were noticeable reductions only in areas undergoing active logging (Deramakot) and one area of tree plantation (FMU 17A). This shows that sustainable forest management can provide suitable habitat for sun bears over time, as long as protection from poaching is in place.

Understanding how different poaching offenders use the landscape can help managers of protected and conserved areas plan anti-poaching operations. We used a three year anti-poaching patrol dataset in an occupancy framework to identify areas of high "use" by two distinct offender types, gaharu collectors and wildlife hunters, in Deramakot and FMU 17A (**chapter 4**). We found that our model predictions of offender "hotspots" overlapped with areas of known poaching activity. We highlight the importance of site-level ranger knowledge in anti-poaching planning and the usefulness of applying occupancy-based predictions in policing vast forested landscapes.

ZUSAMMENFASSUNG

Es gibt verschiedene Faktoren, die die Artenvielfalt Südostasiens bedrohen. In diesem globalen Hotspot der Artenvielfalt hat die kommerzielle Wilderei deutlich zugenommen, vor allem auf dem südostasiatischen Festland. Dies führte dazu, dass große Säugetiere wie Tiger und Nashörner an einigen Orten aus ihren besten Lebensräumen verdrängt wurden. Im maritimen Südostasien sind vor allem die selektive Abholzung und industrielle Rohstoffplantagen für die massive Zerstörung und den Wegfall von Lebensräumen verantwortlich. Aufgrund der Vielzahl laufender Initiativen von Regionalregierungen zur Verbesserung des Landnutzungsmanagements und zum Schutz der Artenvielfalt ist es sinnvoll, die Auswirkungen dieser Initiativen auf die Artenvielfalt quantitativ zu messen. Das erste Ziel dieser Dissertation bestand darin, die Auswirkungen der Forstwirtschaft auf eine bestimmte Spezies mit hohem Erhaltungswert auf verschiedenen Ebenen zu untersuchen. Das zweite Ziel war es, zu testen, inwiefern die räumliche Modellierung den Schutz der Biodiversität verbessern kann. Der Standort dieser Studie war Sabah, ein Bundesstaat Malaysias auf der Insel Borneo.

Die Gesamtverbreitung der Sonnenbären *Helarctos malayanus* in den Waldlandschaften von Sabah war bisher nicht quantifiziert worden. Wir nutzten die umfangreichen Daten zu Sonnenbären, die durch zahlreiche Kamerafallen-Studien im gesamten Bundesstaat zur Verfügung gestellt wurden, sowie angewandte Besiedelungsmodelle, um die aktuelle und die zukünftige Eignung der Lebensräume für die Spezies zu bewerten und vorherzusagen (**Kapitel 2**). Wir haben herausgefunden, dass alle großen Waldgebiete von Sabah sich als geeignet erweisen. Fast die Hälfte der Fläche befindet sich innerhalb von Wäldern, in denen die Abholzung und die Plantagenentwicklung bereits stattfindet oder in Zukunft stattfinden wird. Wälder mit einer höheren oberirdischen Kohlenstoffdichte (d. h. intaktere Wälder) waren den Prognosen zufolge besser geeignet als Wälder mit einer geringeren oberirdischen Kohlenstoffdichte. Wir schließen daraus, dass die Umwandlung von Wäldern in Plantagen in Zukunft Auswirkungen auf Sonnenbären haben wird. Außerdem sollten weiterhin ausreichend Ressourcen zur Bekämpfung der Wilderei zur Verfügung gestellt werden, um die großen Waldlandschaften zu schützen, in denen die Bären derzeit leben.

Die nachhaltige Forstwirtschaft in Sabah, vor allem das Reduced Impact Logging (der schonende Abholzung), wird in Sabah seit beinahe 20 Jahren praktiziert. Wir haben Daten zu Sonnenbären an zwei ausgewählten Standorten, Deramakot und FMU 17A, die vom Forest Stewardship Council zertifiziert sind, in zwei aufeinander folgenden Untersuchungsperioden im Abstand von vier Jahren mit Hilfe von Besiedlungsmodellen untersucht, um Veränderungen in der Eignung als Lebensraum für Sonnenbären zu bestimmen (**Kapitel 3**). Unsere Ergebnisse zeigten, dass sich die Lebensraumeignung für den Sonnenbären in Deramakot und FMU 17A über einen Zeitraum von vier Jahren grundsätzlich verbessert hat, jedoch nicht signifikant. Deutliche Reduzierungen wurden lediglich in Gebieten mit aktiver Abholzung (Deramakot) und in einem Gebiet mit Baumplantagen (FMU 17A) verzeichnet. Dies zeigt, dass durch eine nachhaltige Forstwirtschaft im Laufe der Zeit ein geeigneter Lebensraum für Sonnenbären geschaffen werden kann, solange der Schutz vor Wilderei gewährleistet ist.

Das Wissen darüber, wie verschiedene Wilderer die Landschaft nutzen, kann den Verwaltern von Naturschutzgebieten bei der Planung von Maßnahmen gegen Wilderei von Vorteil sein. Wir haben Daten von dreijährigen Patrouillenmaßnahmen gegen Wilderei in einem Besiedelungsrahmen verwendet, um die „beliebtesten" Gebiete zweier unterschiedlicher Wilderer – Sammler von Gaharu und Wildtierjäger – in Deramakot und FMU 17A zu ermitteln (**Kapitel 4**). Wir haben festgestellt, dass unsere Modellprognosen für „Hotspots" von Wilderern sich mit den bekannten Wilderei-Gebieten überschnitten. Wir möchten betonen, wie wichtig das Wissen der Ranger über die Gebiete bei der Planung von Maßnahmen gegen Wilderei ist und wie wertvoll besiedelungsbasierte Prognosen bei der Überwachung großer Waldlandschaften sein können.

CHAPTER 1

GENERAL INTRODUCTION

Southeast Asian biodiversity and threats

Southeast Asia is a global biodiversity hotspot, with high concentrations of endemic species (Sodhi et al., 2004). As has been highlighted extensively within the last decade, this biodiversity is facing pressures from overexploitation (Gray et al., 2017; Tilker et al., 2019) as well as forest loss and degradation (Curtis et al., 2018). In some parts of the region, intense poaching has led some mammals to become very rare or locally extinct (Gray et al., 2018). Several recent studies have documented this "defaunation" (Tilker et al., 2018, 2019), showing the very real threat of once-biodiverse areas losing iconic species (Rasphone et al., 2019) and resulting in "empty" forests with low species richness (Harrison, 2011).

However, the threat of commercial poaching-induced defaunation does not seem to be evenly present throughout Southeast Asia (Tilker et al., 2019). While levels of commercial poaching, particularly snaring, may be lower in parts of maritime Southeast Asia, e.g. in Borneo, than in mainland Southeast Asia, other threats are more pronounced. In particular, forest loss and degradation are highlighted as major threats to biodiversity in Malaysia and Indonesia (Gaveau et al., 2014).

Situation in Borneo

The island of Borneo in Southeast Asia comprises territory for three different countries: Brunei Darussalam, Malaysia and Indonesia. While defaunation has been well documented occurring in certain parts of mainland Southeast Asia, there is so far less evidence that high levels of defaunation are also occurring on Borneo (Tilker et al., 2019). Although large scale poaching may not be a major threat, Borneo has a history of lowland (< 500 m above sea level [asl]) forest loss, primarily because of the expansion of industrial commodity plantations for timber and oil palms (Gaveau et al., 2016). In total, 30% of Borneo's original forest cover in 1975 has been converted to other land uses by 2010, with most of that conversion happening in lowlands (Gaveau et al., 2014). Despite this, Borneo is still a key site for both conservation and sustainable development in Southeast Asia, with transboundary initiatives such as the "Heart of Borneo" continuing for more than a decade.

Malaysian territory on Borneo comprises two states, Sabah and Sarawak. When compared to the other regions in Borneo, Sabah experienced with 39% one of the highest historical deforestation rates during the period 1975 – 2010. A large portion (60%) of the remaining forests were degraded by selective logging (Gaveau et al., 2014). As this forest loss was mostly concentrated in the lowlands and particularly in parts of eastern Sabah, there are still large tracts of natural forest remaining. Large mammals of conservation concern still persist in Sabah's "degraded" forests, including the Sunda clouded leopard *Neofelis diardi*, the Bornean orangutan *Pongo pygmaeus* and the sun bear *Helarctos malayanus* (Sollmann et al., 2017; Deere et al., 2018).

Sustainable forest management in Sabah

As part of the federal governance system, Malaysian states are fully responsible for forests within their borders. The authority for forest reserves in the state is the Sabah Forestry Department, which has implemented its version of sustainable forest management since 1997, using the principles of multiple-use (social, environmental and economic; Sabah Forestry Department, 2018). Since then, sustainable forest management in Sabah has grown holistically to focus on protected area management, nature-based tourism, rural socio-economic development, and forest/carbon financing besides harvesting of timber (Sabah Forestry Department, 2018).

Sabah's forest reserves can be divided into seven classes, with three of these classes considered to be totally protected areas, totaling an area of ~16,700 km^2 (Sabah Forestry Department, 2022). Together with parks, wildlife sanctuaries and wildlife conservation areas (under the authority of other state agencies), the size of totally protected areas in the state is ~19,400 km^2 (Sabah Forestry Department, 2022). Sabah forest reserves account for 86% of this area (Sabah Forestry Department, 2022), placing a large responsibility on the Sabah Forestry Department. Aside from totally protected areas, another major class of forest reserves are the commercial forest reserves, totaling ~16,600 km^2 (Sabah Forestry Department, 2022). Commercial activities permitted within these forest reserves are reduced impact logging and, in degraded areas, land clearing for the development of tree plantations. Several forest reserves, both protected and commercial areas, have been certified according to standards set by the Malaysian Timber Certification Council (MTCC) and the international Forest Stewardship Council (FSC).

Commodity plantations in Sabah

A major commodity cultivated in Sabah is the oil palm, with eastern Sabah in particular holding large swathes of industrial-level plantations. Oil palm replacement of natural forests peaked in 2009, since then there has been a steady decline of oil palm expansion in forests (Gaveau et al., 2019). This trend, along with Malaysia's moratorium on oil palm expansion in forested areas in 2019 and mandatory national certification requirements (Sanath Kumaran et al., 2021), have resulted in limited expansion of this commodity at the expense of natural forest. Currently, the major commodity to expand within some of Sabah's commercial forest reserves are tree plantations (Sabah Forestry Department, 2018). The reason for these plantations is to gradually replace diminishing timber stocks reduced by selective logging (Sabah Forestry Department, 2018). There is a major policy-led push for the development of tree plantations, including the provision of tax incentives and a focus on third-party certification for best practices (Sabah Forestry Department, 2018). This expansion is very likely to have some impacts on biodiversity, especially in the early stages of planting when hill terracing may be required (pers. obs.). A study in Sarawak showed that a landscape of small-scale tree plantations and natural forest mosaics could still harbor complete terrestrial mammal assemblages, although the planted areas had slightly lower species richness (Wong et al., 2022). Other studies indicated more drastic differences between natural forests and tree plantations (McShea et al., 2009; Yaap et al., 2016), but these should be viewed within the context of plantation size and configuration and overall landscape heterogeneity (Wong et al., 2022).

The Deramakot Forest Reserve

Deramakot Forest Reserve is the first commercial tropical forest to have been certified according to FSC standards globally. The reserve has been a focal point and testing ground in Sabah's sustainable forest management journey, beginning in 1989 when the Sabah Forestry Department collaborated with the German Agency for Technical Cooperation (Sabah Forestry Department, 2018). In fact, Deramakot was the location for testing and improving the model for reduced impact logging, which was then implemented in other forest reserves later on. Today, Deramakot remains a model of a well-managed tropical forest, further gaining recognition for nature-based tourism as well as its joint management with local communities. Deramakot is adjacent to a block of four FSC-certified forest reserves (Tangkulap, Sg Talibu, Timbah and Sg Pinangah, collectively known as Forest Management Unit 17A) and one MTCC-certified forest reserve (Sg Lokan), forming a continuous tract of lowland and hill dipterocarp forest (Sabah Forestry Department, 2015). Deramakot was historically better managed with regards to selective logging than its neighbouring reserves (Ong et al., 2013). In terms of biodiversity, studies have shown that Deramakot has better habitat suitability for most mammals than its neighbouring reserves (Sollmann et al., 2017). The logged forest in Deramakot even fares better in terms of mammal habitat use and species richness than the protected but more heavily-poached forests in central Vietnam and Lao People's Democratic Republic (Tilker et al., 2019).

A High Conservation Value species: the sun bear

Recently, the Sabah Forestry Department has explored the suitability of using the distribution of certain species and ecosystems of high conservation value (HCV) to assist in landscape-level conservation planning. A species is identified as an HCV if it is Rare, Threatened and Endangered (RTE), as classified by the IUCN Red List, CITES Appendices and national legislation (Brown et al., 2013). Combining these HCV species distribution maps with HCV ecosystem distribution maps, the Sabah Forestry Department developed new and larger landscape management units called Large Landscapes (R. Ong, Sabah Forestry Department, pers. comm.). These new landscape management units would encompass multiple forest reserves and other totally protected areas (TPA), and allow for planning and managing at a larger scale than is currently in use (R. Ong, Sabah Forestry Department, pers. comm.).

One of the HCV species used in the identification of Large Landscapes is the sun bear. The species range covers large sections of mainland Southeast Asia as well as the islands of Sumatra and Borneo (Scotson et al., 2017). In mainland Southeast Asia, its range overlaps with that of the Asiatic black bear (*Ursus tibetanus*) in seasonal tropical forests, whereas it is the only bear species present in the evergreen tropical forests of the Malay Peninsula, Sumatra and Borneo. Here, sun bears can survive in forests in varying degrees of degradation (Guharajan et al., 2022). Deforestation in terms of rapid forest loss has a clear negative impact on the availability of habitats for this species (Wong et al., 2012), whereas they have a far higher tolerance to low intensity logging such as reduced impact logging, at least in in Sabah (Guharajan et al., 2021). One of the main threats to sun bears is commercial poaching, largely because of the high value of their body parts for the illegal wildlife trade (Crudge et al., 2019). Selective logging and commodity plantation expansion have further exacerbated poaching pressure, as access to once remote forests were made easier with logging and plantation roads (Crudge et al., 2019). Interestingly, in forest areas that abut oil palm plantations sun bears will feed on oil palm fruits (Cheah, 2013), although they are not widely viewed as pests by plantation managers (Guharajan et al., 2017).

Protecting high conservation value species *in-situ*

Provided there is sufficient forest habitat, sun bears are able to survive and persist as long as there is adequate protection against poaching. It is therefore imperative that managers institute robust anti-poaching initiatives across the protected and conserved areas of Southeast Asia. Policing vast and remote forests is a challenging task and compounded by the fact that poachers are quick in adjusting to increased enforcement (Marescot et al., 2019). In order to make law enforcement planning easier and more effective, several predictive methods have been tested, including artificial intelligence-based patrol optimisation techniques (Xu et al., 2020, 2021). One recent study has also used hierarchical modelling and remote sensing to identify patterns of landscape use by poachers (Tilker et al., 2023). There are some examples of success stories in policing forested areas, but such results require a sustained effort over time (Duangchantrasiri et al., 2016) and, on a national scale, large amounts of resources (Department of Wildlife and National Parks Peninsular Malaysia, 2021). Having a good understanding of poaching, especially the spatial distribution of poaching activity and offender specific behaviours, becomes therefore very important for protecting HCV species *in-situ*.

Although commercial poaching is not at a level matching some areas in mainland Southeast Asia (Tilker et al., 2019), action still needs to be taken to ensure effective protection is in place for Sabah's totally protected areas and commercial forest reserves. These forested landscapes still harbour mammals valued by the illegal wildlife trade, such as the Sunda pangolin *Manis javanica* (Challender et al., 2014) and the sun bear (Crudge et al., 2019) as well as prized exotic meat and trophies from banteng *Bos javanicus* (Sabah Wildlife Department, 2019).

Aim of the study

We specifically used sun bears as our focal HCV species as it is targeted by the illegal wildlife trade (Crudge et al., 2019) and as there was a large amount of data from different landscapes across Sabah collected by our research group and other institutions. In addition, we felt the forest-dependent sun bear would be a good HCV species to examine the effects of Sabah's sustainable forest management practices. We aimed to predict the distribution of the sun bear across the forested landscapes of Sabah. Given the sustainable forest management practices Sabah has been implementing, this predicted distribution would be a good way to visualise highly suitable habitat for the species. Furthermore, we wanted to predict how future forest degradation and loss, through selective logging and the expansion of tree plantations, might affect their suitability as a habitat for this species.

We then focused on one important landscape, the adjacent Deramakot and Forest Management Unit 17A (FMU 17A) areas, to examine how well managed logging and some poaching pressure affects sun bear habitat use. We focused on Deramakot and FMU 17A, since this area – and in particular Deramakot – has been under sustainable forest management for almost 20 years. Finally, we continued to keep our focus on Deramakot and FMU 17A to examine how anti-poaching operations can be planned to improve the disruption of different types of poachers (offenders). The main objectives of the study were to:

1) Predict the distribution of sun bears across Sabah and examine the impact of future forest loss and degradation on that distribution.
2) Investigate trends in sun bear habitat suitability over a four year period in the production forests of Deramakot and FMU 17A.
3) Understand patterns of landscape use and predict the distribution of different poacher types in Deramakot and FMU 17A.

Structure of the dissertation

Following the general introduction (Chapter 1), this dissertation is divided into four more chapters:

Chapter 2: This chapter is titled "Determinants of sun bear *Helarctos malayanus* habitat use in Sabah, Malaysian Borneo and its predicted distribution under future forest degradation and loss" and compiles data from multiple camera trap surveys in Sabah over a ten year period. Sun bear habitat use is evaluated using an occupancy framework with remotely sensed data, and sun bear habitat suitability is predicted across all forested areas in the state that were similar to those surveyed. The results show that there are still large forest areas available as suitable habitat, with the highest suitability in the most intact (carbon-rich) forests. The doctoral student was involved in data collection, data analysis and writing the article.

Chapter 3: Understanding changes in habitat suitability can be useful for monitoring changes in species distribution. In the context of Sabah's sustainable forest management approach, such monitoring can serve to evaluate the effects of selective logging on HCV species. The chapter "Sustainable forest management is vital for the persistence of sun bear *Helarctos malayanus* populations in Sabah, Malaysian Borneo" uses two camera trap datasets (2014 and 2018 respectively) from similarly designed surveys to estimate changes in sun bear habitat suitability in Deramakot and FMU 17A. Suitability increased overall in relation to forest regeneration, but declined in the compartments that underwent selective logging between 2014 and 2018, as expected. The doctoral student was involved in data collection, data analysis and writing the article.

Chapter 4: For protected and conserved area managers to effectively stem poaching, they require the right information to assist in planning patrols. The chapter "Identifying illegal activity hotspots to support anti-poaching operations" uses patrol data collected over a three year period (2017-2019) along with an occupancy model to determine the distribution of poachers in Deramakot and FMU 17A. Unlike earlier studies that used patrol data to predict poaching hotspots in protected areas and treated offenders as one homogeneous group, we considered two offender types in the model, wildlife hunters and gaharu collectors, to separate their respective patterns of use. This allowed us to predict distributions that highlight different areas of use by distinct offender types. The doctoral student was involved in data collection, data analysis and writing the article.

Chapter 5: The general discussion summarizes the findings of Chapters 2-4 and highlights the implications of their results within the context of sustainable forest management in Sabah.

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CHAPTER 2

Determinants of sun bear *Helarctos malayanus* habitat use in Sabah, Malaysian Borneo and its predicted distribution under future forest degradation and loss

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CHAPTER 3

Sustainable forest management is vital for the persistence of sun bear *Helarctos malayanus* populations in Sabah, Malaysian Borneo

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CHAPTER 4

Identifying illegal activity hotspots to support anti-poaching operations.

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Introduction

Species extirpations and decline in abundance of species (Dirzo et al., 2014), can have a profound impact on tropical ecosystems, including forest regeneration and carbon sequestration (Bello et al., 2015; Fricke et al., 2022). In Southeast Asia, poaching (illegal hunting) represents a major threat to the persistence of wildlife in forested landscapes (Gray et al., 2018; Tilker et al., 2019). One important facet of protected and conserved area governance is the reduction and prevention of illegal activities, especially poaching (Rija et al., 2020). This is can be especially difficult in Southeast Asian protected areas that are generally remote and have limited manpower and budgets (Tilker et al., 2020). Utilizing patrol staff effectively to achieve maximum effect then becomes imperative for managers (Rija et al., 2020). In order to plan anti-poaching operations, protected and conserved area managers need information on how and where to use their limited resources (Rija et al., 2020). By deploying resources more effectively, managers can then achieve high impact even with existing resources.

In Sabah, one of two Malaysian states on the island of Borneo, poaching does occur (Or et al., 2017; Daineh, 2018), but likely not to the scale observed in parts of mainland Southeast Asia, where there is intensive snaring of large mammals (Gray et al., 2018; Tilker et al., 2019). While in other parts of Southeast Asia the majority of poaching is done using snares (Rasphone et al., 2019; Marescot et al., 2019), this is not necessarily case in Sabah. Alongside snares, poachers also rely heavily on shotguns. Anecdotal information from enforcement personnel indicates that there are two broad kinds of poaching offenders. The first tend to rely more on snares, while spending time in the forest searching for valuable wood chips from gaharu trees (*Aquileria* spp.; hereafter called gaharu collectors). The second offender primarily use shotguns with limited reliance on snares to target ungulates (hereafter called wildlife hunters). While managers already have this broad knowledge, at the site level there is still limited actionable information on specific offender drivers and hotspots. This prevents more effective anti-poaching and site protection actions, which are deemed necessary as set out by state forestry policies and wildlife action plans (Sabah Forestry Department, 2018; Sabah Wildlife Department, 2019a, 2019b).

For protected and conserved area managers to command resources effectively, they require detailed information on where illegal activities are occurring. One study from Vietnam attempted to do this by investigating the distribution of snares across a variety of landscape features (Tilker et al., 2023), and highlighted the importance of taking into account the imperfect detection of poaching signs by the patrol team when using a quantitative framework. The authors of this study suggest that occupancy models (MacKenzie et al., 2006) are well suited to such datasets, as they allow for probabilities of detection and occupancy to vary depending on covariates. Another use of occupancy models with patrol datasets assessed poacher-wildlife relationships spatially as well as temporally (Marescot et al., 2019).

In this study, we use past records of illegal incursions in an occupancy framework to identify “hotspots” of illegal activity, thereby identifying areas where rangers can maximize patrol effort. We further attempt to separate incursions by offender type, allowing for more detailed patrol planning for specific offenses. Previous studies have generally treated offenders as a singularity, with no distinction between groups of offenders. Separating detections by offenders allows us to take into account group behavioral traits, such as preference for certain landscape features or targeting of specific wildlife species. We devised three research questions that could potentially help improve site protection strategies: 1) Are certain offenders prioritizing areas with faster travelling time (easier to access)?; 2) Are certain offenders using ridgelines to travel in the forest?; and 3) Are offenders targeting ungulates more likely to focus efforts in the degraded areas, while others targeting gaharu more likely to focus efforts in less degraded forests where they are likely to detect gaharu trees?

Methods

Study area

We collected data on illegal incursions within two adjacent forest blocks in Sabah’s Heart of Borneo. Deramakot Forest Reserve (Deramakot; ~55,000 ha) is a production forest reserve managed directly by the Sabah Forestry Department, where reduced impact logging has been in use since 1995. Deramakot has received Forest Stewarship Council certification since 1997 for its good management practices. The second forest block, Forest Management Unit 17A (FMU 17A; ~50,000 ha), consists of three forest reserves that are totally protected areas (Tangkulap, Sg Talibu, Timbah Forest Reserves) and one forest reserve that is comprised of forest plantations (Sg Pinangah Forest Reserve). FMU 17A has also received Forest Stewardship Council certification since 2011. Both Deramakot and FMU 17A are important lowland forest areas with near-complete Bornean mammal assemblages (Sollmann et al., 2017; Tilker et al., 2019), with Deramakot having higher species richness and density due to its longer history of sustainable logging (Mohamed et al., 2009, 2019; Sollmann et al., 2017).

Deramakot has no public roads, and the only access points for incursions are along the southern (Milian and Kinabatangan rivers) and the northern border (oil palm estate). FMU 17A has several public roads passing through the block, with private land bordering most of the western and southern border. The Sabah Forestry Department has four permanently staffed stations throughout the two forest blocks, with additional infrastructure for another two temporary stations.

Data collection

Data on incursions were collected during camera trap surveys and joint anti-poaching patrols with the Sabah Forestry Department during 2017 - 2019. Field teams recorded any trails, tree markings, rubbish or camps that were identified as belonging to an illegal incursion. We distinguished illegal incursion signs from forestry ranger signs by cross checking locations of current and past trails and camps used by the forestry rangers. If a sign was on a trail or in a sampling plot used by forestry rangers, we did not count those signs as belonging to illegal incursions. We avoided double counting a sign during a repeat patrol in the same location by only recording new or fresh signs after the first visit.

Illegal incursion signs were further differentiated to the two specific offender types: wildlife hunters and gaharu (*Aquileria spp*.) collectors, which were identified based on discussions with forestry rangers. Wildlife hunter trails were generally short, with small camps used for one night stays in the forest (Panthera, unpublished data). These hunters primarily relied on shotguns, with some also using snares and traditional methods (i.e. hunting dogs and spears). Gaharu collector trails were much longer and they left behind multiple large camps during their longer periods of stay (up to two months; Panthera, unpublished data). As gaharu collectors were mostly non-Malaysians, the plastic waste left behind were often of food types and brands not commonly found. In addition, gaharu collectors relied on gurney sacks to make backpacks and often left behind old ones. Gaharu collectors used mostly snares, and only rarely relied on shotguns. Snares were differentiated between offenders based on their location, i.e. if a snare was found along a trail or close to a camp identified to gaharu collectors, then the snare would also be assigned to gaharu collectors. All data were stored in the Spatial Monitoring and Reporting Tool (SMART) database. Both offender types also differed in their target species. While hunters largely targeted ungulates (sambar and bearded pigs) for wild meat consumption, gaharu collectors targeted valuable species such as sun bears and helmeted hornbills for the illegal wildlife trade as well as species for consumption such as bearded pigs.

Data processing

We divided our study area into a grid of 200 x 200 m cells. We used this grid cell size based on several considerations. First, we required a resolution that could retain enough detail to elucidate offender sign distribution across our heterogeneous landscape (many ridges and valleys). Second, a 200 x 200 m cell has a higher chance of including an entire cluster of sign than a cell with smaller dimensions. As much as possible, we aimed to reduce offender sign clusters from extending beyond a single cell, as that would violate one of the assumptions of occupancy models (detection in one grid cell is independent of detection in another grid cell; MacKenzie et al., 2006). Third and very importantly, this grid cell size is still computationally feasible, while finer resolution grids make computations increasingly difficult.

We converted data on incursion signs into detection/non-detection matrices using monthly occasions for each grid cell. We further calculated monthly patrol effort using patrol tracklogs (total km) for each grid cell. Patrol effort referred to the percent area of each grid cell that was visited each month.

Covariates

For the detection component of our model, we selected two covariates: patrol effort and offender-year. Offender-year was a categorical covariate referring to the offender identified to the sign and the year the sign was detected. We had six categories for this covariate (i.e. wildlife hunter-2017, gaharu collector-2017, etc.).

For the occupancy component of our model, we selected three remotely sensed covariates that pertained to our research questions: remoteness, Topographic Position Index (TPI) and forest height. Remoteness was a form of least cost path calculation, i.e. the amount of time it took to move from an access point to a particular grid cell in the forest reserve. This covariate is likely to capture accessibility better than linear "distance to measurements", with access being a main driver of poaching pressure (Xu et al., 2020; Deith & Brodie, 2020; Tilker et al., 2023). To obtain these values, we used GIS layers of roads and large rivers and converted the nodes to points (access points) in QGIS. We then used Tobler's off-path hiking function in the R package "movecost" (Alberti, 2019) to calculate the travel time between the closest 50 access points to the centroids of each grid cell. We used a 30 m STRM digital elevation model (DEM) as the surface layer for this calculation, and selected the lowest value as the final remoteness value for each grid cell.

TPI referred to the difference in elevation between a grid cell and the mean of its surrounding cells. We used a 30m STRM DEM to calculate the median elevation per grid cell. We then used the "terrain" feature in the R package "raster" (Hijmans, 2019) to obtain TPI values for each grid cell, specifying a 7x7 neighborhood and bilinear calculation. We included TPI to see if there was a relationship between high TPI values (ridgelines) and offenders (particularly gaharu collectors). Ridgelines have been shown to be heavily-used travel ways for offenders accessing remote forests (Lam, 2017), and gaharu collectors in our landscape are likely to behave similarly.

We used forest height as a measure of forest degradation, in order to assess how different offenders selected areas in relation to the level of degradation. Wildlife hunters may have preferred areas with more undergrowth as these might be frequented by ungulates, whereas gaharu collectors may prefer the opposite with more gaharu trees. We chose forest height as we felt it would be easier to interpret from a management standpoint as opposed to other measures such as normalized difference moisture index (NDMI) or above-ground carbon biomass. Higher forest height values correspond to areas that are logged less intensively, and lower forest height values indicated areas that were more degraded and having more understory growth. Forest height was calculated using Google Earth Engine's 30 m resolution Global Forest Canopy Height 2019 layer (Potapov et al., 2021).

We centered and scaled all continuous covariates. Finally, we checked for collinearity between covariates using Spearman's rank correlation coefficient.

Occupancy modelling and predictions

We used the R package "ubms" (Kellner et al., 2021) to run an occupancy model with three covariates for the occupancy component: remotesness, TPI and forest height. For the detection component, we included patrol effort as a fixed effect and offender-year as a random effect. We used offender-year as a random effect as we hypothesized that offender detection would change due to offender's modifying their behavior in response to increased patrolling. For the occupancy component, we allowed for an interaction effect between offender and the three occupancy covariates. This would allow us to examine covariate relationships with each offender. We used 5000 iterations with 3 chains and 3 cores.

Due to our small grid cells, we interpreted occupancy as “use”, i.e. if a grid cell was occupied it was considered to be used by offenders. To predict offender use across our study area, we used raster of the three covariates along with the posterior parameter estimates from our occupancy model. We predicted offender use separately for wildlife hunters and gaharu collectors.

Results

We patrolled a total of 4098 grid cells during 2017 – 2019 (Table 1). Most of the grid cells were visited in 2018 (3818 grid cells patrolled) as it coincided with two large scale camera trap surveys. From 2017 - 2019, we detected gaharu collector signs in 243 grid cells and wildlife hunter signs in 104 grid cells. In total, we detected 357 signs of illegal incursions. In 2017 and 2018, the majority of these signs belonged to gaharu collectors (52 and 195 signs, respectively) with far less wildlife hunter signs (31 and 59 signs, respectively). However, in 2019 we obtained very few gaharu collector signs (2) as compared to wildlife hunter signs (18).

Our covariates were not highly correlated (all Spearman’s rank correlation coefficients < 0.7). Our occupancy model indicated that gaharu collectors had a positive relationship with forest height and TPI. Wildlife hunters had a positive (but less apparent) relationship with forest height while having a weak negative relationship with TPI. Both offenders had a negative relationship with remoteness, with wildlife hunters displaying a more drastic one.

Our predictions highlighted areas in southern Deramakot and western FMU 17A were mostly likely to be used by gaharu collectors. For hunters, areas close to the northern borders (Deramakot and FMU 17A), southern riverine borders (Deramakot and FMU 17A), western border (FMU 17A) and public roads (FMU 17A) were more likely to be used, with almost no probability of use in central Deramakot.

Discussion

Our study modelled the spatial extent of illegal incursions, while accounting for different offender type. We found that gaharu collectors and wildlife hunters had different relationships with our covariates. While both offenders used more remote areas and higher canopy forest, there was a clear difference in the strength of the relationship. In terms of the covariate TPI, gaharu collectors preffered ridgelines while wildlife hunters preferred valleys. Our predictions highlighted that both offenders used different parts of the study area, a finding that can be informative for future anti-poaching operations.

Both gaharu collectors and wildlife hunters displayed negative relationships with remoteness, indicating that offenders preferred areas that were faster to reach. Wildlife hunters had a more drastic negative relationship, highlighting that use is almost entirely in areas which they can reach quickly (logging roads or skid trails close to the forest edge). This was expected as wildlife hunters are not seeking long stays in the forest (only one night), preferring hunting areas where they can locate and remove ungulates with ease (Panthera, unpublished data). In contrast, gaharu collector use decreased only slightly with increasing distance from the forest edge. This indicated that gaharu collectors spend much more time in more remote areas of the forest, consistent with our understanding of how they operate over long periods collecting forest products (Panthera, unpublished data). Our results indicating that accessibility is one of the main drivers of illegal activities within protected areas has been echoed by other studies across the tropics (Harrison et al., 2016; Benítez-López et al., 2017).

We found a strong positive relationship between forest height and gaharu collectors. As gaharu is considered to be a well distributed species across different habitats (Faridah-Hanum et al., 2009), gaharu collectors in Deramakot are likely to spend more effort traversing deep into the reserve. Aside from increasing their chances of finding gaharu trees, this behavior might also be a tactic to avoid being detected by forestry rangers. Wildlife hunters had a weaker positive relationship with forest height, indicating that they did not have as strong a preference for hunting in higher canopy forest. This may be related to their target species, ungulates, which do not necessarily show a clear preference for higher canopy (more intact) forest (Brodie et al., 2015; Sollmann et al., 2017). Ungulates in dense tropical forests will also be drawn to areas with ample browsing resources (Chankhao et al., 2022), which would generally have low canopy height.

Gaharu collectors displayed a strong positive relationship with TPI, indicating a preference to use (travel along) ridgelines. A similar trend was observed in another study in Terengganu, Malaysia (Lam, 2017). As they have to travel long distances, gaharu collectors may prefer to use natural features like ridgelines where movement may potentially be easier. As certain wildlife species also travel along ridges, these features also double as ideal places to shoot or set snares for valuable species. A study in Viet Nam and Laos showed that snare probability was increasing with higher TPI (Tilker, Niedballa et al., 2023), echoeing the results of this study. In contrast to gaharu collectors, wildlife hunters showed a negative, albeit less drastic, relationship to TPI. This indicated that has some preferred for areas lower in elevation than their surroundings. This reinforces our existing knowledge on wildlife hunters, who tend to use low lying logging roads or skid trails along the forest edge, the edge of oil palm estates and riverbanks to target ungulates (Panthera, unpublished data). Overall, our results show diverging preferences of the two offender types in response to TPI. This highlights the importance of accounting for this during operation planning. Anti-poaching operations targeting gaharu collectors should focus on ridgelines while those targeting wildlife hunters could consider monitoring forest access points systematically to increase risk.

Our predictions highlighted areas in southern Deramakot as highly suitable for gaharu collectors. More recent (after the patrols presented in this study) anti-poaching patrols in these areas have discovered old but well-used ridgeline trails and camps (Panthera, unpublished data). Although western FMU 17A is also highlighted to be very suitable for gaharu collectors, both past and recent patrols recorded very few signs of these offenders. It is likely that this area, while predicted to be highly used by gaharu collectors, is not the right habitat for gaharu trees and thus these collectors avoid the area. Wildlife hunters were predicted to heavily use the northern borders of Deramakot and FMU 17A, the roads in central FMU 17A, the western borders of FMU 17A and certain riverine areas in southern Deramakot. The majority of central Deramakot area was predicted to be unsuitable for wildlife hunters, which is similar to findings during recent patrols. Recent patrols have confirmed that the southern Deramakot riverine areas, western FMU 17A border and northern borders are frequently used by wildlife hunters, echoing the predictions in this study. On a landscape scale, predictions such as these could assist managers in allocating effort and resources. For example, operations to disrupt wildlife hunters could focus on the riverine and northern border access points, not requiring intensive foot patrols in the forest. The more costly and intensive long range patrols could then just be targeted to the southern area of Deramakot where gaharu collectors are predicted to be most active.

There were several caveats to our study. Firstly, the data were collected by teams that were mostly moving on more permeable features (logging tracks and ridgelines). This led to the recording of incursion signs mostly on these features and would potentially bias the results. However, other studies in Terengganu, Malaysia and central Vietnam found that poachers also preferred using features such as ridgelines (Lam, 2017; Tilker et al., 2023). Further, the different covariate responses of gaharu collectors and wildlife hunters indicated that despite the bias in data collection our methods were still able to elucidate these differences. We also recorded all detections of illegal signs, including those that were old, and utilized these data in an occupancy model with covariates that were measured more recently. This would not be an issue for remoteness or TPI as they have not changed over time, but forest height was subject to some changes due to ongoing selective logging in the Deramakot. However, given that selective logging in Deramakot is limited spatially to certain compartments and logging ceased in FMU 17A since 2002, we feel this would not have a major impact in the forest height data. In terms of predictions, our results highlighted western FMU 17A as highly suitable for gaharu collectors but found very few signs of these offenders there. The lack of gaharu collector signs in western FMU 17A is likely due to limitations in our covariate suite, with none reflecting the distribution of gaharu trees across the landscape. Western FMU 17A might exhibit higher TPI and forest height, but gaharu trees may only exist at low densities there and therefore collectors would avoid the area.

With this study, we have demonstrated how occupancy modelling and predictions can be utilized in a framework to aid in prioritizing anti-poaching operations. Indeed, predictive methods can be useful for targeting specific anti-poaching operations at the site level (Lam, 2017; Xu et al., 2020, 2021; Tilker et al., 2023) . Recently, machine learning and artificial intelligence tools have shown promise (Xu et al., 2020, 2021), but are computationally intensive to the point that some models may not be practical (Neil et al., 2020). Further, these tools do not account for detection as holistically as occupancy models, resulting in predictions which often simply reflect areas of intensive patrol effort (Leibniz Institute for Zoo and Wildlife Data, unpublished data). Nevertheless, these myriad solutions will invariably contribute towards making patrol planning convenient for small anti-poaching teams in remote areas. While spatial modelling is helpful, care must be taken not to over depend on these predictions. To this effect, we highlight the importance of distinguishing between offender types when collecting patrol data, which will help with designing more targeted operations (Ingram et al., 2021). If observations were not distinguished, we would not have been able to model the different covariate responses, leading to predictions that would be limited in use. We recommend that ranger input (especially from the field) should be incorporated as much as possible in operational planning, as distinguishing signs of offender types would be impossible without their knowledge. Our results provide a stark reminder of the technical and site-level knowledge needed to effectively plan anti-poaching and site protection operations in a landscape.

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Figure 1: Study area comprised of Deramakot Forest Reserve and Forest Management Unit 17A, with location of the area on the island of Borneo (inset).

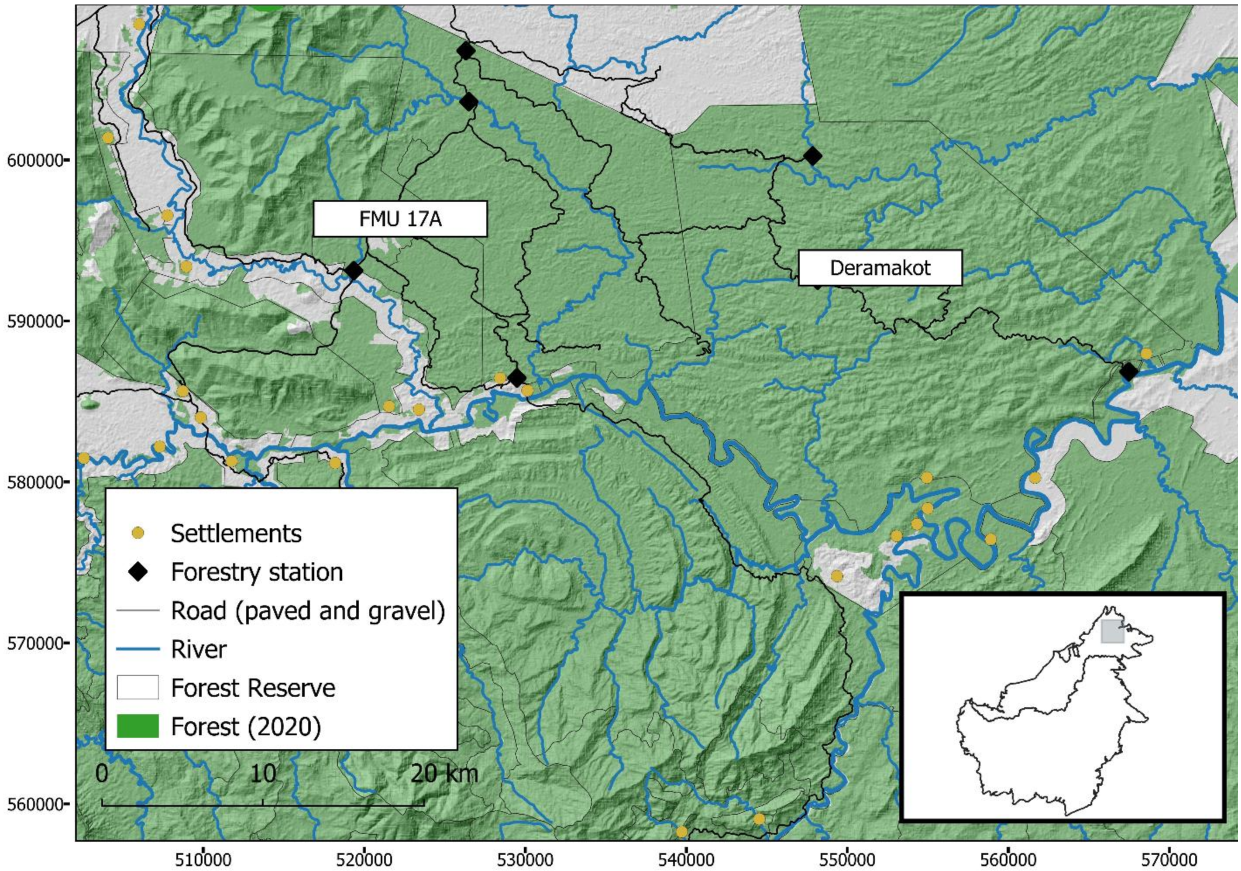

Figure 2: Bayesian occupancy model results showing the effects of the three covariates (remoteness, Topographic Position Index, and Forest height) on offender “use”. Solid lines represents model predicted values while dotted lines represent the upper and lower bounds of the 95% Bayesian Credible Intervals.

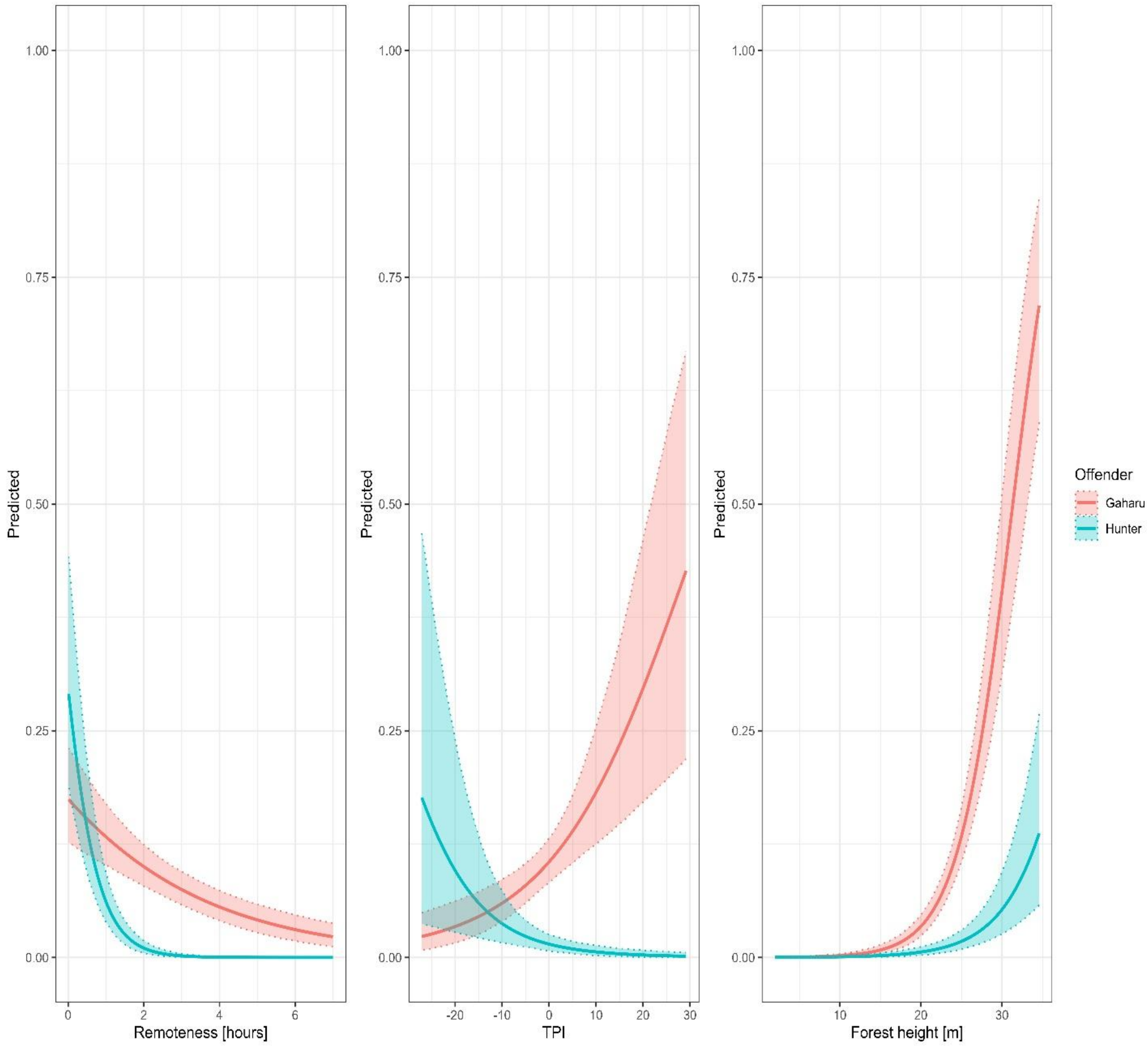

Figure 3: Predicted area "use" for wildlife hunters (top) and gaharu collectors (bottom) throughout Deramakot Forest Reserve and Forest Management Unit 17A.

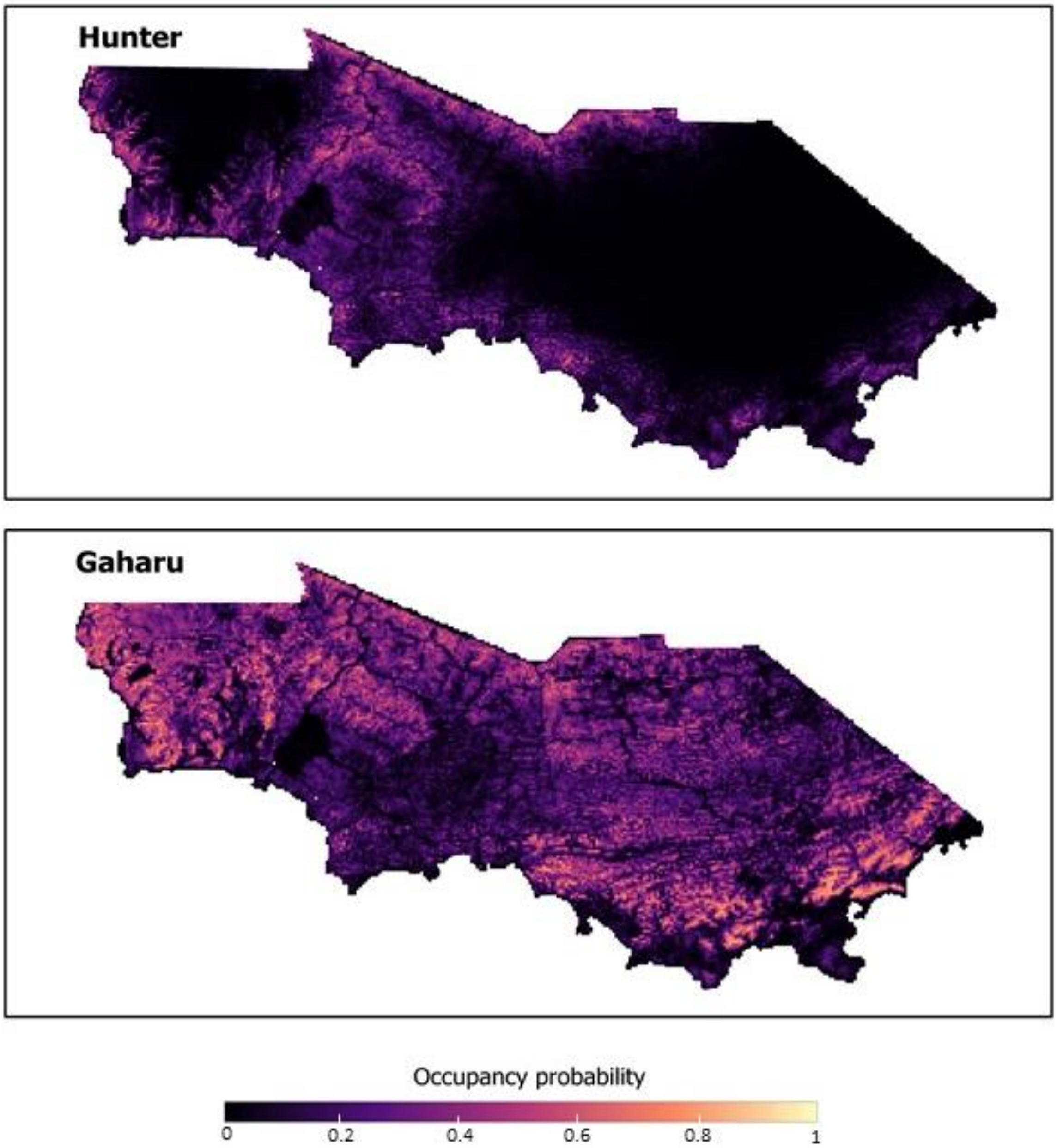

Table 1: Summary of data collected by patrol teams during 2017 – 2019 in Deramakot Forest Reserve and Forest Management Unit 17A. Grid cells refer to the 200 x 200 m sampling grid cells used for our analysis.

Year	Grid cells patrolled	Grid cells with detection	Number of detections
Wildlife hunters			
2017	1308	30	31
2018	3818	58	59
2019	1829	18	18
Gaharu collectors			
2017	1308	52	52
2018	3818	192	195
2019	1829	2	2

CHAPTER 5

GENERAL DISCUSSION

This dissertation focuses on one particular species of high conservation value (HCV; Brown et al., 2013; HCV Malaysia Toolkit Steering Committee, 2021), the sun bear *Helarctos malayanus.* We used the sun bear as our focal HCV species because a large amount of data were available from across Sabah, the species is forest-dependent, and the importance of the species to the illegal wildlife trade.

The first purpose of the dissertation was to investigate sun bear habitat suitability at both the state-wide – for Sabah – and site-specific scale – for Deramakot Forest Reserve and Forest Management Unit 17A. This included a consideration of how habitat may change with future land use plans. The findings from this investigation allowed for an assessment of how Sabah's sustainable forest management and planned future tree plantation expansion affects sun bears. The second purpose of this dissertation was to investigate whether spatial modelling can assist managers of protected and conserved areas in planning anti-poaching operations to disrupt two different offender types, wildlife hunters and gaharu collectors.

Study methodology

To understand sun bear habitat suitability across Sabah, we needed systematically collected datasets with information on detection and non-detection from multiple forested areas. It would have been impractical to accomplish this for one research group, and we thus relied on extensive collaboration with other groups. For almost ten years now Sabah has accommodated many research groups intent on surveying terrestrial medium-sized to large mammals using camera traps, providing a large resource that we could draw on. In our context, we used this large dataset for a relatively "limited" single-species application, and there is potential for future studies to make use of these data to answer questions in a multi-species context. None of the camera trap surveys we obtained data from were specifically targeted at sun bears. Camera trap set ups in the field were mostly similar across surveys – approximately 30cm from the ground facing wildlife trails and logging roads. Only one survey had camera traps set higher off the ground (~50 cm). Despite being non-targeted to sun bears, these surveys were able to contribute robust data to our study. We highlight the value of systematic camera trap studies to research beyond the target species.

Of particular interest are data from long-term monitoring efforts using camera traps instead of one-time surveys. For example, our focal study area in central Sabah, Deramakot Forest Reserve (Deramakot) and Forest Management Unit 17A (FMU 17A), has had systematic surveys in 2014 and 2018 with similar survey designs (Tilker et al., 2019; Guharajan et al., 2021), allowing for the examination of possible changes in habitat suitability. This was the only location with multi-year data available in our dataset. We highlight the need for research groups in Sabah to consider implementing monitoring programmes instead of one-time surveys so that more rigorous assessments of biodiversity and its change can be conducted (Garshelis et al., 2022).

Our second dataset came from SMART patrol data collected in Deramakot and FMU 17A. At the onset of this study, there was little patrol data from areas away from major forest roads. The addition of our research team assisted the Sabah Forestry Department rangers in building up a much larger patrol dataset, covering previously unpatrolled areas of forest. The experience of our research assistants together with forestry rangers also allowed us to differentiate offender signs and incorporate this into the SMART data model. In fact, most other studies conducted in the region using patrol data have not taken offender type into account (Marescot et al., 2019; Xu et al., 2020; Tilker et al., 2023). We acknowledge that offender type may not be a point of interest for all protected area managers, especially in situations where a single poaching method such as cable snaring is clearly dominant. However, even when poaching methods are mostly uniform at a site, offenders may still be different (Lam et al., 2023). To that effect, we highlight that managers of protected and conserved area should at least consider including offender type in patrol data collection in order to make the best use of ranger knowledge.

The versatility of occupancy models allowed us to use this statistical approach for all three of our datasets: 1) Sabah-wide sun bear detection/non-detection, 2) Deramakot and FMU 17A sun bear detection/non-detection in 2014 and 2018 and 3) Deramakot and FMU 17A offender detection/non-detection from 2017-2019. Modelling the offender dataset (Chapter 4), with multiple years and two offender types, required Bayesian estimation (Dorazio et al., 2006) so that we could include random effects (for detection) and interactions (for occupancy). For the simpler single-species datasets (Chapter 2 and 3), we could rely on maximum likelihood estimation. Our applications highlight how occupancy as a modelling tool is highly relevant and useful even outside of wildlife-specific applications (Marescot et al., 2019; Tilker et al., 2023). Even with the advent of artificial intelligence tools in predicting poaching hotspots (Xu et al., 2020, 2021), occupancy seems to perform better in disentangling effort (detection) from actual occupancy (Leibniz Institute for Zoo and Wildlife Research, unpublished data). Throughout this dissertation, we highlight that our interpretation of occupancy is "use" as our camera trap stations (for sun bear data) and grid cells (for offenders) were not large enough to actually be considered "occupied" (MacKenzie et al., 2006). This was possible for us as our study did not focus on estimating the number of sites occupied (Sunarto et al., 2012; Duangchatrasiri et al., 2019), but rather on predicting habitat suitability across landscapes based on covariate relationships (Sollmann et al., 2017; Wong et al., 2022).

We exclusively relied on remotely sensed covariates or covariates derived from remote-sensed data. Such covariates are extremely useful as they allow us to predict habitat suitability across large landscapes, beyond just surveyed locations (Sollmann et al., 2017; Brozovic et al., 2018; Wong et al., 2022). However, they can present some issues especially when the covariates and the detection/non-detection data were derived during different temporal periods. Where possible, we attempted to account for this by calculating covariate values that came from the same time periods as the field data (Chapter 3). The occupancy-based habitat suitability projections provided an intuitive way to identify and prioritise areas of best available habitat for a target species, in our case sun bears. In fact, areas of Sabah that are recognised as highly suitable habitat for sun bears in this study are contained within the Large Landscape framework which is being developed by the Sabah Forestry Department to aid in land-use planning (R.C. Ong, pers. comm.). Aside from identifying highly suitable habitat for HCV species, we also showed how a manager of a protected or conserved area can visually identify areas within a landscape targeted by different offender types. More recent patrols (from the year 2020 onwards) conducted by the Sabah Forestry Department and nongovernment organisations have confirmed that certain areas highlighted as heavily used by offenders in our study are in fact frequently used by these poachers.

Habitat implications for a species of high conservation value: the sun bear

We found that for our focal species of high conservation value (HCV), the sun bear, habitat suitability was moderate to high across most of the large forested landscapes in Sabah, with almost 50% of suitable habitat located within totally protected areas (Chapter 2). The Sabah government's commitment to gazetting new protected areas over the last decade has certainly been positive for the protection of sun bears and many other HCV species, with more protected areas planned in the coming years (Sabah Forestry Department, 2018). The other ~50% however lies within commercial forest reserves, in which some areas are slated for tree plantation development. If such development occurs in these reserves, it will certainly have an impact on the species, although the spatial extent of such development nor the size of each planted area is not publicly known at this point in time. If areas of tree plantation are interspersed with natural forests, as they are in some areas now (pers. obs.), the effects of these developments could be mitigated to some degree (Yaap et al., 2016; Wong et al., 2022). Sun bear use of tree plantations is currently gleaned only from camera trap detections (McShea et al., 2009; Yaap et al., 2016; Wong et al., 2022), with little information available on how exactly the sun bears use these areas. Further sun bear focused research could attempt to answer ecological questions about the use of these tree plantations (i.e. food sources and resting sites) as well as whether there is potential for human-sun bear conflicts in these areas.

At the site scale (Deramakot and FMU 17A), we found that sun bear habitat suitability was most clearly affected by forest quality as measured by the Normalised Difference Moisture Index, more so than proxies of poaching pressure such as settlement density and accessibility (Chapter 3). We found evidence that this landscape potentially increased in overall habitat suitability for sun bears over a four year period. The reduced impact logging, employing a rotational system (Ong et al., 2013), seems to have minimal landscape-level effects on sun bears in Deramakot. Interestingly, the actively logged Deramakot had a higher (although not significantly so) overall habitat suitability than FMU 17A. While we cannot treat these results as representative of the situation throughout Sabah, it does give us an idea on the potential status of sun bears in other commercial forest reserves managed for reduced impact logging, which is currently the standard for all logging licenses in the state. In other parts of Borneo, a similar trend is suggested where logged forests are not necessarily poorer habitat for sun bears (Jati et al., 2018). As degradation via selective logging has already affected large forest areas in Borneo in the past (Gaveau et al., 2014), it is encouraging that a forest dependent species such as the sun bear has demonstrated resilience to these habitat changes.

Protecting high conservation values *in situ*

Effective protection of HCV forests and species in large landscapes has always been a challenge in some of the remote protected and conserved areas of Southeast Asia. Encouragingly, there have been successful government-led efforts in the region. In Thailand, sustained patrol vigilance contributed to the slow recovery of tigers (Duangchantrasiri et al., 2016). In Malaysia, a national effort involving forestry and wildlife rangers supported by police has boosted HCV protection capacity (Department of Wildlife and National Parks Peninsular Malaysia, 2021). While top-down approaches such as these are clearly needed, flexibility is also needed at the site-level such as individual forest reserves, in order to respond adequately to area-specific threats (Lam et al., 2023).

We highlighted the need for site-level anti-poaching operations to incorporate local or site-specific knowledge of different offenders and their different activities (Chapter 4). Our results showed that both offender groups acted either differently or at different magnitudes with respect to the selected covariates. Our projections also highlighted the difference in space use between offender groups across Deramakot and FMU 17A. This particular level of differentiation could be valuable in assisting managers when they plan anti-poaching operations. In a situation where any advantage over poachers is important (Gray et al., 2021), the use of patrol data and occupancy models shows some promise. However, using occupancy models to identify areas for targeted patrols also has its drawbacks, as sufficient data from previous patrols are needed to obtain a decent power and accuracy for the model (Tilker et al., 2023). Protected areas for which little data on previous patrols were available would not be able to rely on this form of predictive modelling to guide their operation planning. This issue would not be limited to occupancy-based projections, as methods using artificial intelligence also require sufficient training data from previous patrols for their application (Xu et al., 2020, 2021). The use of predictive modelling then is limited to managers who have access to data from previous patrols for the protected or conserved area they are responsible for.

If commercial-level poaching can be sustainably disrupted at the site level, then sun bears can occur in large areas of forest habitat even though these forests may be degraded (Chapter 2 and 3). This is encouraging, as sun bears are prized in the illegal wildlife trade (Crudge et al., 2018), and there is a risk of syndicates exploiting poorly protected forests in Sabah. We note that the effects of commercial level poaching are often time-lagged, and defaunation effects are only really felt when species become extremely difficult to detect (Tilker et al., 2018, 2020). Therefore, a precautionary and proactive approach must be taken to protect all HCV species in Sabah. It is encouraging to note that there has been attention and resources placed towards countering poaching and wildlife crime in recent years (Department of Wildlife and National Parks Peninsular Malaysia, 2021). We can therefore hope that Sabah will not experience drastic spikes in commercial-level poaching at the current time or in future.

Conservation implications for sustainable forest management in Sabah

As there is no more large scale expansion of oil palm, remaining forested areas in Sabah are crucial for the forest-dependent sun bear and other HCV species. The focus then is on how to improve the management and protection of this habitat via continuous refinements in sustainable forest management. In terms of reduced impact logging, our study adds to the evidence that forests under reduced impacting logging can maintain populations of HCV species. The next crucial planning step will be where tree plantations will be erected in future. If planned well, tree plantations interspersed with natural forest could potentially provide steady income to the state via timber royalties while minimising the impact on HCV species. In terms of protection, there has been a push to professionalise enforcement capacity within agencies responsible for forestry and wildlife in Sabah. We highlight the need for proper patrol data management and the need to incorporate ranger knowledge at the site level as a starting point for any manager to begin planning operations. With continuous reforms in these fields as highlighted in state policy (Sabah Forestry Department, 2018), we can be optimistic about the future of Sabah's HCV species.

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CURRICULUM VITAE

Due to data protection reasons, the curriculum vitae is not published in the electronic version of this thesis.