USING NOVEL GPS LOGGERS TO ESTIMATE THE HOME RANGE AND MOVEMENT PATTERNS OF CLOUDED MONITOR LIZARDS (VARANUS NEBULOSUS) IN THE DRY DIPTEROCARP AND DRY EVERGREEN FORESTS OF SAKAERAT ENVIRONMENTAL RESEARCH STATION

JESSE GOODYEAR

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Environmental Biology

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การใช้เครื่องระบุตำแหน่งโลก (GPS) เพื่อการประเมินขอบเขตถิ่นที่อยู่อาศัยและรูปแบบการเคลื่อนที่ของตะกวดลายเมฆ (*Varanus nebulosus*) ในพื้นที่ป่าเต็งรังและป่าดิบแล้งในสถานีวิจัยสิ่งแวดล้อมสะแกราช

นายเจสซี่ กู๊ดเยียร์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต

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เจสซี่ กู๊ดเยียร์ : การใช้เครื่องระบุตำแหน่งโลก (GPS) เพื่อการประเมินขอบเขตถิ่นที่อยู่อาศัยและรูปแบบการเคลื่อนที่ของตะกวดลายเมฆ (*Varanus nebulosus*) ในพื้นที่ป่าเต็งรังและป่าดิบแล้งในสถานีวิจัยสิ่งแวดล้อมสะแกราช. อาจารย์ที่ปรึกษา : อาจารย์ ดร.คอลิน โทมัส สไตร์น. 127 หน้า.

คำสำคัญ: Varanus, จีพีเอส, พื้นที่หากิน, รูปแบบการเคลื่อนไหว, การเลือกพื้นที่อยู่อาศัย

รายงานการศึกษาตะกวดลายเมฆ (*Varanus nebulosus*) ที่สถานีวิจัยสิ่งแวดล้อมสะแกราช จังหวัดนครราชสีมา ทั้งหมด 3 เรื่อง เรื่องแรกเป็นการติดตามตะกวดลายเมฆทั้งหมด 14 ตัว (ตัวเมีย 5 ตัวและตัวผู้ 9 ตัว) โดยใช้สัญญาณคลื่นวิทยุ (radio telemetry) เป็นระยะเวลาเฉลี่ย 149.5 ± 73.4 วัน จากการประเมินขนาดพื้นที่หากินของตะกวดลายเมฆ โดยใช้ Autocorrelated Kernel Density Estimators (95% AKDE) พบว่า มีขนาดพื้นที่หากิน 28.99 ± 6.01 เฮกตาร์และจากการใช้แบบจำลอง Dynamic Brownian Bridge Movement (95% dBBMM) เพื่อหาพื้นที่การกระจายและความแปรปรวนของการเคลื่อนที่ของตะกวดลายเมฆ พบว่า มีพื้นที่ในการกระจาย 13.17 ± 3.84 เฮกตาร์ โดยมีค่าความแปรปรวนเฉลี่ย 3.17 ± SE 0.88 เมตร (0.13 ถึง 11.75 เมตร) ในการศึกษาการเลือกถิ่นที่อยู่อาศัยแบบเฉพาะได้ใช้การวิเคราะห์แบบ Integrated Step Selection Functions (ISSF) เป็นแบบจำลองระดับประชากรซึ่งได้ระบุความสัมพันธ์เชิงบวกของตะกวดลายเมฆกับต้นเคี่ยมคะนอง (*Shorea henryana*)

เรื่องที่สองเป็นรายงานครั้งแรกเกี่ยวกับการจำศีลของตะกวด ซึ่งตรงกันข้ามกับรายงานก่อนหน้านี้ที่ระบุว่า ตะกวดไม่มีการจำศีล จากการติดตามตะกวดลายเมฆจำนวน 10 ตัวในช่วงที่ไม่มีการเคลื่อนไหว พบว่า มี 7 ตัวได้เข้าไปจำศีลภายในโพรงของต้นเคี่ยมคะนองและจากต้นไม้ที่ตะกวดลายเมฆเลือกทั้งหมด พบว่า จะเลือกโพรงที่หันหน้าไปทางระหว่างทิศตะวันออกและทิศใต้ (90°—180°) โดยใช้ระยะเวลาในการจำศีลเฉลี่ย 100 วัน (86—113 วัน มีค่าเบี่ยงเบนมาตรฐาน = 10.7) การจำศีลเริ่มต้นในเดือนพฤศจิกายนซึ่งเป็นช่วงที่อุณหภูมิและความชื้นลดลงและการจำศีลสิ้นสุดในต้นเดือนมีนาคมเมื่ออุณหภูมิและความชื้นกลับมาปกติและในช่วงจำศีลมีตะกวดจำนวน 8 ใน 10 ตัว โผล่ตัวออกมาอาบแดดบางส่วนหรือออกมาทั้งตัวจากโพรงหลายครั้ง อย่างไรก็ตาม ตะกวดลายเมฆ 2 ตัวจาก 8 ตัว ได้ย้ายออกจากโพรงเดิมไปยังโพรงใหม่ในช่วงจำศีลหลังจากระยะเวลาจำศีลยืดออกไป ผล

การศึกษานี้ได้ให้ข้อมูลเชิงลึกว่า ตะกวดลายเมฆมีความสัมพันธ์กับต้นเคี่ยมคะนองในบริเวณป่าดิบแล้งในภาคตะวันออกเฉียงเหนือของประเทศไทย

เรื่องที่สามการประเมินประสิทธิภาพการใช้ประโยชน์จากจีพีเอสที่ราคาไม่แพงเทียบกับข้อมูลการติดตามด้วยสัญญาณคลื่นวิทยุ ซึ่งใช้ข้อมูลมาตราส่วนเชิงพื้นที่และเชิงเวลาในช่วงเดียวกัน โดยวิเคราะห์แบบจำลอง 3 แบบ ได้แก่ dBBMM, AKDE และ ISSF จากการติดจีพีเอสจำนวน 9 ตัว (ตัวเมีย 3 ตัวและตัวผู้ 6 ตัว) พบว่า ใช้เวลาติดตามเฉลี่ย 72.3 ± 36.7 วัน โดยใช้จีพีเอสในภาคสนามจำนวน 18 ครั้ง มีอัตราความสำเร็จในการทำงานของอุปกรณ์ 61.1% และอัตราความสำเร็จในการรวบรวมข้อมูล 48.3% (อัตราความสำเร็จในการรวบรวมข้อมูลขึ้นอยู่กับความสำเร็จในการทำงานของอุปกรณ์ 61.1%) ในการคำนวณหาพื้นที่การกระจายและความแปรปรวนของการเคลื่อนที่โดยใช้แบบจำลอง 95% dBBMM พบว่า ข้อมูลที่ได้จากสัญญาณคลื่นวิทยุมีขนาดพื้นที่การกระจาย 9.59 ± 3.57 เฮกตาร์และมีค่าความแปรปรวนของการเคลื่อนที่ 3.10 ± 1.06 เมตร ในขณะที่ ข้อมูลที่ได้จากจีพีเอสมีขนาดพื้นที่การกระจาย 7.78 ±1.93 เฮกตาร์และมีความแปรปรวนของการเคลื่อนที่ 2.37 ± 0.71 เมตร ตามลำดับ ขนาดของพื้นที่หากินที่ประเมินโดยใช้แบบจำลอง AKDE พบว่า มีขนาดพื้นที่หากินเท่ากับ 19.36 ± 0.02 เฮกตาร์ (9.31 ถึง 190.90 เฮกตาร์) แต่ข้อมูลนี้การใช้คลื่นความถี่วิทยุไม่สามารถประเมินขนาดพื้นที่หากินจำนวน 3 ตัว ในขณะที่การศึกษาโดยใช้จีพีเอสสามารถประเมินขนาดพื้นที่หากินได้ทุกตัว โดยพบว่า มีขนาดพื้นที่หากิน 48.15 ± 11.27 เฮกตาร์ (1.39 ถึง 214.90 เฮกตาร์) ผลการศึกษาการเลือกใช้ถิ่นที่อยู่อาศัยโดยใช้การวิเคราะห์แบบจำลอง ISSF พบว่า ตะกวดลายเมฆมีการเคลื่อนที่สัมพันธ์กับตำแหน่งของต้นเคี่ยมคะนองจากการติดตามด้วยสัญญาณคลื่นวิทยุ ในขณะที่การติดตามด้วยจีพีเอส พบว่า ไม่มีสอดคล้องกับตัวแปรที่ใช้ในการทดสอบถิ่นที่อยู่อาศัยทั้งหมด

สาขาวิชาชีววิทยา	ลายมือชื่อนักศึกษา ______
ปีการศึกษา 2564	ลายมือชื่ออาจารย์ที่ปรึกษา ______

JESSE GOODYEAR : USING NOVEL GPS LOGGERS TO ESTIMATE THE HOME RANGE AND MOVEMENT PATTERNS OF CLOUDED MONITOR LIZARDS (*VARANUS NEBULOSUS*) IN THE DRY DIPTEROCARP AND DRY EVERGREEN FORESTS OF SAKAERAT ENVIRONMENTAL RESEARCH STATION. THESIS ADVISOR : COLIN THOMAS STRINE, Ph.D. 127 PP.

Keywords: Varanus, GPS, Home Range, Movement, Habitat Selection

Herein we report the results of three studies on the Clouded Monitor Lizard (*Varanus nebulosus*) at the Sakaerat Environmental Research Station, Nakhon Ratchasima, Thailand. First, we tracked a total of 14 individuals (5 females, 9 males) using radio telemetry for a mean of 149.5 days ± 73.4 days. We assessed home range using Autocorrelated Kernel Density Estimators (AKDE); mean 95% contour AKDE area of 28.99 ±6.01 ha. We investigated occurrence distributions and motion variance with dynamic Brownian Bridge Movement Models (dBBMM); the mean 95% confidence area was 13.17 ±3.84 ha; the mean motion variance was 3.17 ± SE 0.88 m; range 0.13 to 11.75 m. We evaluated if individuals selected specific habitat features with Integrated Step Selection Functions (ISSF); Models at the population level identified a positive association of *V. nebulosus* to the *Shorea henryana* tree species.

Second, we made the first records of brumation within this monitor lizard species. This contrasts with earlier reports of the same species where no brumation was recorded. We successfully tracked 10 individuals throughout their inactive period and found that seven of the monitors selected tree hollows within the endangered *Shorea henryana* tree. All tree hollows selected faced between the east and south cardinal points (90°-180°). The average brumation period was 100 days (range = 86-113 days, standard deviation = 10.7), beginning in November at a time of falling temperatures and humidity and ending in early March when these variables had been restored. Eight of the 10 monitors basked partially or completely out of their shelter sites on multiple occasions. Of those eight monitors, two individuals moved between shelter sites during brumation after an extended period in one location. Our observations provide insight into the relationship between *V. nebulosus* and the tree *S. henryana*, in the dry evergreen forests of north-eastern Thailand.

Third, we evaluated the performance of an inexpensive GPS logger against traditional radio telemetry data collected over the same spatial and temporal scales using three separate analyses: dynamic Brownian Bridge Movement Models (dBBMM), Autocorrelated Kernel Density Estimators (AKDE) and Integrated Step Selection Functions (ISSF). We tracked 9 individuals (3 females, 6 males) using GPS loggers for a mean of 72.3 days ± 36.7 days. We deployed GPS devices in the field on 18 occasions with a 61.1% success rate and a 48.3% fix success rate (FSR; based on the 61.1% successful devices). Occurrence distributions and motion variance was evaluated with dBBMM analysis: the mean 95% confidence area was 9.59 ± 3.57 ha with an average motion variance of 3.10 ± 1.06 m for data collected with VHF transmitters; the mean 95% confidence area was 7.78 ± 1.93 ha with an average motion variance of 2.37 ± 0.71 m, for data collected with GPS loggers. Home range was estimated using AKDE analysis: we were unable to obtain range residency for three individuals using traditional radio telemetry, the mean 95% home range estimate was 19.36 ha ± 0.02 with a range from 9.31 to 190.90 ha; We obtained range residency for all individuals with location data collected with GPS loggers, the mean 95% home range estimate was 48.15 ± 11.27 ha with a range from 1.39 to 214.9 ha. Habitat selection was investigated with ISSF analysis: VHF-derived results suggested that *V. nebulosus* movements are associated with locations of *Shorea henryana* trees; GPS-derived outputs suggested a strong avoidance with all habitat covariates tested.

School of Biology　　　　Student's Signature ____________

Academic Year 2021　　　　Advisor's Signature ____________

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During the last few years, my life has revolved around this research project, which has allowed me to experience a new culture and live amongst wildlife that I have dreamed about seeing since childhood. Despite the long grueling days in the field, looking for missing lizards or trekking with traps strapped onto my back through the thorn Moraceae forest, this Master's degree has ultimately resulted in the most remarkable and memorable experiences of my life. First and foremost, I'd like to thank my advisor, Dr. Colin Strine, for believing in me and guiding me throughout this entire process, while still giving me the freedom to make mistakes and ultimately grow as a researcher. I will forever be grateful for this opportunity and all the skills I have learned and picked up along the way. I would also like to thank my committee members, Dr. George Gale, Dr. Sirilak Chumkiew and Director Surachit Waengsothorn for their patience, support, and encouragement throughout my entire study. Next, I would like to thank the Suranaree University of Technology (SUT) School of Biology Institute of Science, the National Research Council of Thailand, The Department of National Parks and the Thailand Institute of Scientific and Technological Research for providing financial and logistical support as well as, research permissions to conduct my study on Clouded Monitor Lizards in Thailand. I would like to thank Dr. Inês Silva, for her expertise and feedback on my home range analysis and for sacrificing her time to help run my analysis through HPC in Germany. I'd like to show my appreciation to Siravich Viriyataveekul for all your help in the field and hard work in getting my project off the ground. It was a huge learning curve for both of us but together we made it work and had a blast along the way. Last, I'd sincerely like to thank Anji D'Souza for her friendship, consistent banter, amazing sense of humor and ability to always provide words of encouragement or lend an open ear when needed.

Jesse Goodyear

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LIST OF ABBREVIATIONS

AIC: Akaike information criterion

AKDE: Autocorrelated Kernel Density Estimators

dBBMM: dynamic Brownian Bridge Movement Models

DEF: Dry evergreen forest

DDF: Dry dipterocarp forest

DOF: Depth of field

EHPE: Environmental horizontal positioning error

FSR: Fix Success Rate

GPS: Global Positioning System

HDOP: Horizontal Dilution of Precision

IID: Independent identically distributed

ISSF: Integrated Step Selection Functions

KDE: Kernel Density Estimates

LE: Location Error

MCP: Minimum Convex Polygon

MDF: Mixed deciduous forest

OU: Ornstein-Uhlenbeck

OUF: Ornstein-Uhlenbeck motion with foraging

PCB: Printed circuit board

SBR: Sakaerat Biosphere Reserve

SE: Standard Error

SERS: Sakaerat Environmental Research Station

SMD: Surface Mount Device

SVL: Snout-vent Length

TL: Total length

TW: Tail width

UD: Utilization distribution

UERE: User Equivalent Range Error

VHF: Very High Frequency

CHAPTER I

INTRODUCTION

Figure 1.1 Clouded Monitor Lizard (*Varanus nebulosus*).

1.1 Introduction

Traditionally, researchers have used radio telemetry to track individual animal movements and map their home ranges (Ujvari and Korsos, 2000). However, in recent years GPS transmitters and loggers have become more affordable and may provide an efficient alternative to radio telemetry (Cagnacci et al., 2010; Hebblewhite and Haydon, 2010; Joo et al., 2020). GPS loggers and transmitters can be set to record an animal's location at specific time intervals, providing a higher frequency of data, resulting in more accurate movement pathways for individual animals (Cagnacci et al., 2010). In 2013, researchers modified an inexpensive commercially available GPS logger (i-gotU GT-120) and tested it out for wildlife research (Allan et al., 2013). When paired with a VHF transmitter researchers found that the GPS logger performed successfully in the field, with around 70% of GPS fixes within 10 m of accuracy (Allan et al., 2013). Although prices of GPS loggers and transmitters have come down over the last decade, they're still quite high with average price per device costing around $2,000 USD. Therefore, modifying inexpensive commercial loggers for wildlife research may provide an alternative method for small-scale research projects.

Some studies have assessed the accuracy of very high frequency (VHF) transmitters to global positioning system (GPS) transmitters/loggers on larger animals such as; White Tailed Deer (*Odocoileus virginianus*; Coulombe et al., 2006), Florida Panthers (*Puma concolor coryi*; Land et al., 2010) and the American Alligator (*Alligator mississippiensis*; Skupien et al., 2016). Results of these studies found more accurate movement pathways with GPS technology and identified more habitats used than with data collected with VHF transmitters. Although few studies have compared the accuracy or efficiency of VHF to GPS technology, on medium and small sized organisms— none have done so with monitor lizards.

The main difference between GPS transmitters and loggers lies in the transmission of the data collected; GPS transmitters have remote data collection capabilities while the data from GPS loggers must be manually collected. Because loggers do not transmit any type of signal, they are paired with a VHF transmitter to be incorporated into wildlife research. The GPS logger records GPS data points while the signal from the VHF transmitter allows researchers to locate the organism and collect the device later on.

Radio telemetry, while effective, may introduce bias because researchers must be in the field to collect location data (possibly altering the animal's behavior). If data from GPS loggers are more reliable than VHF transmitters, then there is the potential to eliminate bias and time constraints from fieldwork. Instead of going into the field 2-3 times per day, researchers would only need to go 4-6 times annually; capture the animal, collect the data points, and charge the batteries (keeping the study animal for no more than 24 hours).

This study will produce home range estimates (autocorrelated Kernel Density Estimates), movement pathway occurrence distributions (dynamic Brownian Bridge Movement Models) and habitat step selection models from Integrated Step Selection Functions (ISSF), from both VHF transmitters and GPS loggers at Sakaerat Environmental Research Station in Northeastern Thailand. The model organism is the Clouded Monitor Lizard *Varanus nebulosus;* a medium sized animal with a maximum total length of 1.7 m.

1.2 Objectives and hypothesis

The objectives of this study are:

1. Increase scientific knowledge on *V. nebulosus* by analyzing home range, movement models and habitat selection of radio tracked lizards.
2. Document any inactive periods of monitor lizards and record the specific shelters sites used if any.
3. Assess the effectiveness of implementing novel (via fix success rate within acceptable margins) GPS loggers in Sakaerat Biosphere Reserve in a densely canopied forest for semi-arboreal monitor lizards
4. Identify differences in AKDE home range estimates of *V. nebulosus* at SBR with both VHF and GPS technology.
5. Evaluate differences in predicted movement pathways from dBBMM estimates produced from simultaneously collected VHF and GPS data on tagged *V. nebulosus*.

6. Assess the precision in ISSF analysis on habitat features driving lizard movement produced from simultaneously collected VHF and GPS data on tagged *V. nebulosus*.

The corresponding hypothesis are:

1. The *V. nebulosus* will utilize specific habitat types and features within their set occurrence distributions.
2. I predict that *V. nebulosus* will have an inactive period during the cold dry months at the SBR.
3. The fix success rate (FSR) of GPS loggers will be over 70% within the densely canopied dry evergreen forest.
4. AKDE Home range estimates modeled using data collected from GPS logging devices will be more accurate than estimates modeled using VHF data.
5. dBBMM movement pathways modeled using data collected from GPS logging devices will show more movement pathways between shelter sites than estimates modeled using VHF data.
6. Step selection analysis from GPS data will reveal specific habitat features driving movement, to the same degree or more than VHF data (for overlapping time periods).

1.3 Scope and limitations

This study was conducted within the dry evergreen and dry dipterocarp forests of Sakaerat Biosphere Reserve (SBR), in Northeast Thailand. Data was collected for one year through the wet and dry seasons between July 2020, and July 2021. During this period, I collected radio tracking data on 15 individuals (10 males and 5 females), all 15 individuals were tracked with radio transmitters and 9 of these individuals were also fitted with GPS logging devices.

I plan on providing a detailed report of the efficiency and economical methodology for future spatial ecology studies by assessing: the fix success rate (FSR) of novel GPS loggers; the AKDE home range estimates from GPS loggers compared to radio telemetry data; the occurrence distributions and motion variance of GPS logger data to radio telemetry data and habitat selection using ISSF between GPS and radio telemetry data. We hope that our study can answer questions on when it is effective to use GPS tracking devices and radio telemetry devices depending on the research questions presented. Lastly, we plan to provide baseline ecological data on *V. nebulosus*—which are underrepresented in current literature—within the dry dipterocarp and dry evergreen forests of SBR.

The limitations of this study were any factors that could hinder fieldwork or data collection, such as: heavy rainfall, lightning storms, equipment failure or malfunction, lost study animals and lack of field assistants.

1.4 Applied and theoretical applications of study

Findings from this will update the current scientific knowledge on *V. nebulosus* by addressing their home range size, occurrence distributions, motion variance and selection to specific habitat features. This research project may also serve as a template and suggested guideline for future studies implementing the igotU GT-120 GPS logger in wildlife research. We hope that insights and shortcomings from our study will benefit future projects and help mitigate the potential weaknesses and technical errors associated with building your own GPS tracking device for research.

CHAPTER II

LITERATURE REVIEW

2.1 Radio telemetry

Elucidating patterns of movement for any group of wild animals is important to understanding the ecology of species and radio telemetry has provided one of the most universal methods to study movement patterns and home range (JSmith and Griffiths, 2009; Ujvari and Korsos, 2000). Since its creation in the 1960's radio telemetry has been implemented across taxa and has allowed researchers to uncover the life history strategies of even some of the most cryptic species (Dunn and Gipson, 1977; Hebblewhite and Haydon, 2010). Benefits of radio telemetry consist of the ability to uncover specific behavior habits such as: breeding season, home range, movement pathways, population dynamics and human conflict (Goodrich and Miquelle, 2010; Hodges et al., 2021; Jones et al., 2021; Smith et al., 2021). Although, three are many negative factors such as: field intensive days tracking animal locations, high cost to fund tracking teams, human presence induced movement bias and inability to track in inclement weather or rough terrains

2.2 GPS loggers

Global positioning system (GPS) loggers have become more affordable and lightweight, making them ideal for studying small animals (Glasby and Yarnell, 2013). Loggers can be programmed to capture an animal's location at chronological intervals, providing: a larger data set, increased scope of animal movements and less time in the field. Loggers can take sampling frequencies that are short (5 min) or long (8 hours); larger data sets provide more accurate inferences into animal behaviors and habitat usage (Deon et al., 2002). VHF transmitters require a technician in the field to collect data points; GPS loggers can record an animal's activity (overnight and during inclement weather) when it is difficult to collect data with traditional methods (Beyer and Haufler, 1994; Tomkiewicz et al., 2010). There are many advantages to GPS technology such as more data points, the ability to collect data at all hours of the day, and removing the risk of human-induced bias. GPS technology does have a major drawback with the variability in location accuracy—caused by topography, habitat type, the behavior of the animal, canopy cover, and atmospheric interference—compared to VHF transmitters (Frair et al., 2010; Merrill and Mech, 2003; Musiani et al., 1998).

2.2.1 Novel GPS loggers

The i-gotU GT-120 model GPS logger is commercially available and can be bought from most online shopping websites for around $50 USD. I have provided a price comparison in Table 2.1, with some common wildlife GPS transmitters with similar dimensions to the i-gotU GT-120 logger. This GPS logger has been used in many wildlife studies, although the majority of these studies didn't make any modifications to the device and therefore the tracking durations were typically less than seven days (Harris et al., 2012; Hervías et al., 2014; Stevenson et al., 2013). The first long-term study using these devices was on *Varanus panoptes* in Australia, the authors modified the device by adding a larger battery which allowed them to maximize the tracking duration to 115 days (Lei et al., 2017). Although little has been done to assess the accuracy and effectiveness of the data collected by these loggers, in fact in almost every case there is no mention of GPS accuracy of the data in any of the aforementioned studies.

Table 2.1 Table showing the prices of the commercially available i-gotU GT-120 model GPS logger and GPS transmitters that are produced specifically for wildlife research. Asterisks denote devices that require a monthly subscription for services. Contact refers to companies which require an inquiry for product pricing.

Device Name	Type	Supplier	Weight	Price	Contact?
i-gotU Gt-120	Data logger	Mobile Action Sports	~120g	$50	-
GPS Backpack	Data Transmitter	Telemetry Solutions	~100g	$2195	+
SeaTag TT	Data Transmitter	Desert Star Systems	17-30g	$990	-
GPS/GSM 20-70	Data Transmitter	Microwave Telemetry	70g	$3650*	+
ES-150	Data Transmitter	Cellular Tracking Technologies	15g	$1800	+
GPS-PTT	Data transmitter	GeoTrak Inc	105g	$2700*	+
W500	Data Logger	Advanced Telemetry Systems	65g	$1,495	+

2.3 Comparing GPS to VHF

A study of American Alligators (*Alligator mississippiensis*) found the data gathered by GPS loggers produced larger more relevant MCP home ranges (identified more habitats used than VHF transmitters) but they were outperformed by VHF transmitters when the animal went underground (Skupien et al., 2016). Another study on Florida Panthers (*Puma concolor coryi*), found that the results from the GPS and VHF transmitters were very similar although, the GPS transmitters showed a wider range of used habitat types—since they take locations throughout the day and night (Land et al., 2010). Last, a study on Capercaillie (*Tetrao urogallus*) found 84% of the GPS locations taken under heavy canopy cover were within their range of accepted standard deviation (Wegge and Kastdalen, 2007). Results of these studies found more accurate movement pathways with GPS technology and identified more habitats used than with data collected with VHF transmitters. Although few studies have compared the accuracy or efficiency of VHF to GPS technology, on medium and small sized organisms— none have done so with monitor lizards.

2.4 The genus *Varanus*

All monitor lizards are grouped within the genus *Varanus,* which contains the largest living species of lizards on the planet; monitor lizard sizes range from 20cm to over 3m long (Pianka and King, 2004). Monitor lizards are found from Africa, the Arabian Peninsula, the Middle East, Asia and South into Australia (Koch et al., 2013). Varanids have adapted to many different types of environments across their distribution and ecologically, species are very distinct from each other (adapting to terrestrial, aquatic and arboreal habitats; Pianka and King, 2004). Although the majority of monitor lizards are carnivores there are three species from the Philippines, which are frugivores (Law et al., 2018). Many varanids face a wide variety of threats such as; exploitation from the leather trade (Pernetta, 2009; Shine et al., 1996), Habitat destruction (Sodhi et al., 2004), human consumption and use in traditional medicines (Auffenberg, 1994; Klemens and Thorbjarnarson, 1995). The conservation status of all *Varanid* species are in need of an update and most species (72%) have not been assessed at all (Koch et al., 2013; Merrill and Mech, 2003).

2.4.1 The Clouded Monitor Lizard (*Varanus nebulosus*)

The Clouded Monitor Lizard (*Varanus nebulosus*) is a cryptic species with a broad distribution from Southern Myanmar, Thailand, Southern Vietnam, Sumatra, Java and the Malaysian Peninsula (Koch et al., 2013). This will be the first long term project to study their movements, home range and behavior. *V. nebulosus* is a semi-arboreal species utilizing trees for shelter and basking sites; due to human development suitable habitat is often destroyed for agriculture and urbanization. Because of this, *V. nebulosus* is restricted to protected habitats throughout much of their range (Duengkae and Chuaynkern, 2009). Despite its wide distribution, there is not a lot of information available on this species in the wild.

The International Union for Conservation of Nature (IUCN) lists *V. nebulosus* as a subspecies of the Bengal monitor lizard *V. bengalensis* and therefore as a species of least concern (Cota et al., 2021). Although, many researchers regard the two as separate but closely related species (sister species). this is apparent from; distinguishable oblique ventral scale counts (*bengalensis* 88-110, *nebulosus* 70-90) (Auffenberg, 1994), distinct hemipenal differences (Ziegler and Böhme, 1997), differences in scale morphology and micro-structures (Bucklitsch et al., 2016) and mitochondrial DNA (Ast, 2001). Therefore, *V. nebulosus* needs an updated evaluation to understand its current conservation status in the wild. In Malaysia, from January 2007 to August of 2009, around 28,000 Clouded Monitor Lizards were confiscated in seizures of illegally trafficked animals (Shepherd and John, 2010).

Since *V. nebulosus* is under-represented in current literature it is crucial to study its natural history and spatial ecology to better understand its ecological role. This study will collect data to better understand the behavior and ecology of *V. nebulosus* in Northeastern Thailand that can help inform future conservation efforts throughout its range. By documenting important habitats and shelter sites crucial for its survival, conservation efforts can be more effectively tailored to protect areas of high importance to the species.

Table 2.2 A detailed guide to setting up GPS loggers for research purposes.

Step 1.

Obtained I-gotU GT120 GPS devices, these are traditionally used for keeping track of things such as; suitcases, laptops and vehicles. They will be repurposed to be used for wildlife tracking. The total cost of repurposing each unit will be $100 USD plus the cost of a VHF transmitter it will be paired with. Which in this case is $200 USD equating to $300 USD per GPS unit. While traditional GPS collars start around $1,000 USD (Table 2.1).

Step 2.

Using a hacksaw, gently shave away the corner to remove the plastic casing. Taking caution not to damage the actual device.

Table 2.2 (Continued).

Step 3.

Use pliers to gently remove the device from the plastic casing. Taking caution not to damage the chipboard or the USB plug.

Step 4.

Remove the battery the device came with and attach a new 3.7V battery of higher mAh. Using a soldering iron to attach the wires to both the battery and the GPS chipboard.

Table 2.2 (Continued).

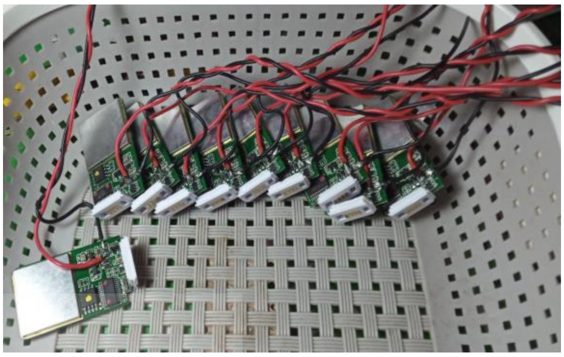
Step 5. Cover the on/off button and USB plug with putty. Then spray the entire device and battery with silicone spray, allowing at least 24 hours for the device to dry. The silicone spray will help protect the device from water damage while deployed in the field.	
Step 6. Prepare a 2-part epoxy mixture and coat the entire GPS chipboard excluding the on/off button and USB plug. Allow to dry, the GPS logger is now ready to be placed into a harness with a VHF transmitter and attached to *V. nebulosus*.	

Table 2.2 (Continued).

Step 7. Next epoxy the GPS logger to the VHF transmitter and fit them inside of a piece of heat shrink which will serve as the harness.	

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CHAPTER III

DRAGON TALES: HOME RANGE, HABITAT SELECTION AND OCCURRENCE DISTRIBUTIONS OF THE CLOUDED MONITOR LIZARD *VARANUS NEBULOSUS* IN NORTH-EASTERN THAILAND

3.1 Abstract

Knowledge of an animal's space use and movement patterns are key aspects to begin understanding the general ecology of many species. Herein we report the home range, movement patterns and habitat selection of Clouded Monitor Lizards (*Varanus nebulosus*) at the Sakaerat Environmental Research Station, Nakhon Ratchasima, Thailand. We tracked a total of 14 individuals (5 females, 9 males) for a mean of 149.5 days ± 73.4 days. We assessed home range using Autocorrelated Kernel Density Estimators (AKDE); mean 95% contour AKDE area of 28.99 ± 6.01 ha. We investigated occurrence distributions and motion variance with dynamic Brownian Bridge Movement Models (dBBMM); the mean 95% confidence area was 13.17 ± 3.84 ha; the mean motion variance was 3.17 ± 0.88 m; range 0.13 to 11.75 m. Lastly, we evaluated if individuals selected specific habitat features with Integrated Step Selection Functions (ISSF); Models at the population level identified a positive association of *V. nebulosus* to the *Shorea henryana* tree species. This is the first in depth project on *V. nebulosus* and the first study done on monitor lizards which accounts for autocorrelation and home range residency assumptions.

3.2 Introduction

The continued expansion of the human population is causing both fragmentation and, in some instances, the complete loss of natural habitats worldwide (Brooks et al., 2002; Haddad et al., 2015; Hughes, 2017). To mitigate the negative impacts of habitat destruction, proper conservation and management planning are required for the survival of biodiversity (Quétier and Lavorel, 2011; Underwood, 2011). Implementing conservation efforts that support and sustain species richness, require baseline data on species movements and habitat use (Haddad et al., 2015; Hays et al., 2019). Southeast Asia has the highest rate of deforestation of all tropical regions worldwide; it is projected to lose three quarters of its original forests by 2100, and up to 42% of its biodiversity (Sodhi et al., 2004). Habitat loss is mainly due to agricultural expansion, logging, habitat fragmentation and urbanization (Hughes, 2017; Sodhi et al., 2010; Zhu et al., 2021). Habitat loss and fragmentation are the leading causes of species extinctions worldwide (Harrison and Bruna, 1999). Palm oil and paper-pulp industries continue to encroach on lowland dipterocarp forests due to global demands for: food, biofuel and other commodities (Sodhi et al., 2010). Dipterocarp forests support many species such as the Clouded Monitor Lizard (*Varanus nebulosus)*, by providing adequate shelter sites like the *Dipterocarpus obtusifolius* tree (Duengkae and Chuaynkern, 2009).

Monitor lizards are contained within the monophyletic genus *Varanus*, despite large differences in morphology (ranging from 20 cm to over 300 cm in length) and ecology (terrestrial, arboreal and aquatic; Koch et al., 2013; Pianka and King, 2004). Varanids are nearly all carnivorous except for a few frugivores species from the Philippines (Law et al., 2018). Monitor lizards are considered an old-world group, since they do not occur naturally within the Americas, ranging from Africa to Asia and south into Australia (Koch et al., 2013; Pianka and King, 2004). The Clouded Monitor Lizard (*Varanus nebulosus*) has a large distribution ranging from Myanmar to Vietnam and southern China to Indonesia (Koch et al., 2013). From a couple of short notes that have been published, it's apparent that *V. nebulosus* is semi-arboreal (utilizing trees for basking and shelter sites) and feeds predominantly on insects (Duengkae and Chuaynkern, 2009; Traeholt, 1997). This species is often illegally harvested from the wild for the bushmeat and leather trade (Shepherd and John, 2010). However aside from this information, there is nothing else known about them and therefore a large knowledge gap that needs to be filled.

Knowledge of an animal's space use and movement patterns are key aspects to begin understanding the general ecology of many species. One of the most widespread methods to study animal movement and home range size is radio telemetry, which has been used since the 1960's (Dunn and Gipson, 1977; Martin et al., 2009). Radio telemetry has proven critical in studying multiple factors even for cryptic species within hard to access habitats, such as: shelter site selection, daily and seasonal activity patterns, home range, habitat selection and movement pathways; Cagnacci et al., 2010; Ujvari and Korsos, 2000). Home range size, movement pathways and habitat selection are all important factors which are used to inform decision makers in conservation management projects (Mitchell and Powell, 2004; Powell and Mitchell, 2012).

Home range is defined as the area used by an individual over the course of its life (Burt, 1943). Movement refers to the path and direction which an animal takes within its home range (Gurarie et al., 2009; Jonsen et al., 2005). There is a lot of confusion within scientific research about the difference between an animal's home range and its movement pathways and how this pertains to research questions (Fieberg and Börger, 2012). In order to estimate an animal's home range researchers, need to collect spatial and temporal data over the course of a set duration. Home range estimates follow a utilization distribution (UD); which is defined by Van Winkle, 1975, as the relative frequency distribution of locations over a set time period; Worton, 1989, took this definition further to consider the UD as, how frequently animals use specific areas within their home range. Home range estimates account for the total area that could be used by a study animal over its life, given the data collected during a study period, therefore these estimates extrapolate the given area to estimate the total potential area used by an animal (Crane et al., 2021). On the other hand, movement models do not estimate the total potential area used by an animal but instead estimate the potential movement pathways between the given collected data parameters (Crane et al., 2021; Kranstauber et al., 2012).

Larger species need more energy than smaller species and generally will occupy larger areas to obtain adequate nutrients, unless the food exists locally in high abundance (Mcnab, 1963; Tucker et al., 2014). If all or part of the home range is defended against other individuals of the same species then it is regarded as a territory (Odum, 1955). Understanding the home range size of a species is the prerequisite to understanding its behavioral ecology and creating science based conservation management planning (Bekoff and Mech, 1984; Johansson et al., 2016; Metcalfe et al., 2015; Parsons, 2016).

To address the lack of knowledge regarding this species we aimed to 1) investigate home range sizes of individual monitor lizards, using Autocorrelated Kernel Density Estimators (AKDE's), 2) quantify space use through temporal movement patterns, using dynamic Brownian Bridge Movement Models (dBBMM) and 3) determine if monitor lizards select specific habitat features within their home range. This is the first in-depth study of Clouded Monitor Lizards (*Varanus nebulosus*) and the first study done on monitor lizards to analyze positional data as autocorrelated movement data.

3.3 Methods

3.3.1 Study site

We conducted our research at the Sakaerat Biosphere Reserve (SBR) in Northeastern Thailand (14.44 – 14.55°N, 101.88 – 101.95°E). The biosphere reserve has three main areas: the core, buffer and transitional. The Sakaerat Environmental Research Station consists mainly of dry evergreen forest (DEF) and dry dipterocarp forest (DDF) with fragments of mixed deciduous forest (MDF), bamboo patches and reclaimed plantation forest. For our study we mainly conducted fieldwork within the DEF and DDF of the core area and the DEF and reclaimed plantation forests of the buffer zone. The biospheres climate is defined as a tropical savannah (Aw) based on the Köppen climate classification (Rubel and Kottek, 2010). For a detailed description of the research station and habitat characteristics please see chapter 3 on the brumation of Clouded Monitor Lizards.

3.3.2 Study animals

We opportunistically captured Clouded Monitor Lizards through visual surveys conducted on foot and by road surveys conducted on a motorcycle. Lizards that were found through road surveys we attempted to capture either by hand or with the help of a noose; lizards that were found through visual surveys were typically found basking or perched on trees, for these individuals we set traps around the base of the tree to capture them (Figure 3.9). Once captured, lizards were brought back to the research station for processing, which consisted of taking morphometric measurements such as: snout-vent length (SVL), total length (TL), head length (HL), head depth (HD) and mass. We used measuring tape for the larger measurements (SVL, TL), calipers for smaller measurements (HL, HD) and an electronic scale to measure the mass. To sex the lizards, we used a variety of different techniques such as popping (applying pressure with our thumbs just below the cloaca to expose the hemipenes), probing (inserting a small metal rod into the cloaca towards the tail) and last to be completely sure we brought each individual to the Nakhon Ratchasima Zoo, where one of the veterinarians assisted us in performing x-rays and sonograms. We gave each lizard a unique ID based on their sex and the individual capture sequence (M06, F16). We then inserted a pit tag into the dorsal portion of the thigh on the rear right leg, in case the lizard was captured again in the future. Lizards that were large enough to be included in our radio telemetry study were fitted with a VHF radio transmitter (Holohil AI-2B model) above the base of the tail and secured around the pelvic girdle following the technique used by Klug et al., 2015 (Figure 3.10). We attempted to minimize the holding time of each lizard to roughly 24 hours although, in some instances, the holding time was longer due to inclement weather and working around the veterinarian's availability. After processing and attaching a radio transmitter to each lizard we released them at the exact location of their capture and began radio-tracking them the following day.

3.3.3 Data collection

Our VHF tracking protocol shifted during our study period as we increased our sample size: originally, we conducted four location fixes per day at 6-hour intervals; as the sample size increased, we settled our tracking schedule at one relocation fix per day between the hours of 06:00 and 20:00. This was done due to a lack of available field technicians and limitations imposed by each animal's location and the terrain of our field site. We used a mixture of homing and three-point triangulation to locate the lizards: homing was done when it was apparent that the lizard was sheltering and not moving, to identify the species of tree being utilized; triangulation was done when the lizard was active to minimize our impact on their behavior. We defined fixes as any time we recorded the location of a lizard regardless of if it had moved or not. We defined relocations as times we recorded the location after it had moved from its previous location. When locating an animal we recorded the time, Universal Transverse Mercator (UTM WGS-84), relocation distance (straight line distance measured using a handheld GPS; Garmin 64s; Garmin International, Inc., USA), GPS accuracy (m) measured with a handheld GPS (Garmin 64s). Although we aimed for daily fixes, there were a handful of occasions where we were unable to conduct daily radio telemetry due to inclement weather or because the animal was being housed at the research station for a routine checkup. Despite this we still managed an average tracking lag time of 21.9 (SE ± 0.18 hours; range =0.57-106.73 hours; Table 3.1) between consecutive fixes.

We radio tracked a total of 14 individuals (9 males and 5 females) during our study period. We classified an individual as an adult female when the SVL >400 mm and the mass was >1500 g and an adult male when SVL >400 mm and mass >2000 g; this was based on previous data by (Auffenberg, 1994), that detailed male *V. nebulosus* are generally heavier than females. Individual tracking durations varied (mean = 149.5 days ± 73.4 days, range = 51-273 days Table 3.1; Figure 3.7).

3.3.4 Home range

We used R studio version 4.0.3 (R Core Development Team, 2020) for all data manipulation and visualizations. We used Autocorrelated Kernel Density Estimators (AKDE) to calculate the home range size of our lizards (Fleming and Calabrese, 2017). Traditional home range estimates such as minimum convex polygons (MCP) and kernel density estimates (KDE), have long been used in wildlife research to estimate the home range and land use of species (Mohr, 1947; Worton, 1989). Minimum convex polygons essentially function by drawing a rectangle around the outermost recorded locations; this type of analysis is not suitable for comparisons against other studies because they are influenced by tracking duration, tracking frequency and GPS accuracy (Silva et al., 2020). Kernel density estimates are also unsuitable for comparisons because they are highly dependent on kernel parameters (which are different for each study) and changes in tracking duration and frequency (Averill-Murray et al., 2020; Silva et al., 2020). Despite all of this, MCP’s and KDE’s are still widely used by researchers even though it has been well documented that they produce biased overestimation (commission) and underestimations (omission) of the home range

(Burgman and Fox, 2003; Crane et al., 2021). Both estimates assume that sequential locations are independent of each other; using traditional radio telemetry techniques with large temporal gaps between consecutive data points, this assumption is likely met (Laver and Kelly, 2008). Although, for tracking protocols which record daily or multiple locations each day these assumptions are likely not met and each sequential location is dependent on the previous. The AKDE analysis uses a fitted movement model to estimate not only the area used but the total space use of an animal during its life stage (Fleming and Calabrese, 2017).

We used the R package *ctmm* v.0.6.1 (Calabrese et al., 2021; Fleming and Calabrese, 2017) to model the spatial requirements of *V. nebulosus.* We visually assessed all variograms to ensure that our lizards met the range residency home range assumption of the AKDE's; we discarded any lizards which didn't meet the assumption.

3.3.5 Movement models

We used dynamic Brownian Bridge Movement Models (dBBMM) to explore movement pathways and occurrence distributions of our lizards with the R package *move* v.4.0.6 (Kranstauber et al., 2018). Traditional Brownian Bridge Movement Models (BBMM) generate the probability of an animal being in an area based on: the starting and ending locations, time between both points and the speed of the movement (Horne et al., 2007). The BBMM quantifies the occurrence distribution (how animals use areas within their home range) of the study animal based on its movement path rather than individual points (Kranstauber et al., 2012). The BBMM provides direct results based on definite assumptions therefore, it may be applied to a wide range of movements (Lonergan et al., 2009). BBMM's major flaw is that it assumes a constant movement between the starting and ending location; animal movement consists of many movement behaviors from point A to point B (Horne et al., 2007; McClintock et al., 2012; Morales et al., 2004). The dBBMM was created by Kranstauber and colleagues in 2012, it incorporates the behavioral change point analysis (BCPA); which determines where along an animal's path behavioral movement changes occur (Gurarie et al., 2009; Kranstauber et al., 2012). Thus, the dBBMM goes beyond the BBMM by incorporating differences in animal behavior and accurate estimates of the area between location data points (Byrne et al., 2014; Kranstauber et al., 2012). We used a window size of 15 and a margin of 7. These values were chosen based on observations of lizard behavior during our tracking regime, the window size of 15 is long enough to capture the motion variance when the lizards were active for extended periods of time and the margin of 7 was short enough to capture variations during times when the lizards were inactive. The contours are somewhat unpredictable and therefore we opted to look at three varying levels (90%, 95% and 99%) to estimate dBBMM occurrence distributions using the R packages: *adehabitatHR* v.0.4.19 (Calenge, 2006) and *rgeos* v.0.5.5 (Bivand and Rundel, 2020).

3.3.6 Habitat selection

In simple terms habitat selection is the area within a habitat which an individual spends its time, this could be due to factors such as; inter- and intraspecific competition, food and available shelter sites (Hildén, 1965). In order to study habitat selection we used Integrated Step Selection Function (ISSF) analysis, with the R package *amt* v.0.1.4 (Signer et al., 2019), which allows researchers to assess habitat selection at both the individual and population levels. By understanding an animal's habitat selection scientists can better understand the drivers of animal movements, since both selection and movement are closely linked together (Van Moorter et al., 2016). Within this analysis each fixed location is called a step and the model works by generating random steps between two known steps; this is done in order to guess the possible pathways which an animal took to get from each known location (Thurfjell et al., 2014). Therefore, the random steps in between known steps are accounting for the available habitat to the animal against the preferred known habitats used.

Due to the large area encompassed in our study we chose to only focus on individual lizards that were located within the DEF of the core area (this was our highest congregation of study animals; F3, F9, F16, M6, M10). Due to the relatively low frequency of relocations within VHF datasets we were not limited by computational power and were able to set our random steps to 200 between each known relocation. We then ran the ISSF analysis against the Euclidean distance to our known habitat features (roads, DDF, *Shorea henryana* trees and streambeds) to determine an avoidance or association to each feature. We created our *Shorea henryana* shapefile by mapping each tree that was >20 m tall over the entire course of our study period, we used a handheld GPS (Garmin 64s) to record the location and a rangefinder to measure the tree height (Nikon Forestry Pro II). We created the streambed shapefile by manually walking the stream from the beginning through the end of the lizard's home range (using a handheld GPS, marking the location at 10-20 m intervals). Shapefiles for the roads and DDF were provided to us through the staff at the research station.

We assessed habitat selection at both the individual level and population level. For the individual level, we created eight models assessing movement to our habitat covariates: the first model was a null with only step length and turning angle, the next four models assessed habitat features independently, and the final three models were multivariate, each modeling the effects of three different habitat features on movement. We then used AIC scores to assess the best fit models for each individual.

To model ISSF at the population level we created four models using the same habitat raster files as in the individual ISSF. For the stratum-specific related effect, we followed (Smith et al., 2021) and used the fixed prior precision of 0.0001, the Penalized Complexity prior, PC (1, 0.05) for the other random slopes (individual), lastly, we used an uninformative normal priors, Normal (0, 10^3) for the fixed effects. We fit all models using the R package *INLA* v.20.03.1748 (Rue et al., 2009).

Table 3.1 Morphometric and tracking summary by individual. Start and end dates are shown as month-day-year. ± indicate standard error associated with means.

ID	Mass (g)	SVL (mm)	Start date	End date	Days tracked	Data points	Lag-time (hr)	Relocation
F1	2025	464	9/5/2020	4/20/2021	226.78	253	21.6 ± 0.52	45
F3	1575	434	7/15/2020	4/15/2021	273.77	370	17.81 ± 0.51	46
F9	2285	494	11/14/2020	4/20/2021	157.00	155	24.47 ± 0.58	30
F15	2115	458	3/7/2021	4/30/2021	53.75	53	24.81 ± 1.36	30
F16	2805	478	3/7/2021	4/27/2021	51.00	50	24.98 ± 1.47	21

Table 3.1 (Continued).

ID	Mass (g)	SVL (mm)	Start date	End date	Days tracked	Data points	Lag-time (hr)	Relocation
M4	1070	376	8/8/2020	4/2/2021	237.22	331	17.25 ± 0.50	35
M6	2545	472	9/2/2020	4/16/2021	225.84	256	21.26 ± 0.56	35
M7	6010	591	10/24/2020	4/24/2021	181.79	175	25.07 ± 0.79	29
M10	2985	505	11/14/2020	4/16/2021	153.03	150	24.65 ± 0.67	25
M11	1346	398	11/18/2020	5/6/2021	168.98	168	24.28 ± 0.45	39
M12	2870	480	11/27/2020	4/21/2021	145.02	144	24.34 ± 0.55	19
M13	2490	483	12/29/2020	4/21/2021	113.18	111	24.69 ± 0.72	33
M14	1720	426	2/26/2021	4/20/2021	52.91	52	24.9 ± 1.41	27
M17	2645	481	3/25/2021	5/17/2021	52.66	52	24.78 ± 1.29	35

3.4 Results

3.4.1 Tracking summary

We tracked a total of 14 individuals (5 females, 9 males) for a mean of 149.5 days ± 73.4 days with a range of 51-273 days (Figure 3.6; 3.7). We located individuals on average at 21.9 hour intervals (SE ± 0.18 hours; range = 0.57-106.73 hours; Figure 3.6). We collected a total of 2,320 location fixes with 449 of those being relocations.

3.4.2 Home range

We found that 10 out of the 14 lizards met the range residency assumption required for AKDE home range estimators (Figure 3.1). The average home range crossing time was 9.76 ± 2.05 days with strong variations between individuals (1.06-27.78 days). Males had lower home range crossing times 8.93 ± 2.85 than females 10.2 ± 2.88. The average effective sample size (the temporal tracking duration divided by home range crossing events) for home range estimation was 31.24 ± 41.83, therefore justifying the use of pHREML fitting method and weighted AKDE (wAKDE) areas (Silva et al., 2021). Effective sample sizes ranged from 1.89 to 65.38, and two individuals had low effective sample sizes (<10: F16, M17; Table 3.5). Both individuals did not meet the range stability assumption of the AKDE's based on their variograms and were discarded from the analysis. Of the 10 individuals which met the range residency assumption, there was a mean 95% contour AKDE area of 28.99 ± 6.01 (the lowest CI was 3.02 and the highest CI was 56.31; Table 2).

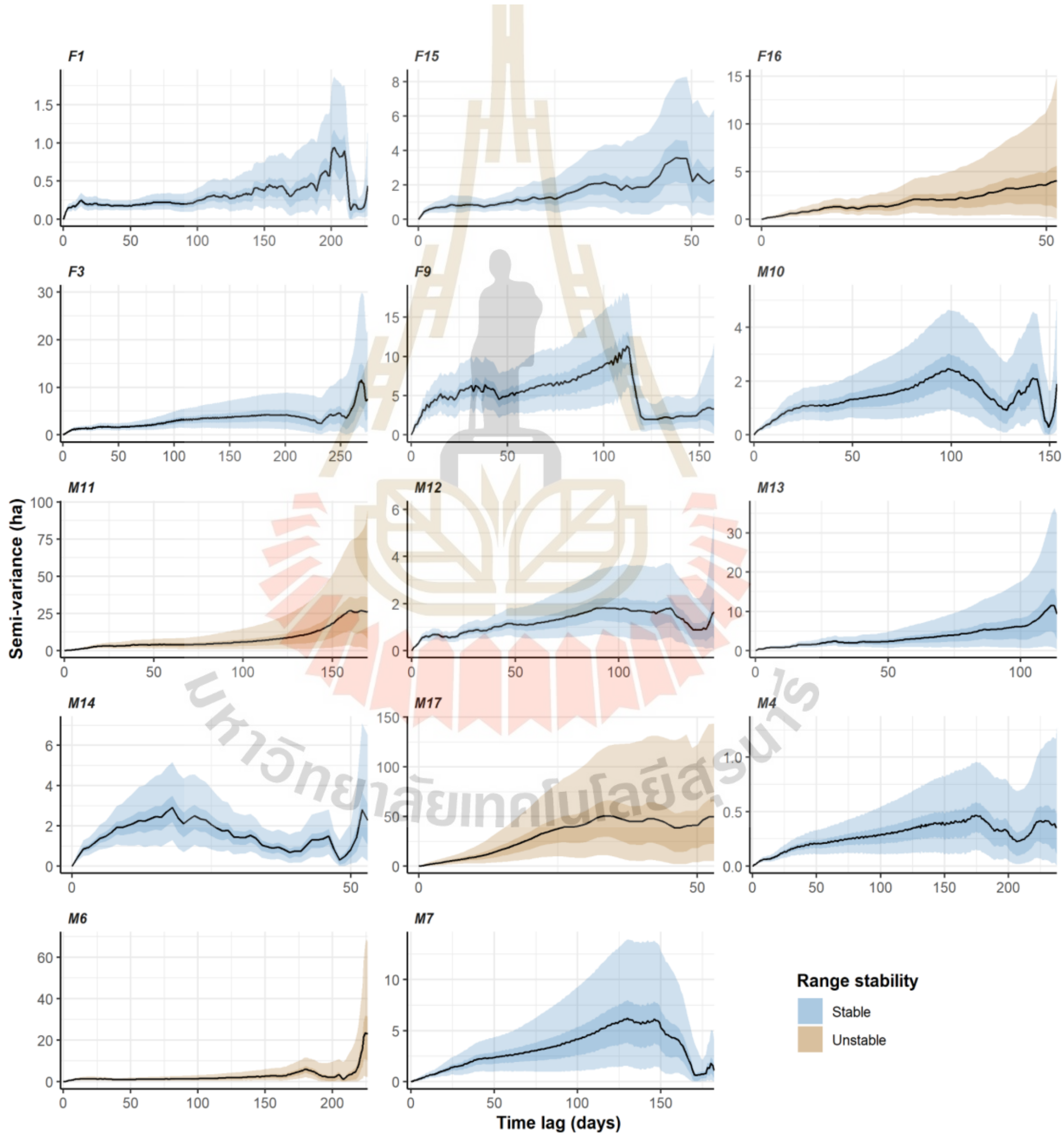

Figure 3.1 Variograms displaying semi-variance (ha) of home range area estimates for each individual's tracking duration. Shaded areas are displaying the 50% and 95% confidence intervals.

Table 3.2 Autocorrelated Kernel Density Estimate (AKDE) results per individual and the movement model used to produce the estimates. Lower and upper confidence intervals are the 95% contour. AKDE estimates are in hectares.

ID	AKDE lower CI	AKDE estimate	AKDE higher CI	Movement Model
F1	2.32	3.02	3.83	OU anisotropic
F3	24.72	46.61	75.34	OU anisotropic
F9	27.47	50.58	80.62	OU anisotropic
F15	12.94	22.53	34.73	OU anisotropic
M4	1.97	4.36	7.67	OU anisotropic
M7	17.16	56.31	118.29	OUF anisotropic
M10	9.50	20.27	35.04	OU anisotropic
M12	8.42	14.63	22.52	OU anisotropic
M13	19.51	39.6	66.69	OU anisotropic
M14	16.12	32.05	53.36	OU isotropic

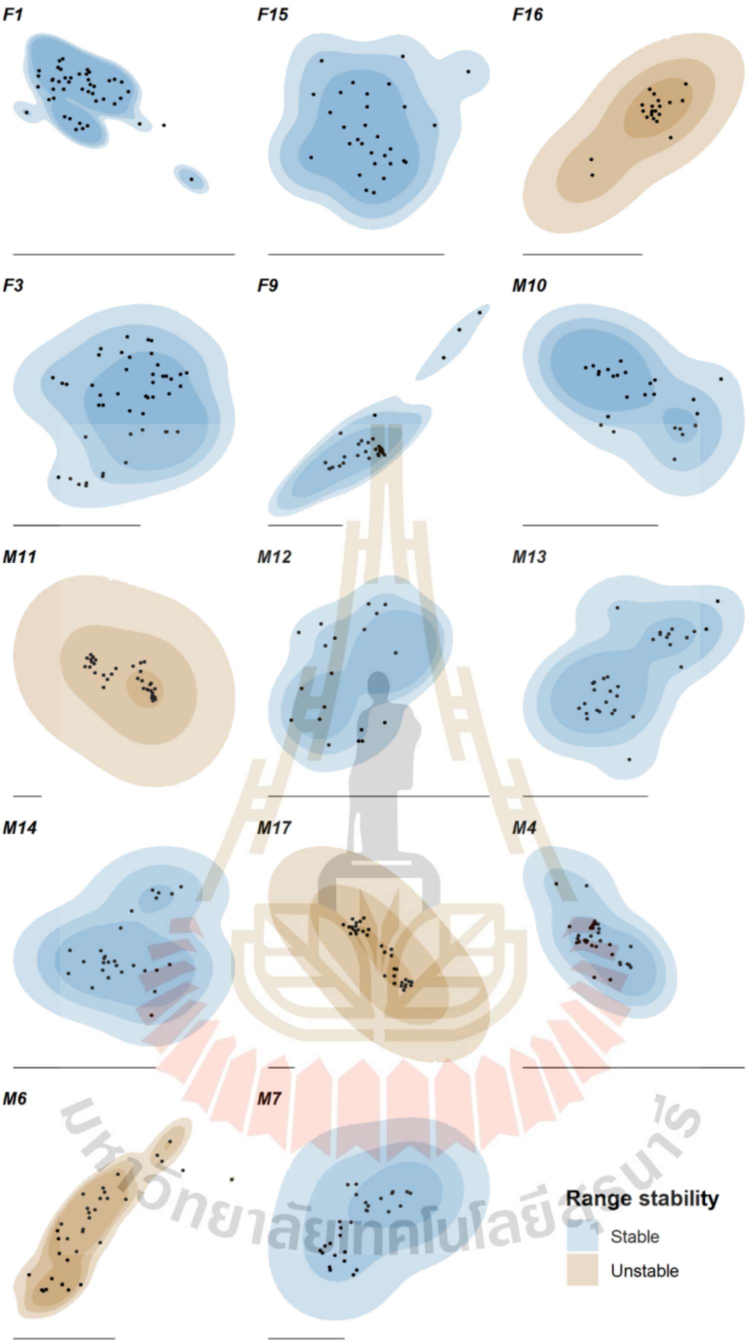

Figure 3.2 Visual representation of the 95% contour AKDE area estimates. Scale bars represent 500 m.

3.4.3 Movement pathways

We calculated the occurrence distributions for all tracked lizards at the 90%, 95% and 99% confidence intervals (Figure 3.3; Table 3.3). The mean 90% confidence area was 7.97 ± 2.70 ha with a range from 0.04 to 40.21 ha. The lizard with the smallest 90% area was M11 which was a male that lived within the buffer zones DEF and reclaimed plantation forest; the lizard with the largest 90% area was M17 which was only tracked for 52 days and resided within the reclaimed plantation forest. The mean 95% confidence area was 13.17 ± 3.84 ha, with a range from 0.49 to 52.84 ha; M4 and M17 were the individuals with the least and most areas, respectively. The mean 99% confidence area was 28.86 ± 9.13 ha, with a range from 1.126 to 129.65 ha. The lizard with the smallest area was M4 which was the second longest tracked lizard within the study. The lizard with the highest 99% confidence area was F9, which was a female from the DEF of the core area.

We calculated the motion variance for all tracked lizards (Table 3.3; Figure 3.4). Motion variance was generally low throughout all study animals (mean 3.17 ± 0.88 m; range 0.13 to 11.75 m; Figure 3.4). The lizards with the highest motion variance were the male, M17 (11.75 ± 1.05 m) and the female, F9 (7.04 ± 2.48 m). The lizards with the lowest mean motion variance were both males, M4 (0.13 ± 0.01 m) and M7 (0.44 ± 0.07).

Table 3.3 Dynamic Brownian Bridge Movement Model occurrence distribution outputs for Clouded Monitor Lizards (*Varanus nebulosus*) at the sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand. The summary includes: number of data points for each individual, the number of days tracked, lag time between consecutive location fixes, the number of relocations, mean motion variance with standard error and the 90%, 95% and 99% confidence areas (ha).

ID	Data points	Days tracked	Lag-time (hours)	Relocations	Motion Variance	90%	95%	99%
F1	253	226.78	21.6 ± 0.52	45	0.91 ± 0.15	1.60	3.37	9.38
F3	370	273.77	17.81 ± 0.51	46	1.45 ± 0.14	6.71	11.78	22.31
F9	155	157.00	24.47 ± 0.58	30	7.04 ± 2.48	12.21	35.36	129.65
F15	53	53.75	24.81 ± 1.36	30	5.68 ± 0.98	7.99	10.85	17.78
F16	50	51.00	24.98 ± 1.47	21	2.44 ± 0.22	3.65	5.65	10.96
M4	331	237.22	17.25 ± 0.5	35	0.13 ± 0.01	0.29	0.49	1.126
M6	256	225.84	21.26 ± 0.56	35	2.29 ± 0.34	7.65	13.62	27.75
M7	175	181.79	25.07 ± 0.79	29	0.44 ± 0.07	3.39	6.49	12.33
M10	150	153.03	24.65 ± 0.67	25	0.94 ± 0.17	3.01	5.29	10.56
M11	168	168.98	24.28 ± 0.45	39	1.25 ± 0.25	0.04	1.09	18.71
M12	144	145.02	24.34 ± 0.55	19	1.17 ± 0.19	3.59	7.23	14.69
M13	111	113.18	24.69 ± 0.72	33	3.17 ± 0.5	9.14	14.86	27.97
M14	52	52.91	24.9 ± 1.41	27	5.73 ± 0.57	12.06	15.49	22.81
M17	52	52.66	24.78 ± 1.29	35	11.75 ± 1.05	40.22	52.84	78.07

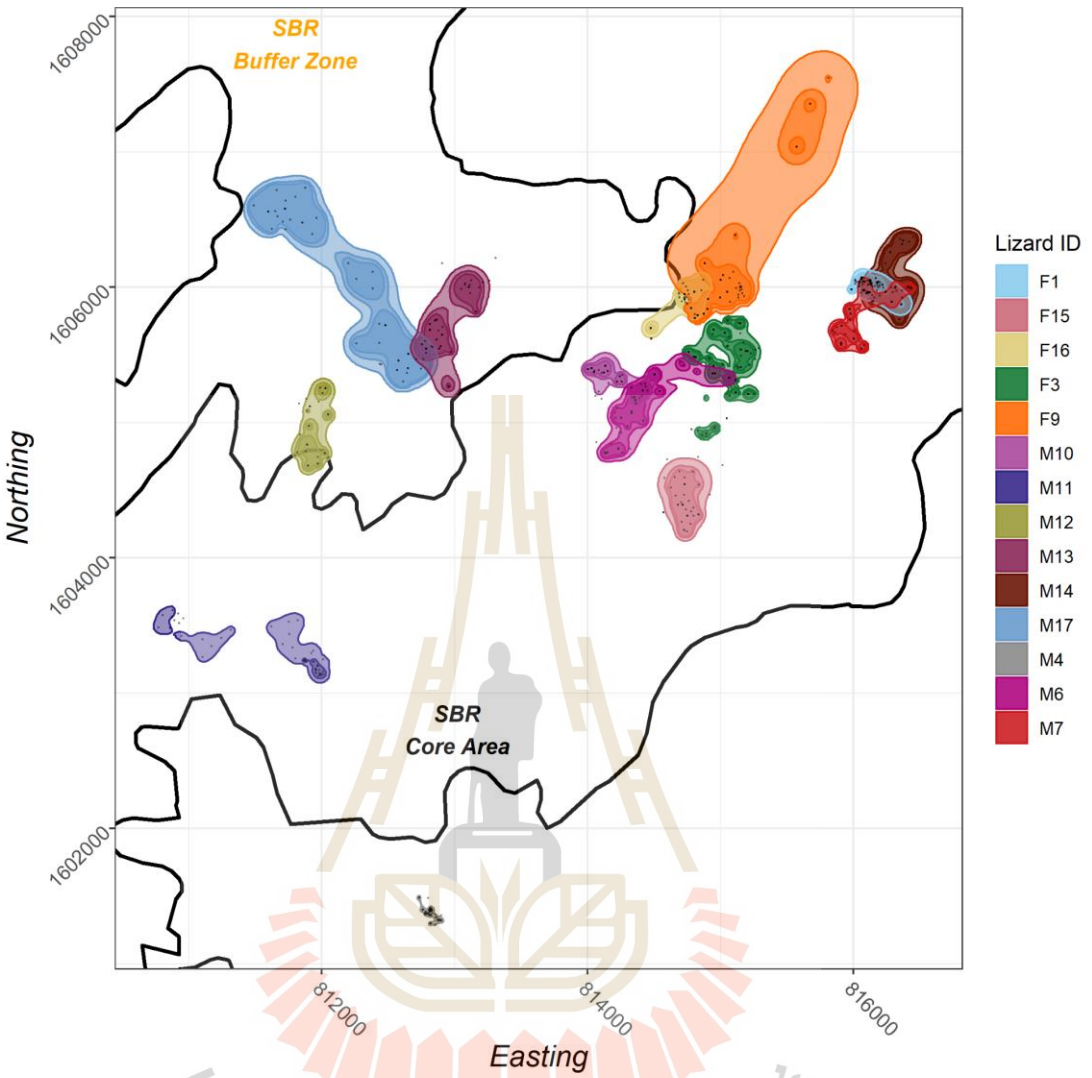

Figure 3.3 Dynamic Brownian Bridge Movement Model occurrence distributions (90%, 95% and 99% confidence areas) for radio tracked Clouded Monitor Lizards (*Varanus nebulosus*) in the Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand. Dark colored dots represent location fixes of individuals.

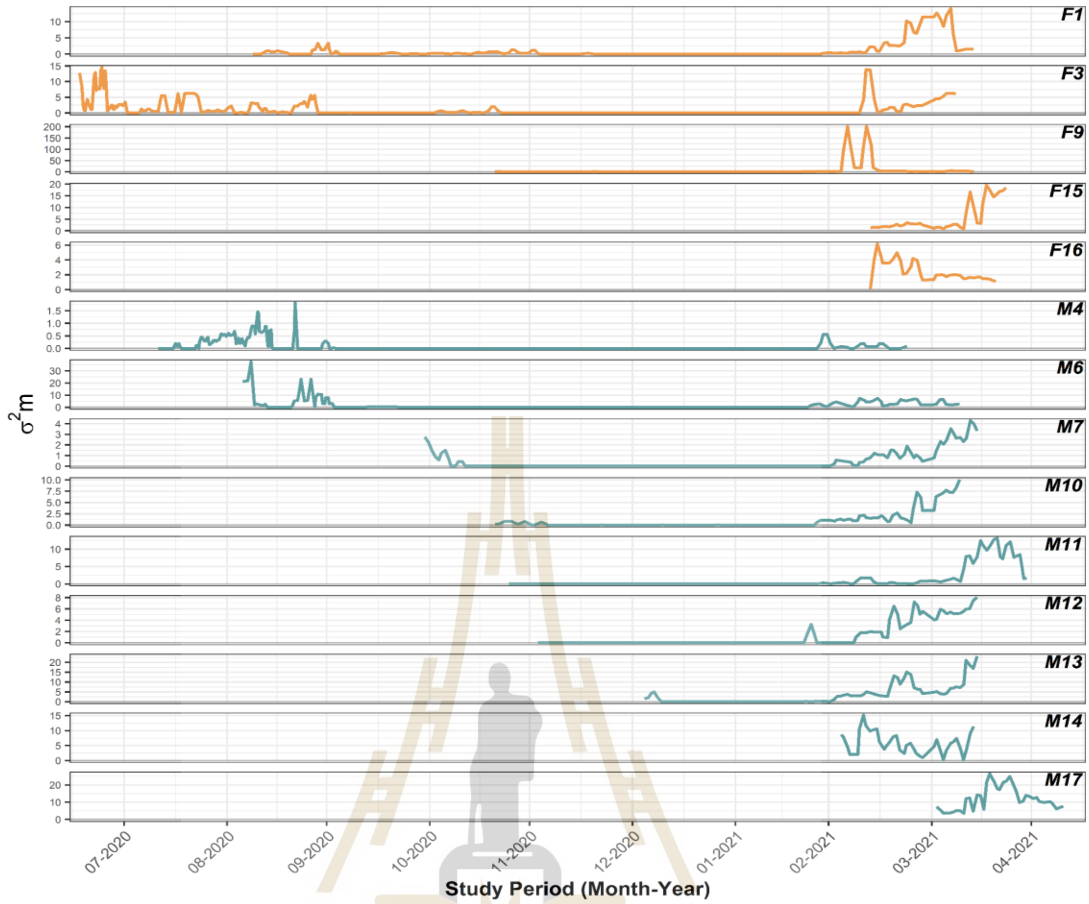

Figure 3.4 Motion variance for radio-tracked Clouded Monitor Lizards (*Varanus nebulosus*) in the Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand. Motion variance is plotted for each individual, orange plots represent female lizards while blue plots represent males.

3.4.4 Habitat selection

For habitat selection we only included lizards that were tracked within the DEF of the core area (F3, F9, F16, M6 and M10), due to the large spatial scale between all tracked lizards. The population models showed a clear association of monitor lizards to *Shorea henryana* trees (95% confidence interval ~.0000125 to .00005; Figure 3.5). Although, we failed to detect any other notable associations or avoidances with this analysis. The models assessing distances to streams, roads and the DDF, all resulted in unambiguous credible intervals that were equally fitted around zero.

When analyzing habitat selection at the individual level there was a positive correlation to *Shorea henryana* trees with lizards: F16, M6 and M10; although there was an avoidance to the same habitat feature recorded in F3 and F9 (Figure 3.8). There were no other clear distinctions made between the other habitat features. Of the eight movement models tested, there were three top performing models which best illustrated habitat selection (Figure 3.8); model four (associated with *Shorea henryana* trees), model six (distance to streambeds, trees and roads) and model seven (distance to streambeds, dry dipterocarp forest and trees). Of these three models, number seven was the top performing model for 3 individuals (M10, M6, F9). Model four, which was solely used to model association to *Shorea henryana* trees, was the top model for F3. Model six, which modeled the distance to streambeds, trees and roads, was the top performing model for F16.

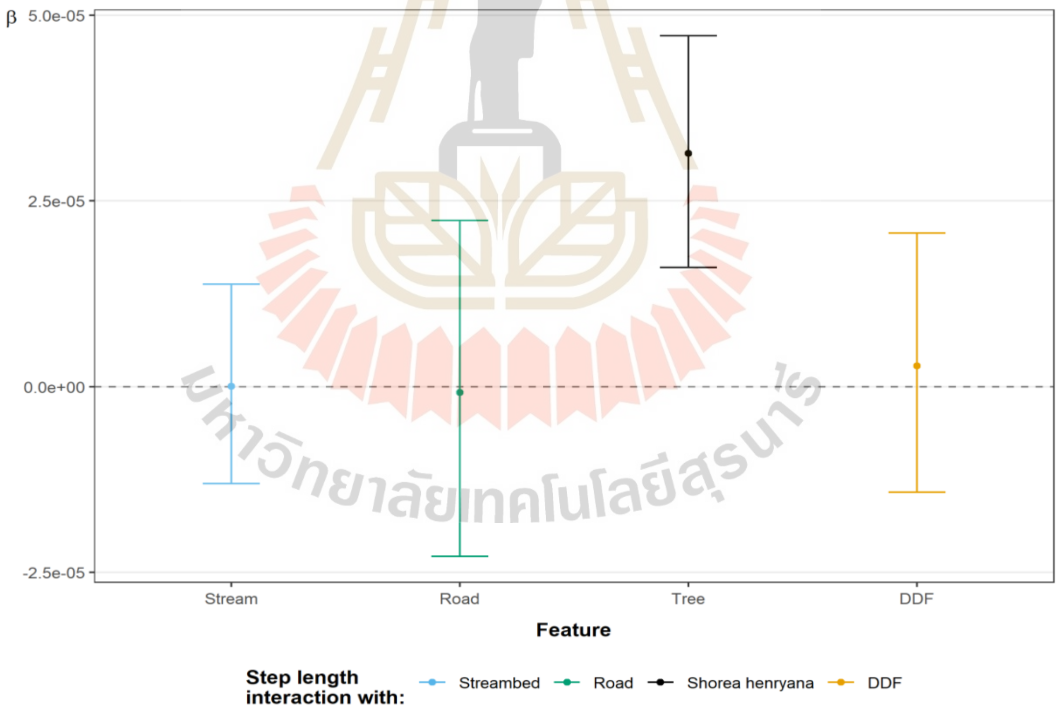

Figure 3.5 Population level habitat selection for lizards that were tracked within the dry evergreen forest of the core area at the Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand. Selection is based on distance to habitat features with positive estimates relating to association. Error bars represent the 95% confidence intervals.

3.5 Discussion

3.5.1 Home range

Herein we evaluated the home range size of an understudied species of monitor lizard (*Varanus nebulosus*) through a newly developed analysis (AKDE). This is the first study on monitor lizards to account for autocorrelation and empirically test for home range residency (Fleming and Calabrese, 2017). When analyzing variograms we found that 10 of the 14 lizards showed range residency. Two of the four lizards which didn't meet the range residency requirement were tracked for a short period of time (F16 tracked for 51 days; M17 tracked for 52.66 days). The other two individuals were tracked for longer durations although a large part of this time was spent brumating: M6 was tracked for 225.84 days and brumated for 111 days; M11 was tracked for 168.98 days and brumated for 96 days. Therefore, we believe if we had continued tracking these individuals for a longer duration, we would eventually reach range residency.

The top fit models were selected based on the Akaike Information Criteria (AIC) and adjusted for small sample size (AICc) and model weights (Fleming et al., 2015; Fleming and Calabrese, 2017; Silva et al., 2021). We tested four different movement models: independent identically distributed (IID) model which is similar to kernel density estimation (KDE) and doesn't account for autocorrelation in the data (Worton, 1989), a Brownian motion model with no home range (essentially a movement model), Ornstein-Uhlenbeck (OU) model which estimates home range size and crossing times and last the Ornstein-Uhlenbeck motion with foraging (OUF) model which goes one step further from the OU model by also accounting for velocity and the mean distance traveled (Calabrese et al., 2021; Fleming et al., 2014, 2015; Fleming and Calabrese, 2017). Home range estimates were then calculated using the best fit movement model. Of the 10 lizards which met the range residency assumption of AKDE's nine of them fell into the OU movement model; while M7 was able to fit the OUF movement model (Table 3.2). In all cases we are able to calculate the home range size but for M7 the data is sufficient enough to look at the velocity and distance between consecutive locations. Also, of the 10 range resident lizards, nine of them had anisotropic home ranges, meaning their home range is in the shape of an ellipse; while M14 had an isotropic home range, in a circular shape.

3.5.2 Space use and habitat selection

We evaluated the movement patterns and motion variance of radio tracked Clouded Monitor Lizards using the dynamic Brownian Bridge Movement Models. Based on the estimated 95% confidence areas, the average area used was 13.17 ± 13.84 ha for all tracked lizards. There were strong variations in movements and home range sizes (estimated from AKDE's) for each individual lizard, which is why the standard error is so high. Four of the study animals had extremely low and exceptionally high 95% confidence areas: both M4 and M11, had 95% confidence areas equal to 0.49 and 1.09 ha, respectively; while F9 and M17, had 95% confidence areas equal to 35.36 and 52.84 ha, respectively (Table 3.3). All of our tracked lizards entered a period of brumation beginning in November 2020 which lasted until March 2021, we will discuss this in depth in chapter 3. The mean motion variance was 3.17 ± 3.16 m; range from 0.13 to 11.75 m (Table 3.3), and we recorded the highest frequency of variations in mean-motion variance after the emergence from the long inactive period. The individual F9, in particular, moved over 1.5 km within two days of emerging from brumation and we documented similar long-distance movements in individuals F3, M6, M11 and M13. Although our tracking duration is limited we hypothesize that Clouded Monitor Lizard's peak activity is from March to May; this time of the year is classified as the hot and dry season (Tantipanatip et al., 2016). Monitor lizard activity slows down with the beginning of the heavy rainy season around mid-July; we documented many of our study animals remaining stationary for up to two weeks during the monsoon season (Figure 3.4).

Throughout our study we observed a very clear relationship between *V. nebulosus* and the *Shorea henryana* tree species. The *Shorea henryana* is a canopy giant and one of the dominant species within the DEF (Bunyavejchewin, 1986, 1999). While tracking monitor lizards, we never documented a lizard sheltering on or below the ground and in nearly every instance, lizards moved in what appeared to be planned routes to *Shorea henryana* trees. We documented multiple instances of reuse with *S. henryana* trees and in many instances multiple individuals utilizing the same trees, both together and separately. We used integrated step selection functions (ISSF) to investigate the relationship between *V. nebulosus* and *S. henryana*. Despite our relatively small sample size we were able to identify three individual lizards which had a positive association with this species of tree using individual level ISSF although the other two individuals had a distinct avoidance. At the population level distance to *S. henryana* was the only habitat feature which had a clear association to movement patterns. We hypothesized that lizards selected this species of tree for two main reasons: protection from potential predators, such as king cobras (Jones et al., 2020), and adequate thermoregulation sites, as it is one of the tallest trees in the forest, typically breaking through the dense canopy (Bunyavejchewin, 1999). It has been argued that thermoregulation is not an important factor for ectotherms living in the tropics (Shine and Madsen, 1996). However monitor lizards are a highly energetic species which must forage and hunt for their prey and therefore require a high amount of daily energy (Bartholomew and Tucker, 1964; Bennett, 1972; Green et al., 1991). In fact, *Varanus panoptes* from Australia which fills a similar niche as *V. nebulosus* has been studied and found to be extremely active especially during the dry season (Christian and Weavers, 1994).

3.6 Conclusion

Our study provides the first known comprehensive assessment on the ecology of Clouded Monitor Lizards (*Varanus nebulosus*) in the wild investigating: the home range size (while considering range residency and autocorrelation of the data), occurrence distributions, motion variance and habitat features driving step selection. Despite the limited temporal scale of our study, we identified trends in habitat selection and movement as well as home range size estimates (for 10 out of 14 lizards).

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3.9 Supplementary Materials

Supplementary material includes:

Figure 3.6 Density plot illustrating time-lags between tracks for all telemetered individuals.

Table 3.4 Top movement model fits and effective sample sizes (DOF area).

Figure 3.7 Total tracking durations from July 2020 to May 2021. Female lizards are colored red and males are colored blue.

Figure 3.8 Individual level habitat selection of Clouded Monitor Lizards (*Varanus nebulosus*) from dry evergreen forest within the core area of the Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand.

Figure 3.9 Trap setup used to capture lizards that were found sheltering on trees.

Figure 3.10 Radio transmitter attachment method on Clouded Monitor Lizards (*Varanus nebulosus*).

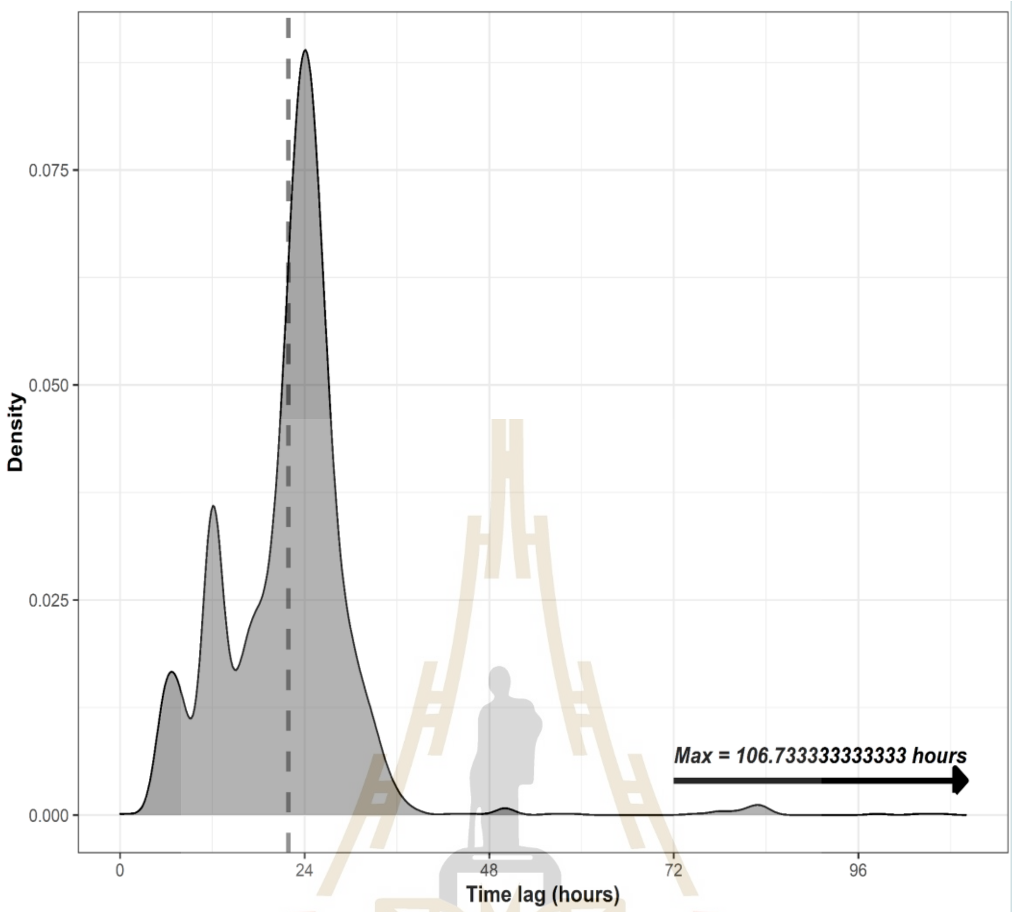

Figure 3.6 Density plot illustrating time-lags between tracks for all telemetered individuals.

Table 3.4 Top movement model fits and effective sample sizes (DOF area).

ID	dRMSPE (m)	DOF area	Movement model	t (crossing time est.)
F1	7.36	61.25	F.OU anisotropic	3.47
F3	61.57	12.85	F.OU anisotropic	18.51
F9	57.62	13.74	F.OU anisotropic	9.96
F15	9.71	16.26	F.OU anisotropic	2.73
F16	56.84	3.67	F.OU anisotropic	9.97
M4	26.15	8.81	M.OU anisotropic	20.39
M6	24.37	26.45	M.OU anisotropic	6.86
M7	80.65	4.59	M.OUF anisotropic	1.06
M10	39.16	9.51	M.OU anisotropic	12.08
M11	389.64	1.71	M.OU anisotropic	4.25

Table 3.4 (Continued).

ID	dRMSPE (m)	DOF area	Movement model	t (crossing time est.)
M12	23.17	16.38	M.OU anisotropic	7.46
M13	43.69	10.65	M.OU anisotropic	8.07
M14	24.67	11.20	M.OU isotropic	4.05
M17	281.40	2.19	M.OU anisotropic	27.76

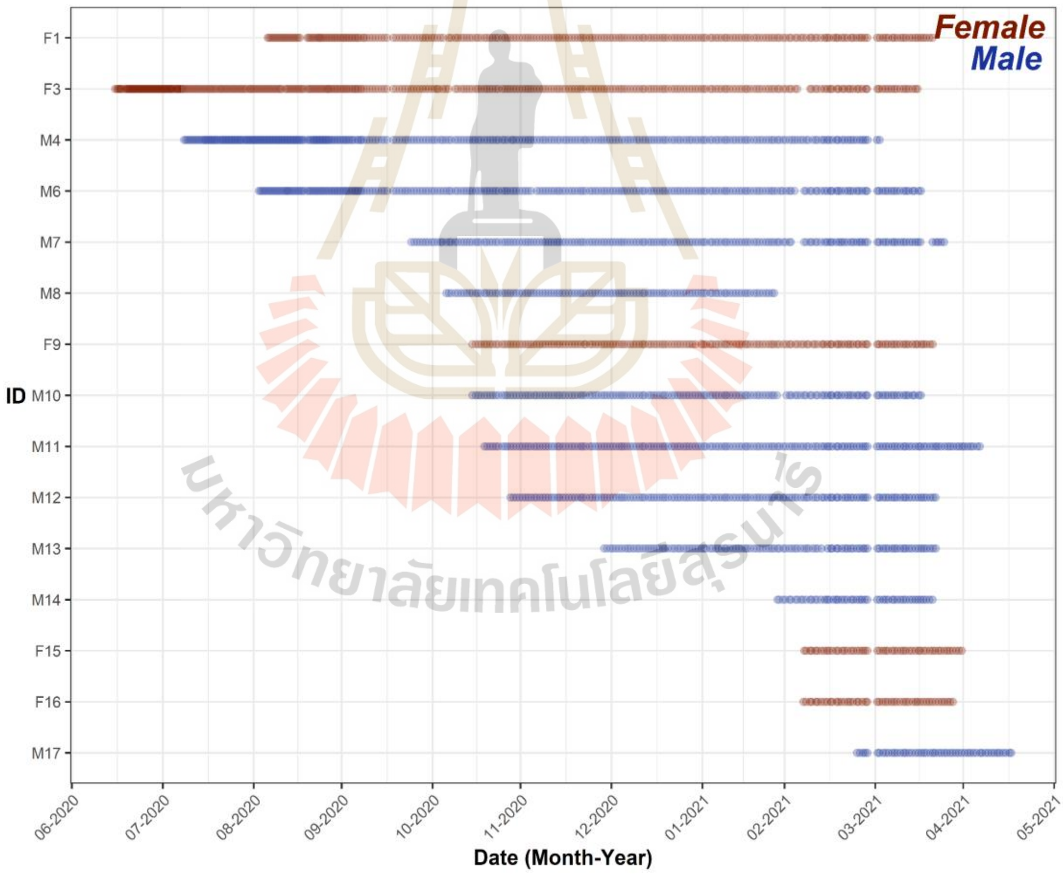

Figure 3.7 Total tracking durations from July 2020 to May 2021. Female lizards are colored red and males are colored blue.

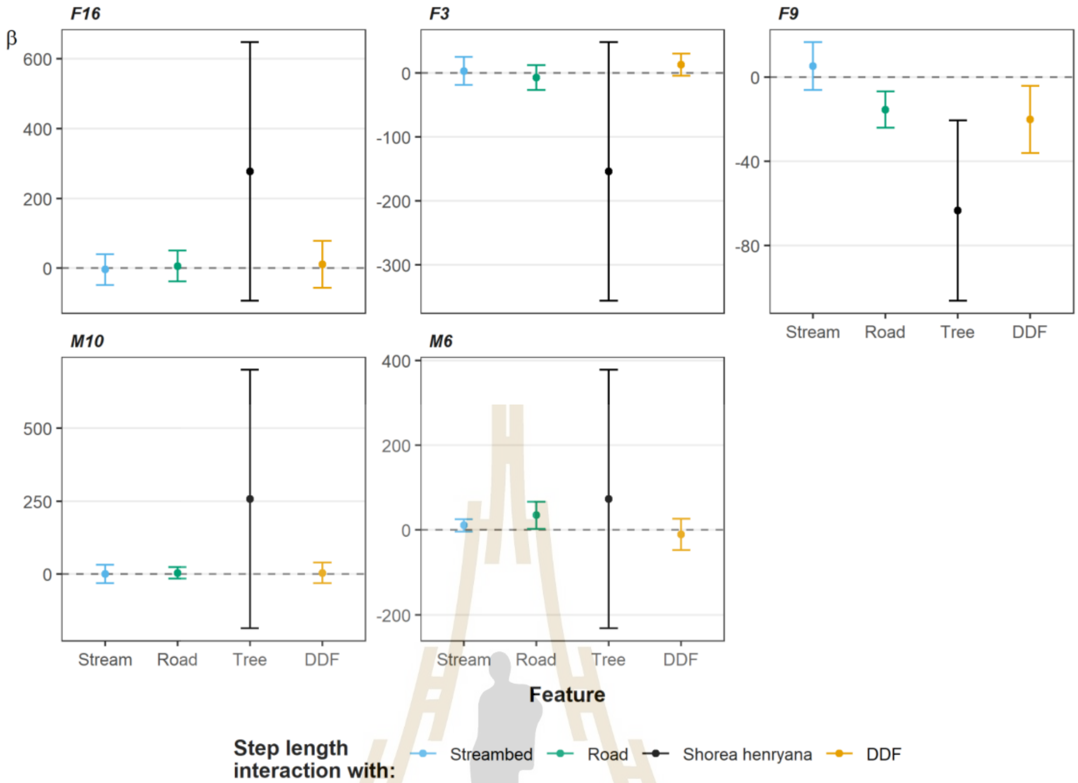

Figure 3.8 Individual level habitat selection of Clouded Monitor Lizards (*Varanus nebulosus*) from dry evergreen forest within the core area of the Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand.

Figure 3.9 Trap setup used to capture lizards that were found sheltering on trees.

Figure 3.10 Radio transmitter attachment method on Clouded Monitor Lizards (*Varanus nebulosus*).

CHAPTER IV

WINTER IS COMING: BRUMATION OF THE CLOUDED MONITOR LIZARD *VARANUS NEBULOSUS* IN NORTH-EASTERN THAILAND

4.1 Abstract

The Clouded Monitor Lizard (*Varanus nebulosus*) is a semi-arboreal lizard widely distributed throughout much of South and Southeast Asia. Despite its wide distribution, there is almost nothing known about the ecology of this species. During an 11-month radio-telemetry study, in a reserve with a tropical savanna climate (Köppen Aw), we made the first records of brumation in this monitor lizard. This contrasts with earlier reports of the same species in a tropical monsoon climate (Köppen Am) where no brumation was recorded. We successfully tracked 10 individuals throughout their inactive period and found that seven of the monitors selected tree hollows within the endangered *Shorea henryana* tree. All tree hollows selected faced between the east and south cardinal points (90°-180°). The average brumation period was 100 days (range = 86-113 days, standard deviation = 10.7), beginning in November at a time of falling temperatures and humidity and ending in early March when these variables had been restored. Eight of the 10 monitors basked partially or completely out of their shelter sites on multiple occasions. Of those eight monitors, two individuals moved between shelter sites during brumation after an extended period in one location. Our observations provide insight into the relationship between *V. nebulosus* and the tree *S. henryana*, in the dry evergreen forests of north-eastern Thailand. Future research should investigate how this tree will be affected by climate change in the coming decades and what that could mean for the future persistence of the Clouded Monitors that appear to rely on it.

4.2 Introduction

Brumation is a form of hibernation in ectothermic animals, defined as a period of inactivity or dormancy, typically associated with changes in environmental temperatures (Mayhew, 1965). Environmental temperature plays a critical role in ectothermic species' ability to: capture prey, avoid predation and regulate their metabolism (Mcconnachie and Alexander, 2004; Naulleau, 1983; Stevenson et al., 1985). Brumation and hibernation are well documented in reptiles, with many temperate species spending two-thirds of their lives inactive (Etheridge et al., 1983). Despite these cycles being such a large part of an animal's life history, there is little understanding of the drivers leading to their onset and emergence, especially for species in the tropics.

The Clouded Monitor Lizard *Varanus nebulosus* (Gray 1831) is a semi-arboreal well camouflaged (low detection rate) species with a wide distribution from Myanmar to Vietnam and southern China to Indonesia (Koch et al., 2013). They are medium-sized varanids reaching a 160 cm maximum length and 8 kg maximum weight (Auffenberg, 1994). Their conservation status in the wild has yet to be assessed, as there is uncertainty among researchers pertaining to species status and the IUCN listing remains under Bengal Monitor Lizard (*Varanus bengalensis*). Numerous studies suggest two separate but closely related species (sister species) apparent from; distinguishable oblique ventral scale counts (*bengalensis* 88-110, *nebulosus* 70-90; Auffenberg, 1994), distinct hemipenal differences (Ziegler and Böhme, 1997), differences in scale morphology and micro-structures (Bucklitsch et al., 2016) and mitochondrial DNA (Ast, 2001). It is suggested that since the number of mature individuals is steadily declining, they will require a "Vulnerable" listing once properly evaluated (Cota et al., 2021). Despite their large size and broad geographical distribution, the general ecology of the Clouded Monitor Lizard remains little known (but see Traeholt, 1997; Duengkae and Chuaynkern, 2009 for records on diet and basking behavior).

Radio telemetry is a commonly accepted method to record—seasonal and daily activity patterns, home range sizes, movement trajectories, macrohabitat use, shelter site preferences and ultimately threats to survival (Cagnacci et al., 2010; Malhotra et al., 2021; Ujvari and Korsos, 2000). The objective of this study was to observe whether the Clouded Monitor Lizard in northeastern Thailand has an annual period of brumation and if so then address the following questions: a) When does brumation occur and what is it's duration? b) Do the monitors select specific species of trees for brumation? c) What specific microhabitat features do they select? d) Do the monitors have a dormant or active brumation (dormant equating to no movement at all; active consisting of thermoregulating and possibly moving between sites)? and, e) Does average daily temperature and humidity contribute to either the onset of, or emergence from, brumation?

4.3 Methods

4.3.1 Study site

From July of 2020, we undertook an 11-month radio telemetry study of the Clouded Monitor Lizard at the Sakaerat Environmental Research Station in north-eastern Thailand. The research station is a part of the Sakaerat Biosphere Reserve (SBR; 14.22–14.73°N, 101.62–102.07°E), encompassing an area of approximately 360 km^2. The biosphere reserve has three main designations: core, buffer and transitional. The core area is predominantly dry evergreen forest (DEF) with large patches of dry dipterocarp forest (DDF) and has active ranger enforcement; the buffer zone consists mainly of both DEF and plantation forest; the transitional zone lacks official protection and is an agricultural matrix with expanding human settlements (Trisurat, 2010). The DEF at SBR, has a mean canopy height of 35-40 m with two subtypes dependent upon the dominant tree species: *Hopea ferrea* dominates the first type and occurs on level ground creating a closed canopy; *Shorea henryanna,* dominates the second type and mainly occurs on slopes, creating a patchy canopy (Bunyavejchewin, 1986, 1999). Both *Hopea ferrea* and *Shorea henryana* are classified as endangered species and are at risk from habitat loss and logging (Ly et al., 2017a andb). In contrast, the DDF at SBR, has a mean canopy height of 11-14 m and a more open canopy. Several species, *Shorea roxburghii*, *Shorea obtusa* and *Dipterocarpus intricatus* are dominant trees in DDF (Lamotte et al., 1998). Based on the Köppen climate classification, SBR is a tropical savanna (Aw) with an altitude range between 280-762 m a.s.l. (Köppen, 1931, Rubel and Kottek, 2010). The SBR has three distinct seasons: dry (November-February), hot (March-May) and wet (May-October; Tantipanatip et al., 2016).

4.3.2 Capture/Tracking techniques

Monitors were located with road and visual surveys, road-cruising on forest roads with a motorcycle, and visual surveys by scanning large trees with binoculars (Figure 4.1). Once found, we captured monitors either with drop traps—placed along the base of the tree with a sheet metal perimeter—or a noose and then equipped individuals with a backpack style harness, fitted around their pelvic girdle, which contained a radio transmitter and GPS logger. We released all individuals at the exact capture site, and we began radio tracking them once daily between 05:00 h and 20:00 h. During this study we recorded a considerable brumation period for all study animals—8 individuals—beginning on 5th November 2020 and lasting until 6th March 2021 (date of last emergence). We defined the onset of brumation as the first date from which a lizard remained in a shelter site for at least 14 days, during a period where we deemed the weather adequate for movement. Although we did record large spans (up to 13 days) of inactivity within our study animals, prior to brumation, these were all during the monsoon season, through periods of heavy rainfall, high cloud cover and lower temperatures.

We also found three new individuals during the brumation period: M11 on 18th November, M12 on 27th November and M13 on 27th December 2020. The first two monitors were basking outside of their brumation sites, so we placed traps along the shelter-tree base. The third individual was found on a forest road, perhaps moving from one shelter site to the next. We documented two of our radio tracked monitors moving between brumation sites around the same timeframe: F01 on 19th December and F09 on 21st December 2020. The traps set for M11 and M12, were checked daily during radio tracking protocols and observations of basking were documented, when possible, on these two individuals. Although we do not know what date these two monitors entered brumation we decided to include them in our dataset because we could determine the exit dates and found each within the range of our other radio tracked monitors entering brumation. However, because M13 was captured late into the brumation cycle we have chosen not to include it in our summary dataset.

4.3.3 Data collection

During radio tracking we recorded: brumation site location (UTM), the onset date, the frequency of basking observations (recorded during each daily fix if the lizard was visible when we were using telemetry to find the individual) and the date of emergence from brumation of each monitor (Figure 4.2). We assessed each monitor's shelter site location by recording: habitat type, species of the tree selected, the diameter at breast height (DBH) using a tape measure, the height of the shelter site and height of the tallest branch (both measured using a Nikon Forestry Pro I rangefinder) as well as the cardinal direction the shelter site was facing measured using the compass feature on a handheld Garmin 64s GPS.

There are five weather stations spread throughout the SBR; each station records the atmospheric temperature and humidity every hour. We collated station weather data and averaged all of the stations together to plot the average temperature and humidity for our study period. We then overlaid the monitor's dormancy duration, to see if there were any relationships between these two climatic factors and the onset of, or emergence from, brumation (Figure 4.3).

We used R studio version 4.0.3 (R Core Development Team, 2020) for data manipulation with reshape2 package version 1.4.4 (Wickham, 2007) data visualizations including ggplot2 version 3.3.5 (Wickham, 2016). To produce the study site map, we manipulated data with dplyr version 1.0.7 (Wickham, 2021) and cowplot version 1.0.0 (Wilke, 2019) and to construct the map we used rgdal version 1.5.27 (Bivand et al., 2021) and scico version 1.2.0 (Pedersen and Crameri 2020). To produce temperature and humidity graphics we employed ggpubr version 0.4.0 (Kassambara, 2020) for final visuals, lubridate version 1.8.0 (Grolemund and Wickham 2011) to control data formats, tidyverse version 1.3.0 (Wickham et al. 2019) for functionality, and viridis version 0.6.2 for colorblind friendly palettes. We have additionally made all data and R scripts available on Open Science Framework (https://osf.io/xd243/).

Figure 4.1 Clouded Monitor F03 basking completely exposed above its tree hollow on a *Hopea ferrea* tree.

4.4 Results

4.4.1 Brumation sites

For the 10 monitors we followed through brumation, we recorded 14 different brumation sites. All study animals spent the duration of brumation within tree hollows, despite differing habitat types. Of the 14 shelter sites documented, 64% were on *Shorea henryana* trees. We were unable to identify two tree species (used by M04 and M07), because both trees were already dead with no identifiable features left. The average shelter site height was 21.6m above the ground (range = 2.7-39.6, standard deviation = 10.8; Table 4.1). The orientations of the tree hollows were all within the east and south cardinal points (90°-180°) and occurred within gaps or clearings of the canopy, allowing open access to direct sunlight (Table 4.1). All shelter trees were large (DBH mean = 252.2 cm, range = 102.5-326.7, standard deviation = 59.6; Table 4.1). We were unable to take measurements on the depth, width and internal features of the tree hollows due to the heights of shelter sites.

Table 4.1 Characteristics of the brumation sites used by *Varanus nebulosus*. Shelter height is the height of the tree hollow utilized by each monitor. Tree height is the height of the tallest branch. DBH is the diameter breast height (girth) of the bole of each tree. Shelter direction is the cardinal direction of the tree hollow selected by each monitor.

Monitor ID	Forest habitat	Tree species	Shelter height (m)	Tree height (m)	DBH (cm)	Shelter direction
F01	MDF	*Shorea henryana*	19.1	27.3	254.4	E
F01*	MDF	*Lagerstroemia calyculata*	21.4	29.8	287.3	E
F03	DEF	*Hopea ferrea*	14.4	17.5	198.6	ESE
M04	HS	Unknown	2.7	2.7	102.5	E
M06	DEF	*Shorea henryana*	26.3	35.7	274.2	ESE
M07	DDF	Unknown	11.4	11.4	190.6	E
M08	DDF	*Pterocarpus macrocarpus*	11.8	21.5	263.2	E
F09	DEF	*Shorea henryana*	19.0	26.7	298.8	SE
F09*	DEF	*Shorea henryana*	37.9	41.2	301.3	ESE
F09*	DEF	*Shorea henryana*	18.3	28.8	243.9	E
F09*	DEF	*Shorea henryana*	21.2	33.2	260.1	ESE
M10	DEF	*Shorea henryana*	38.3	43.9	326.7	SE
M11	DEF	*Shorea henryana*	39.6	45.6	312.5	SE
M12	PLT	*Shorea henryana*	20.6	31.1	216.0	SSE

Habitat Abbreviations: DEF=Dry Evergreen Forest, DDF= Dry Dipterocarp Forest, MDF= Mixed Deciduous Forest, PLT= Plantation Forest and HS= Human Settlement. Shelter Direction Abbreviations: E = East, ESE = East by Southeast, SE = Southeast, SSE = South by Southeast. Asterisks (*) indicate when individual monitors moved from one shelter site to another during the brumation period.

4.4.2 Brumation observations

There was a distinct relationship between the onset of brumation with lower average temperatures and humidity. We observed our first study animals enter brumation shortly after the average daily temperature dropped below 22°C (Figure 4.3). Brumation peaked during the lowest average temperature and humidity for the year. Individuals brumated on average for 100 days (range = 86-113 days, standard deviation = 10.7; Figure 4.2). All Clouded Monitors entered brumation within 29 days of each other and emerged within a 12-day span (Figure 4.2). We observed that all but two individuals (M07 and M10) basked either partially or completely out of their tree hollows (Figure 4.1; 4.2).

Both monitors F01 and F09 moved to different shelter locations during the course of brumation. Monitor F01 moved once on 19th December 2020, from a *Shorea henryana* tree to a *Lagerstroemia calyculata.* Monitor F09, moved three times through the brumation cycle, moving to a *Shorea henryana* each time, on: 21st December 2020, 29th January 2021 and 12th February 2021 (Table 4.1; Figure 4.2).

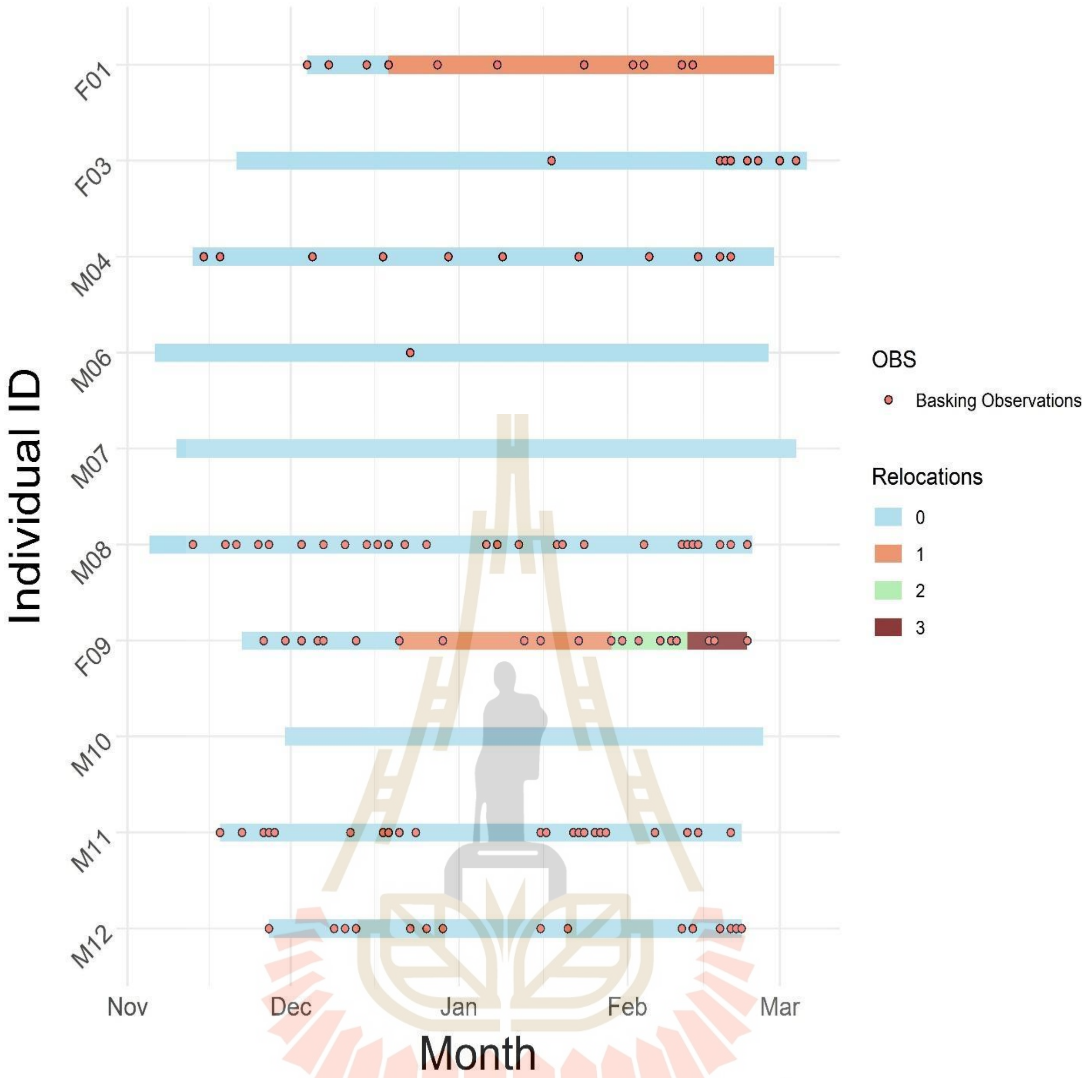

Figure 4.2 Brumation observations of Clouded Monitor Lizards (*Varanus nebulosus*). Most monitors entered brumation in November 2020 and all individuals had completely emerged by early March 2021. Relocations are annotated for monitors which moved to different shelter sites during brumation. Basking observations are listed for each visual observation we made during this period.

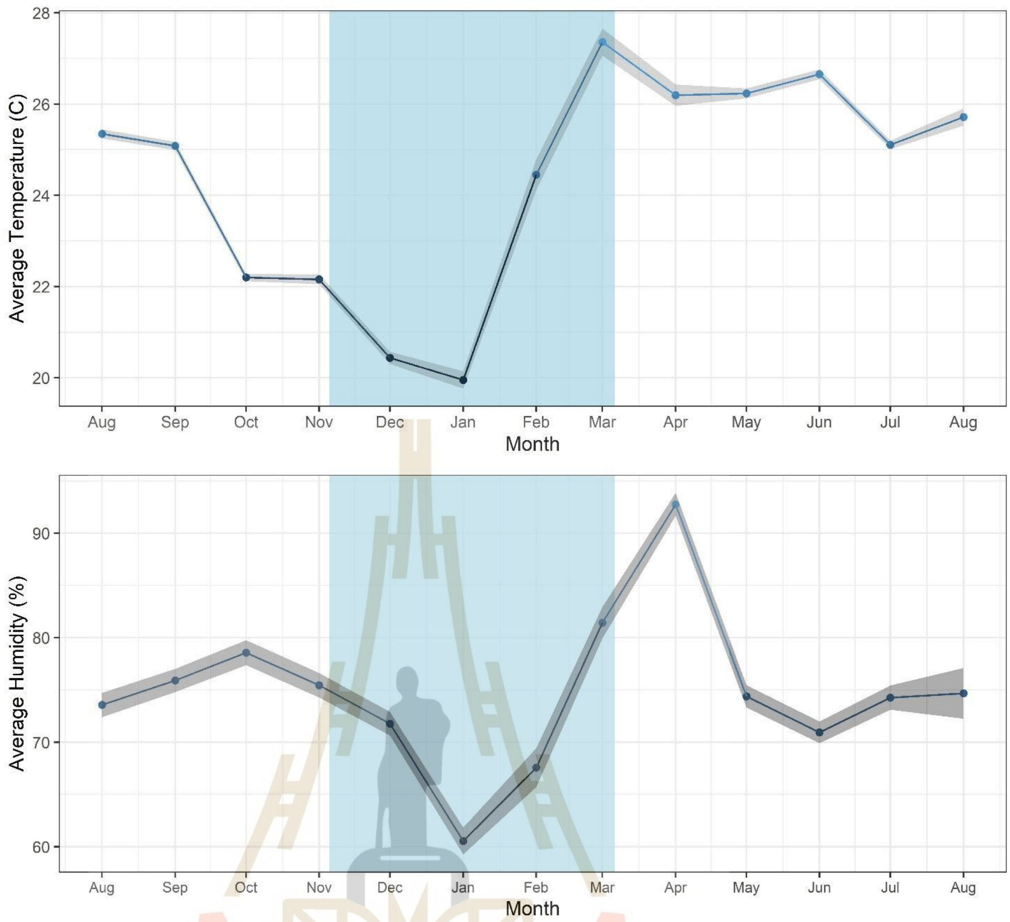

Figure 4.3 Climatic conditions at the Sakaerat Environmental Research Station from August 2020 to August 2021 – A. Mean daily temperature with upper and lower confidence intervals, B. mean daily relative humidity (with upper and lower confidence intervals). In both cases the shaded blue area is the total brumation period, 6th November 2020 to 6th March 2021.

4.5 Discussion

4.5.1 Brumation

Walter Auffenberg, in his seminal work on the Bengal monitor (*Varanus bengalensis*), recorded individuals from Trang province in Thailand (now considered *Varanus nebulosus*), that did not enter a period of inactivity and instead remained active throughout the year (Auffenberg, 1994). The climate of Trang province by the Köppen classification is tropical monsoon (Am), with distinct wet and dry seasons and an almost uniform temperature throughout the year (Rubel and Kottek, 2010). We have potentially demonstrated variation between *V. nebulosus* populations within the same geographic region. It is likely that *V. nebulosus* goes through a brumation period throughout the northern part of its distribution where there is a tropical savannah climate (Köppen Aw) with a distinct cool dry period and that it remains active throughout the year in the southern part where there is a tropical monsoon climate.

4.5.2 Shelter selection

We saw that throughout the brumation period most study animals selected tree hollows within *Shorea henryana* trees. Of the five monitors living within the DEF, four selected *Shorea henryana*. Also, two monitors living in the MDF and plantation forest also sought out this same species of tree within habitats where it is uncommon (Bunyavejchewin, 1999). Monitors within the DDF and HS each selected different species of trees, and this may be due to the forest structure: in the DEF the canopy is mostly closed, so *Shorea henryana* provides a good shelter site for obtaining adequate UV radiation for thermoregulation; the DDF and HS have an open canopy and therefore monitors inhabiting these areas may have a broad range of potential shelter sites. Within the SBR mature *Shorea henryana* individuals are rare and have high mortality rates as young trees (Bunyavejchewin, 1999). However, climate change in the tropical dry forests of northeastern Thailand, likely will lead to a shift to wetter tropical forests by the year 2100; in this scenario the density of *Shorea henryana* trees are likely to decrease at a faster rate than at present (Boonpragob and Santisirisomboon, 1996). Based on our results it is likely that *Shorea henryana* is a critical species for *V. nebulosus,* playing a key role in their brumation cycle and possibly their overall survival in DEF. Future research should investigate how *Shorea henryana* will be affected by climate change in the coming decades and what that could mean for the future persistence of *V. nebulosus* at this site.

4.5.3 Brumation behavior

Every tree hollow that tracked monitors selected, faced between the east and south cardinal points and all shelter sites were fully exposed, either above or within canopy gaps. This feature may be a necessity for survival during the cold season as we observed individuals on numerous occasions thermoregulating on warm mornings and afternoons. Clark et al. (2008) found that rattlesnakes selected overwintering hibernacula on south-facing slopes, which is likely due to southern slopes receiving more solar radiation than north-facing slopes (Hamilton and Nowak, 2009). This same principle is likely the basis for *V. nebulosus* selection of east and south facing tree hollows. East and south basking orientation has also been observed in agamid lizards in Saudi Arabia (Al-Johany, 1995) and in arboreal skinks in Brazil (Maia-Carneiro et al., 2018).

Two individuals moved between shelter sites during the brumation period. F01 moved from a *Shorea henryana* to a *Lagerstroemia calyculata* tree on 19th December 2020. F09 changed shelter sites three times on: 21st December 2020; 29th January 2021 and lastly 12th February 2021. On all three occasions, F09 moved to a different *Shorea henryana* tree and never moved more than 100 m. Cummings (2020) documented a single female desert tortoise which also moved between shelter sites during its brumation period, while all other individuals monitored remained stationary. These observations could have been linked to uncommonly warm days, or perhaps insufficient basking area on the original trees.

In most reptile species documented that brumate or hibernate, the males emerge before the females (Etheridge et al., 1986; Winck and Cechin, 2008). Although with *V. nebulosus*, the only two individuals to move between shelter sites were females and based on the emergence dates we saw no clear distinguishing patterns between male or female emergence. We were unable to collect any microhabitat data which could help deduce why these monitors moved during brumation because shelter sites were too high to safely reach without climbing gear (which we lacked). We assessed the average and daily high temperatures between 18th December and 27th December 2020 since we documented three different individuals (F01, F09 and M13) moving in this period. However, we were unable to come to any clear conclusion about what was driving this behavior, suggesting there are other unknown underlying factors.

4.5.4 Potential drivers of brumation in the tropics

We observed average daily temperature and humidity at our study site during our study period and were able to identify a marker for the onset of brumation— when the average daily temperature fell below 22°C combined with the average daily humidity dropping below 75%. However, when the temperature and humidity rose above average in late January, the monitors all remained dormant suggesting that there are potentially other factors at play. These could include daily photoperiod, prey abundance, rainfall, peak daily temperatures, or a combination of factors (Auffenberg, 1994; Ortiz et al., 2016).

It is imperative to understand the underlying drivers of animal behaviors as the effects of climate change are predicted to alter the structure of many forests around the globe (Boonpragob and Santisirisomboon, 1996). Understanding environmental drivers and microhabitat features utilized by different species is important for planning and implementing effective conservation management (Ljubisavljević et al., 2017). We observed a clear relationship between the tree *S. henryana* and *V. nebulosus* at the SBR; it is important to determine whether this relationship persists throughout northeastern Thailand. If so, what are the implications for populations of *V. nebulosus* in areas where *S. henryana* has been extirpated or severely decreased? It would also be worthwhile identifying the specific factors that lead ectothermic species to brumate when they are living in tropical climates with relatively little annual temperature variation (as in the current study). Despite the limited scope of our study, our preliminary data demonstrate behavior that has not been widely documented and our findings can be used to further bolster understanding of the life histories of ectothermic species in tropical environments.

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CHAPTER V
PRELIMINARY GPS STUDY AT THE SAKAERAT ENVIRONMENTAL RESEARCH STATION FOR GPS CALIBRATION

5.1 Introduction

The use of GPS tracking devices has been widely applied in wildlife research over the last decade (Hebblewhite and Haydon, 2010). GPS devices possess many advantages over traditional radio telemetry such as increased tracking frequencies, lower temporal scales between locations, ability to collect data during all hours and in remote areas (Glasby and Yarnell, 2013; Wegge and Kastdalen, 2007). Although there are limitations such as battery capacity, weight, cost, and technological factors which can lead to gaps or loss of data (Frair et al., 2010). Due to the high cost of GPS tracking technology, studies that have implemented them typically have reduced sample sizes to account for financial restraints. This can be catastrophic for analysis if some of the devices malfunction and do not collect any location data, due to the already low sample size (Frair et al., 2010).

Therefore, researchers have turned to inexpensive commercially available GPS loggers to account for potential failures while still yielding a positive sample size. Despite a large increase in GPS applications in wildlife research, there are relatively few studies using commercially available devices (igotU GT-120 GPS logger) and within those studies, there have been even fewer studies done to evaluate the effectiveness and performance of these devices. The studies that have been done to evaluate the performance have all used stationary tests (Forin-Wiart et al., 2015; Vazquez-Prokopec et al., 2009). These studies have found that location error (LE) and fix success rate (FSR) are comparable to outputs produced by wildlife telemetry companies. Although, none of these studies have evaluated the performance in the field with a wild animal. The main concern with commercially available GPS units is the potential biases in the precision of LE. Location error is dependent on many factors such as canopy cover, forest type, topography, rock structures, animal behavior (at the population and individual levels) and cloud cover (Frair et al., 2010; Glasby and Yarnell, 2013; Hebblewhite and Haydon, 2010; Morris and Conner, 2017). To account for this, it is important to conduct static tests within the study site prior to conducting research. For our preliminary study we aimed to test the performance of the commercially available GPS logger (i-gotU GT-120) by simulating potential animal movements, within our proposed study site, and manually moving the GPS loggers to predetermined locations on a set schedule. We correlated set locations with GPS logger locations with a handheld Garmin GPS (Garmin 64s) within the Sakaerat Biosphere Reserve (SBR), in Nakhon Ratchasima province, Thailand. We assessed the Fixed success rate (FSR) which is the number of successful GPS fixes compared to its attempted number of fixes. We also looked at the environmental horizontal positioning error (EHPE) which is the radius of a circle around the actual location estimated to contain the GPS device (Morris and Conner, 2017).

5.2 Methods

Two GPS loggers were modified, waterproofed, and equipped with a larger 3.7V 3600mAh battery as described in Table 2. The devices were then paired with a VHF transmitter and attached to a mock lizard to simulate how they will theoretically be used in the field (Figure 5.1). By using program R, we simulated animal movements within SBR (fossorial, terrestrial and arboreal locations). One device was placed in the Dry dipterocarp forest (DDF) while the second device was placed in the dry evergreen forest (DEF) of the SBR. Each device was moved 3-4 times a day (depending on weather) to the generated locations, once at 0800h, 1200h, 1600h, and last at 2000h, this was done for 11 days, and each location was documented using a handheld Garmin GPS device. The GPS loggers were set to take location fixes at 10 min intervals 24 hours a day. After 11 days the devices were extracted from the field and the data was downloaded from both the loggers and handheld Garmin 64s to be analyzed using program R.

@http://crocdoc.ifas.ufl.edu/ 1

Figure 5.1 Mock lizards fitted with GPS loggers and radio transmitters. Following the same attachment methods as Argentine black and white tegu *Salvator merianea* from south Florida. We will be utilizing this method of attachment on the actual study organism *Varanus nebulosus*.

5.3 Results/Discussion

The accuracy of the GPS loggers was compared to the accuracy of the handheld Garmin 64s GPS unit. With help from Benjamin Marshall, we generated a comparison map for both the DDF and DEF based on the averages of the GPS logger data as depicted in Figure 5.2.

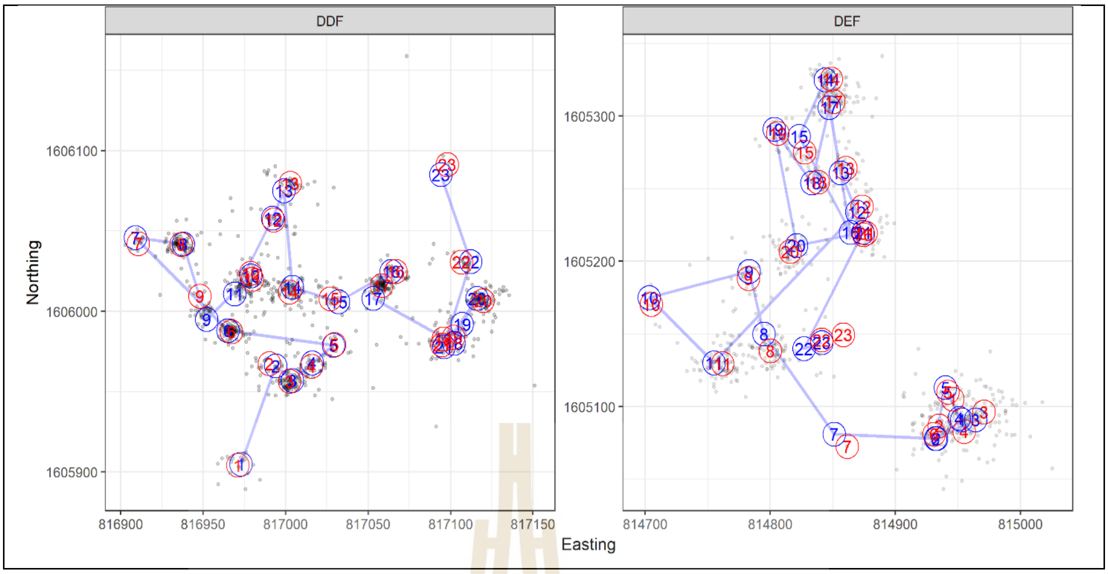

Figure 5.2 The Blue plots are the locations recorded by the Garmin 64s GPS. The Red plots are the averaged locations from the GPS loggers and the grey dots are the raw GPS logger locations.

In Figure 5.2, there is a definite overlap between the location data taken by the handheld Garmin and data recorded with the GPS loggers. Although, there are some slight inaccuracies, particularly for: the DDF locations 9 and 11 and the DEF locations 7 and 23. These are likely due to outliers in the data which we did not filter out. Therefore, skewing the overall location averages.

Table 5.1 Fix success rate (FSR) of preliminary study.

Forest type	Attempted	Successful	FSR	FSR <10 m EHPE	FSR <15 m EHPE
DEF	1536	1216	70.2%	1.4%	6.9%
DDF	1536	1443	94%	13.6%	35.5%

In table 5.1, the FSR differed between the DDF and DEF by around 20%; this can be attributed to the difference in canopy cover between the two forest types. The DEF is characterized by a thick closed canopy therefore, it has a lower FSR than the DDF, which has a primarily open canopy. There was also a significant difference between the EHPE in the two forest types where the DDF had 196 successful fixes <10 m EHPE averaging 17.8 Fixes/day and 512 fixes <15 m EHPE averaging 46.5 fixes/day. The DEF had only 17 fixes <10 m EHPE averaging 1.5 fixes/day and 84 fixes <15 m EHPE averaging 7.6 fixes/day. While traditional radio telemetry studies typically collect 1 to 3 location fixes per week. These differences are likely attributed again to differences in the canopy cover between the two forests.

Therefore, we have based our hypothesis that the GPS loggers will have a higher FSR than 70% within the DEF, from this preliminary study. Since *V. nebulosus* is a semi-arboreal species, taking advantage of the high canopy for thermoregulation. Our results are biased since we were unable to place any of our trial GPS loggers above the canopy to truly simulate monitor lizard movement.

Moving forward, for data exploration we will use the “outlie()” function in the *ctmm* R package, to filter out large outliers within our data. Then we will use the results of this study as a tool to calibrate our GPS error collected during our actual study. To do this we will use the *ctmm* package in program R and within this package, we’ll use the User Equivalent Range Error (UERE) function. The UERE function uses the root mean square value to transform the Horizontal Dilution of Precision (HDOP) into absolute errors. By calculating the absolute errors from GPS devices, which have been left in known locations for a set amount of time, we can standardize this value and use it as a calibration tool for the actual tracking location data.

5.4 References

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CHAPTER VI

EVALUATING NOVEL GPS LOGGERS FOR WILDLIFE RESEARCH ON THE CLOUDED MONITOR LIZARD *VARANUS NEBULOSUS* IN NORTH-EASTERN THAILAND

6.1 Abstract

The field of wildlife research could greatly benefit from the implementation of Global Positioning System (GPS) tracking devices across taxa. Until recently, studies have been limited on implementing GPS technology due to its high costs. Here we evaluate the performance of an inexpensive GPS logger that was repurposed for wildlife research and used to track the movements of Clouded Monitor Lizards (*Varanus nebulosus*). We evaluated the GPS loggers against traditional radio telemetry data collected over the same spatial and temporal scales using three separate analyses: dynamic Brownian Bridge Movement Models (dBBMM), Autocorrelated Kernel Density Estimators (AKDE) and Integrated Step Selection Functions (ISSF). We tracked 9 individuals (3 females, 6 males) for a mean of 72.3 days ± 36.7 days. We deployed GPS devices in the field on 18 occasions with a 61.1% success rate and a 48.3% fix success rate (FSR; based on the 61.1% successful devices). Occurrence distributions and motion variance was evaluated with dBBMM analysis: the mean 95% confidence area was 9.59 ± 3.57 ha with an average motion variance of 3.10 ± 1.06 m for data collected with VHF transmitters; the mean 95% confidence area was 7.78 ± 1.93 ha with an average motion variance of 2.37 ± 0.71 m, for data collected with GPS loggers. The home range was estimated using AKDE analysis: We were unable to obtain range residency for three individuals using traditional radio telemetry, the mean 95% home range estimate was 19.36 ha ± 0.02 with a range from 9.31 to 190.90 ha; We obtained range residency for all individuals with location data collected with GPS loggers, the mean 95% home range estimate was 48.15 ± 11.27 ha with a range from 1.39 to 214.9 ha. Habitat selection was investigated with ISSF analysis: VHF-derived results suggested that

derived outputs suggested a strong avoidance with all habitat covariates tested. Although our sample was small our results support the continued implementation of the igotU-GT 120 GPS logger in future research studies. However, researchers should use GPS and radio telemetry accordingly based on their research questions.

6.2 Introduction

Since the 1960's, researchers have relied on very high frequency (VHF) transmitters to radio track and study the spatial requirements of species (Martin et al., 2009). Telemetry technology has enabled researchers to track animal movement pathways and create home range maps—even for highly cryptic species (Cagnacci et al., 2010). The benefits of VHF transmitters are that they are relatively inexpensive, lightweight and have a long battery lifespan; the major drawbacks to radio telemetry are field and energy intensive tracking schedules, human induced bias to study animal behavior and relatively large gaps between consecutive animal locations.

Advances in Geopositioning System (GPS) tracking devices such as transmitters and loggers are considered one of the greatest achievements to the field of spatial ecology since the turn of the century (Cagnacci et al., 2010). GPS devices have drastically changed the field of animal ecology by increasing the number of relocations and decreasing the temporal scale between those relocations. GPS devices are capable of collecting accurate location data throughout the day, during inclement weather and within areas that are difficult to access; making them the superior choice over radio transmitters (Tomkiewicz et al., 2010). Although, there are some major drawbacks such as: devices are more expensive (limiting the sample size in most studies), heavier (when compared to VHF transmitters), lower GPS accuracy (when compared to triangulation methods of radio telemetry), high device failure rates (more parts equals more opportunities for failure) and they are at risk from habitat driven biases (topography, canopy cover and cloud cover; Cagnacci et al., 2010; Frair et al., 2010; Hebblewhite and Haydon, 2010).

Until recently most studies done with GPS devices were conducted on larger mammals due to the weight of the GPS devices combined with the weight of the battery needed for extended tracking periods. A study by Allan et al., 2013, took a novel approach and modified an inexpensive commercially available GPS logging device (igotU GT-120) and made their own wildlife tracking collar, with great success. Since then, this same methodology has been implemented on many different species such as: cattle (Schieltz et al., 2017), feral cats (Hervías et al., 2014), monitor lizards (Lei and Booth, 2018), tortoises (Paden and Andrews, 2020) and puffins (Harris et al., 2012). Although, no study has compared the GPS logging data to VHF data collected over the same temporal scale to assess the GPS devices actual performance with spatial analysis.

My objective was to assess the GPS logger (igotU GT-120) performance by radio tracking Clouded Monitor Lizards (*Varanus nebulosus*) with VHF transmitters, while simultaneously collecting GPS data points with the data loggers to compare analysis from both detector types over overlapping temporal scales. To accomplish this I planned on assessing four different factors to evaluate GPS performance: 1) the fix success rate of deployed units, 2) compare home range estimates from Autocorrelated Kernel Density Estimators (AKDE), 3) compare movement pathway estimates from dynamic Brownian Bridge Movement Models (dBBMM) and 4) compare habitat selection inferences from Integrated Step Selection Functions (ISSF).

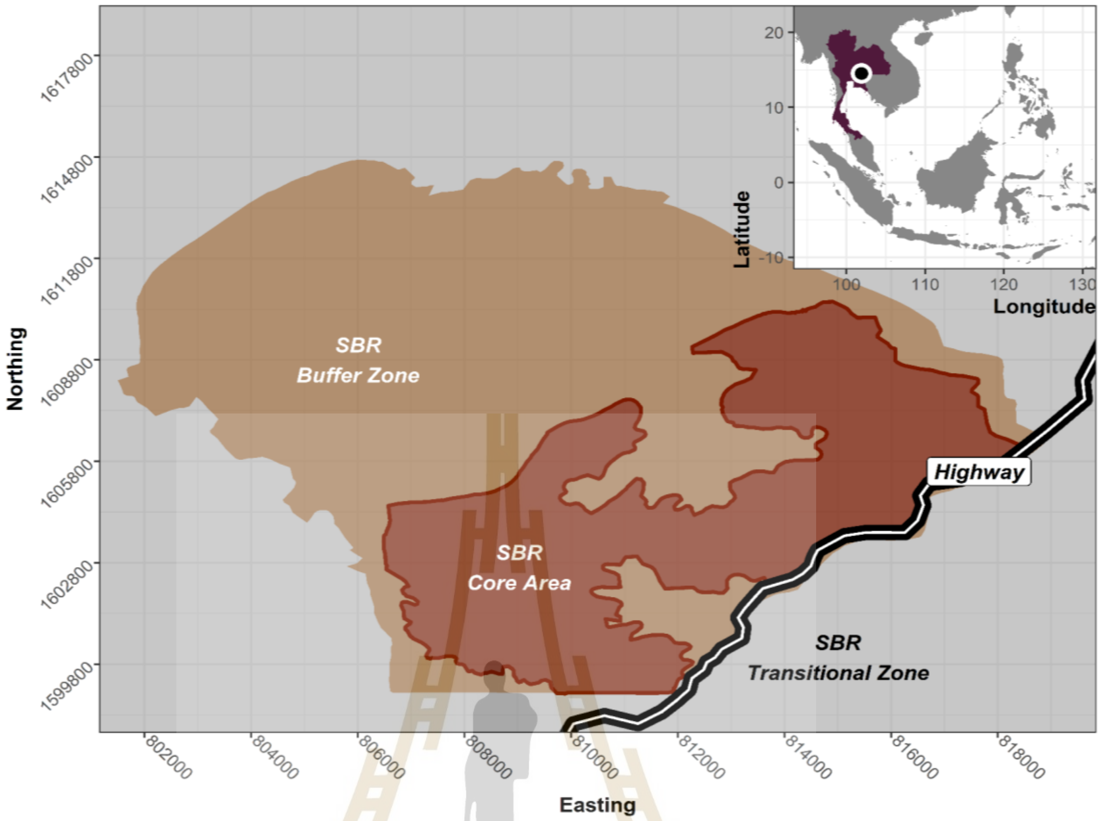

Figure 6.1 The map above illustrates the Sakaerat Biosphere Reserve's core (dark orange), buffer (light orange) and transitional (grey) areas.

6.3 Methods

6.3.1 Study area

We conducted fieldwork from 14 July 2020 to 14 June 2021, at the Sakaerat Biosphere Reserve (SBR), Nakhon Ratchasima province, Thailand (14.22–14.73°N, 101.60–102.07°E; Figure 6.1). This site is predominantly seasonal dry evergreen forest (DEF) and dry dipterocarp forest (DDF) with scattered fragments of bamboo patches and mixed deciduous forests (Trisurat, 2010). The SBR is divided into three designated areas: core which is dominated by DEF and DDF; buffer which contains DEF, reforested areas and reclaimed plantation forests; the transitional zone which is predominantly a combination of human settlements and agricultural lands (Trisurat, 2010). Detailed characteristics of the study site can be found in chapter 3 on the brumation of *V. nebulosus*. For this study, we focused our data collection in the DEF within the core area.

6.3.2 Capture and tracking protocol

We performed on foot visual surveys and motorcycle road cruising surveys, to locate individual animals between July 2020 to March 2021. Once we located an individual, we captured lizards opportunistically through hand captures or with a noose, when the lizards were found on the forest floor and we used drop traps, when lizards were found perched on trees.

Captured individuals were pit tagged and we collected morphometric data such as snout-vent length (SVL), total length (TL), mass and sex (Table 6.1). The lizards were fitted with a backpack-style harness, attached around their pelvic girdle, using a polyurethane-coated 2mm gauge wire. The harness contained a VHF transmitter (Holohil AI-2B model) paired with the GPS logger (i-gotU GT-120) and a 18560 battery (Panasonic 3400mAh, MH12210). The lizards were then released at the location of their capture; we aimed to keep the holding time no more than 24 hours for each individual. The GPS logger for this study was the i-gotU GT-120 model, this unit is marketed as a personal GPS device and weighs just 20g—making it ideal for spatial ecology studies. It comes equipped with a built-in antenna and 230mAh battery; the battery was removed and replaced with a 3,400mAh, 18650 battery (to extend tracking periods). The chipboard was coated with silicone spray and then encased in an epoxy mixture to protect it from environmental conditions. The GPS logger and VHF transmitter were fitted into a heat shrink harness and attached at the base of the tail around the pelvic girdle, following Klug et al., 2015.

6.3.3 Data collection

The GPS loggers were programmed to record an animal's location once every 10 minutes on 24-hour cycles. To calibrate the GPS accuracy on our devices, we conducted a two weeklong preliminary study in September 2018, where we simulated animal movements and manually moved GPS loggers around the DEF and DDF to predetermined locations (please see chapter 4 for a detailed outline). Our VHF tracking protocol shifted during our study period as we increased our sample size: originally, we conducted four relocations per day at 6-hour intervals; as the sample size increased, we settled our tracking schedule at 1 relocation per day between the hours of 06:00 and 20:00. This was done due to a lack of available field technicians and limitations imposed by each animal's location and the terrain of our field site. Each individual was recaptured every 2-3 months in order to download the GPS data points from the GPS devices and recharge the 18650 batteries. We analyzed the GPS and VHF datasets with overlapping temporal scales to assess the effectiveness and feasibility of the i-gotU GT-120 GPS logger's use for wildlife research.

We radio tracked a total of 7 individuals (4 males and 3 females) during our study period. We classified an individual as an adult when the SVL >400 mm and the mass was >1500 g for females and SVL >400 mm and mass >2000 g for males; this was based on previous data by (Auffenberg, 1994), that detailed male *V. nebulosus* are generally heavier than females. Individual tracking durations varied (mean = 73 days ± 39.1 days, range = 106 days) due to unexpected GPS logger and battery failures which are described in Figure 6.2.

6.3.4 Fix success rate

One method we used to assess the performance of our GPS loggers was the fix success rate (FSR), which is a proportion of successful locations over the total number of attempted locations (successful and unsuccessful). We deemed locations with an environmental horizontal positioning error (EHPE) >30 m too inaccurate and excluded them from our data set. We then created subsets based on EHPE (<10 m, <15 m, <20 m, <25 m and <30 m) to explore what percent of the FSR were within a viable resolution (at varying values of EHPE) for data analysis. We also documented when devices were deployed and failed and when possible, defined the causes of the failure (Table 6.1).

6.3.5 Movement models

We used dynamic Brownian Bridge Movement Models (dBBMM) to compare movement pathways generated from our VHF collected data to our GPS collected data. The dBBMM's follow an occurrence distribution and allow researchers to analyze movement trajectories and identify movement corridors within an animal's home range (Crane et al., 2021). We used the R package *move* v.4.0.6 (Kranstauber et al., 2018) to produce the occurrence distributions and motion variance for each individual lizard. The dBBMM requires researchers to input a window size and margin which are biologically significant to the species being analyzed; for our study we used a window size of 15 and a margin of 7. These values were chosen based on observations of lizard behavior with our VHF tracking protocols, the widow size of 15 is long enough to capture the motion variance when the lizards were active for extended periods of time and the margin of 7 was short enough to capture variations during times when the lizards were inactive. We used the same window size and margin values with our GPS derived datasets to keep our models standardized for comparison. We selected the 90%, 95% and 99% contours for our analysis and were able to extract them from our occurrence distributions using the R packages: *adehabitatHR* v.0.4.19 (Calenge, 2006) and *rgeos* v.0.5.5 (Bivand and Rundel, 2020).

6.3.6 Home range estimates

We used R studio version 4.0.3 (R Core Development Team, 2020) for all data manipulation and visualizations. We used Autocorrelated Kernel Density Estimators (AKDE) to calculate the home range size of our lizards and evaluate the performance of the GPS loggers (Fleming and Calabrese, 2017). Traditional "Home range" estimates such as minimum convex polygons (MCP's) and Kernel Density Estimates (KDE's) assume that location data are not autocorrelated and each chronological relocation is independent of the last, which is not valid with most datasets; particularly with data collected through GPS tracking devices with significantly lower temporal frequencies between relocations (Crane et al., 2021; Joo et al., 2020; Silva et al., 2021). GPS collected datasets are nearly all autocorrelated (meaning that the consecutive data points are in fact dependent on each other) due to the small temporal gaps and high frequency of data points, resulting in the independence assumption of MCP's and KDE's not being met (Noonan et al., 2019; Signer et al., 2019). Autocorrelated Density Estimators also are able to model the future space use of an animal and therefore, AKDE's are a more efficient tool to measure the actual home range size of an animal through its life cycle by taking into account the autocorrelation within datasets (Crane et al., 2021; Fleming et al., 2015; Fleming and Calabrese, 2017; Signer and Fieberg, 2021).

We used the R package *ctmm* v.0.6.1 (Calabrese et al., 2021; Fleming and Calabrese, 2017) to model the spatial requirements of *V. nebulosus* within the DEF and to compare home range outputs between data collected with GPS loggers and VHF transmitters, during the same time frames. We assessed all of the variograms to make sure that our lizards were meeting the stable home range assumption of the AKDE's; we discarded all of our GPS data at the 10 m EHPE subset due to all but one individual meeting the range residency assumption.

6.3.7 Integrated step selection functions

We used Integrated Step Selection Functions (ISSF), which take into account the known locations of an animal and generate random steps between each consecutive point to model the possible habitats used (Thurfjell et al., 2014). This type of analysis is used to look at specific covariates and weigh them against each other to evaluate the potential drivers of movement (Avgar et al., 2016). We used ISSF analysis as another method of assessing the effectiveness of the GPS loggers by comparing both VHF and GPS datasets (over the same temporal scale) against each other. For this analysis we only focused on individuals which spent all of their time within the dry evergreen forest therefore, we excluded F1, M7 and M13. We used the R package *amt* v.0.1.4 (Signer et al., 2019) to run ISSF analysis, investigating the Euclidean distance between: roads, streambeds, the dry dipterocarp forest and *Shorea henyrana* trees. We recognized a relationship between this species of tree and *V. nebulosus* early into our project, as viable shelter, and basking locations within the dense canopied dry evergreen forest. We mapped out all the *Shorea henryana* trees with a handheld GPS (Garmin 64s), within our lizard's estimated home ranges over the entire study period. We also created a shapefile of the streambed by walking along it and marking a location on a handheld Garmin 64s GPS at 10-20 m intervals. The shapefiles for the roads and the DDF forest were provided by staff at the research station. All shapefiles were transformed into rasters with continuous values of Euclidean distance between covariates. The rasters were then inverted to avoid zero-inflation and create more intuitive direction-based models.

The ISSF analysis has a high computational cost and the processing power needed goes up exponentially with larger datasets (Thurfjell et al., 2014). The GPS data collected from loggers had an average relocation between one and three hours for all of the individuals and therefore the computational cost was already high for ISSF;

because of this, we decided to use 20 random steps for our GPS analysis. However, the tracking duration for the VHF dataset averaged at one relocation per 24 hours and therefore, we used 200 random steps without suffering from computational outputs of the ISSF.

To model ISSF at the individual level we created eight models assessing movement to our habitat covariates: the first model was a null with only step length and turning angle, the next four models assessed habitat features independently, the final three models were multivariate, each modeling the effects of three different habitat features on movement. We then used AIC scores to assess the best fit models for each individual.

To model ISSF at the population level we created four models using the same habitat raster files as in the individual ISSF. We used code made available by Hodges et al., 2021 which was originally modified by Muff et al., 2020. The main difference with the population analysis was that all individuals were fitted together in each model. We used the same number of random steps as the individual ISSF: 20 for the GPS and 200 for the VHF datasets. Following Smith et al., 2021, for the stratum-specific related effect we used the fixed prior precision of 0.0001, the Penalized Complexity prior, PC (1, 0.05) for the other random slopes (individual), lastly we used an uninformative normal priors, Normal (0, 10^3) for the fixed effects. We fit all of the models using the R package *INLA* v.20.03.1748 (Rue et al., 2009).

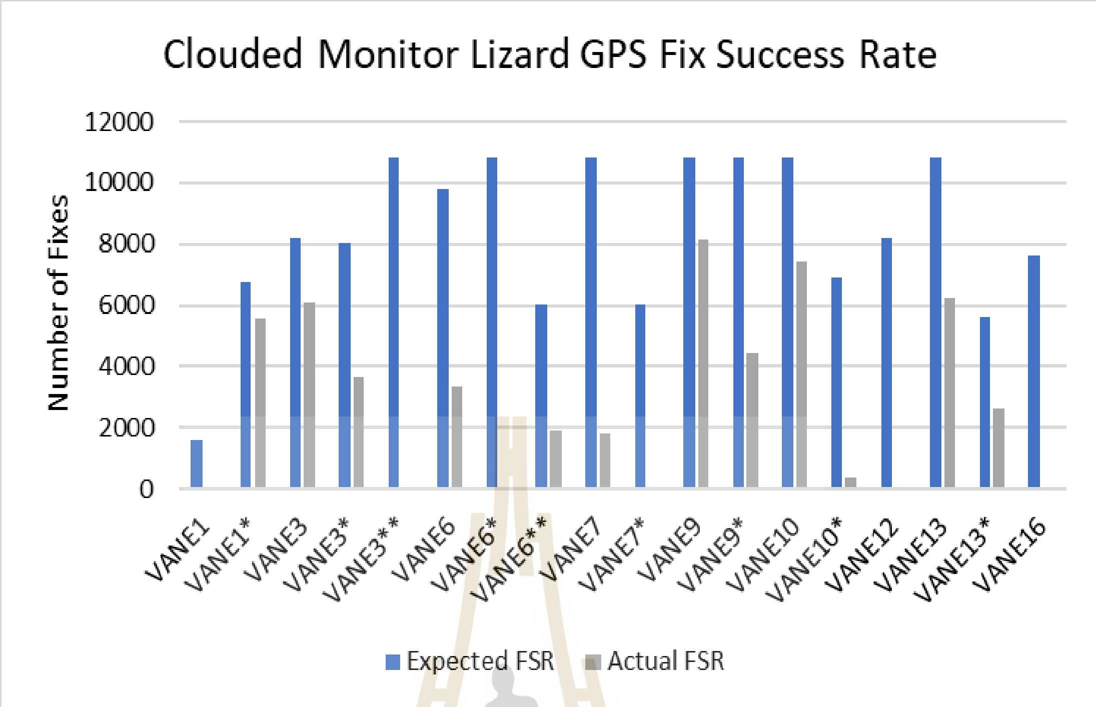

Figure 6.2 Expected (blue) and actual (grey) fix success rate (FSR) from all GPS logger deployments. Asterisks denote multiple GPS deployments.

6.4 Results

6.4.1 Fix success rate

Between 15 July 2020 and 6 March 2021, we captured 9 individual lizards that were large enough to support both the GPS logger and VHF transmitters. All lizards were released at their capture site shortly after being fitted with the backpack harness. Seven of the nine lizards were recaptured, and devices were redeployed after downloading location fixes and recharging their batteries. Of the redeployed lizards only VANE9 and VANE13 had successful full-length tracking durations without any temporal gaps (Figure 6.2; Table 6.1). Of the 18 total deployments we recorded a 61.1% success rate. We lost one device from water damage (despite strong efforts to combat environmental factors) due to VANE1 spending 3 days submerged within a small pond, during its first deployment. Three retrieved devices (VANE3**, VANE9*, VANE16) were unresponsive when plugged into the computer via a USB cable, despite having their batteries completely drained, suggesting they likely recorded data throughout the deployment period (Figure 2;

Table 6.1). We had one device lost during our study period, VANE12 which was recaptured with the VHF transmitter still intact, but the backpack was damaged, and the GPS logger likely snagged on vegetation and fell off. Both GPS loggers from VANE6* and VANE7* failed to record any location data, likely due to software failure.

Of the 11 successful deployments, the average expected number of GPS fixes was 8874 (range 5616 - 10800), the average actual number of GPS fixes was 4301.7 (range 368 - 8117; Table 6.1). Therefore, the Fix Success Rate (FSR) was relatively high (for devices that were successful in acquiring locations), averaging 48.3% (range 5.3% - 82.5%).

Table 6.1 Record of GPS logger deployment periods. Lizard IDs with asterisks represent multiple GPS deployments. Expected fixes are based on the number of days the logger was set out to track or until the date the device malfunctioned.

ID	Deployed	Recovered	GPS start date	GPS end date	GPS status	Expected fixes	Successful fixes
F1	9/5/2020	9/16/2020	9/5/2020	NA	Water damage	1584	NA
F1*	9/18/2020	11/4/2020	9/18/2020	11/4/2020	Recovered	6768	5583
F3	7/15/2020	9/10/2020	7/15/2020	9/10/2020	Recovered	8208	6076
F3*	9/11/2020	11/6/2020	9/11/2020	10/22/2020	Recovered	8064	3642
F3**	11/7/2020	3/8/2021	11/7/2020	NA	malfunction	10800	0
M6	9/2/2020	11/8/2020	9/2/2020	9/29/2020	Recovered	9792	3365
M6*	11/9/2020	3/5/2021	11/9/2020	NA	malfunction	10800	0
M6**	3/6/2021	4/16/2021	3/6/2021	4/16/2021	Recovered	6048	1903
M7	10/24/2020	3/4/2021	10/24/2020	12/9/2020	Recovered	10800	1799
M7*	3/6/2021	4/16/2021	3/6/2021	NA	malfunction	6048	0
F9	11/13/2020	1/29/2021	11/13/2020	1/30/2021	Recovered	10800	8117
F9*	1/30/2021	5/15/2021	1/30/2021	3/27/22021	Recovered	10800	4433
M10	11/13/2020	2/26/2021	11/13/2020	1/31/2021	Recovered	10800	7427
M10*	2/28/2021	4/16/2021	2/28/2021	3/4/2021	malfunction	6912	368
M12	2/24/2021	4/21/2021	2/24/2021	NA	Device Lost	8208	NA
M13	12/28/2020	3/13/2021	12/28/2020	3/13/2021	Recovered	10800	6263
M13*	3/14/2021	4/21/2021	3/14/2021	4/21/2021	Recovered	5616	2644
M16	3/6/2021	4/27/2021	3/6/2021	NA	malfunction	7632	NA

Table 6.2 Dynamic Brownian Bridge Movement Model occurrence distribution outputs from VHF sampled data, for Clouded Monitor Lizards (*Varanus nebulosus*) at the Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand.

ID	Data points	Days tracked	Lag-time (hours)	Relocations	Motion Variance	90%	95%	99%
VANE1	66	46.47	17.16 ± 1.00	11	0.37 ± 0.11	0.47	0.75	1.67
VANE10	79	78.03	24.01 ± 0.38	7	0.08 ± 0.03	0.23	0.45	1.10
VANE13	111	113.18	24.69 ± 0.72	33	3.16 ± 0.50	8.49	14.04	27.33
VANE3	201	98.94	11.87 ± 0.38	26	2.08 ± 0.21	5.14	8.27	16.15
VANE6a	54	27.03	12.24 ± 0.40	10	6.92 ± 1.52	3.92	6.82	13.91
VANE6b	39	39.81	25.14 ± 2.00	22	3.97 ± 0.40	11.35	14.99	22.09
VANE7	43	41.72	23.84 ± 0.61	5	0.37 ± 0.13	0.64	1.26	2.41
VANE9	133	133.07	24.19 ± 0.48	20	7.87 ± 2.93	8.64	30.21	123.88

Table 6.3 Dynamic Brownian Bridge Movement Model occurrence distribution outputs from GPS sampled data, subsetted at <20 m EHPE, Clouded Monitor Lizards (*Varanus nebulosus*) at the Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand.

ID	Data points	Days tracked	Lag-time (hours)	Relocations	Motion Variance	90%	95%	99%
VANE1	1219	46.63	0.92 ± 0.06	1155	0.97 ± 0.23	1.55	2.06	3.13
VANE10	1368	78.91	1.39 ± 0.13	1290	2.02 ± 0.26	1.91	2.92	6.45
VANE13	1784	113.56	1.53 ± 0.08	1726	2.84 ± 0.25	7.33	11.78	23.79
VANE3	4504	98.90	0.53 ± 0.05	3885	0.26 ± 0.02	7.56	11.48	22.23
VANE6a	963	27.03	0.67 ± 0.04	900	1.08 ± 0.26	2.62	4.00	10.81
VANE6b	214	39.07	4.40 ± 0.76	214	6.67 ± 1.12	12.70	16.77	25.88
VANE7	252	42.31	4.05 ± 1.36	252	3.31 ± 0.65	2.23	3.18	6.09
VANE9	3208	134.24	1.00 ± 0.04	2915	1.77 ± 0.15	5.76	10.08	48.50

6.4.2 Movement pathways

We calculated occurrence distributions for all the tracked individuals at the 90%, 95% and 99% confidence areas using both VHF and GPS data with overlapping time scales; we analyzed the GPS data at five different subsets based on EHPE values (10 m, 15 m, 20 m, 25 m and 30 m; Table 6.2; 6.3; 6.8; 6.9; 6.11; 6.12). Upon reviewing the 95% confidence area between all GPS datasets, we found the 20 m EHPE subset to have the lowest average 95% confidence areas (we chose to discard the <10 m subset because of a smaller sample size than the other subsets). The <15 m GPS had a mean 95% confidence interval of 9.44 ± 3.12 ha with a range from 1.38 to 27.17 ha; the mean 95% confidence area for the <20 m GPS dataset was 7.78 ± 1.93 ha with a range from 2.06 to 16.76 ha; the mean 95% confidence interval for the <25 m GPS dataset was 9.99 ± 2.95 ha with a range from 2.61 to 27.38 ha; the mean 95% confidence interval for the <30 m GPS dataset was 11.08 ± 3.08 ha with a range from 3.2 to 29.27 ha. The mean 95% confidence area for the VHF dataset was 9.59 ± 3.57

ha with a range from 0.45 to 30.21 ha; the mean 95% confidence area for the <20 m GPS dataset was 7.78 ± 1.93 ha with a range from 2.06 to 16.76 ha. The lizard with the smallest occurrence distribution from the VHF outputs was VANE10 with a 90% area of 0.23 ha; The lizard with the lowest 90% area occurrence distribution from the <20 m GPS outputs was VANE1 with an area of 1.55 ha (Table 6.2; 6.3).

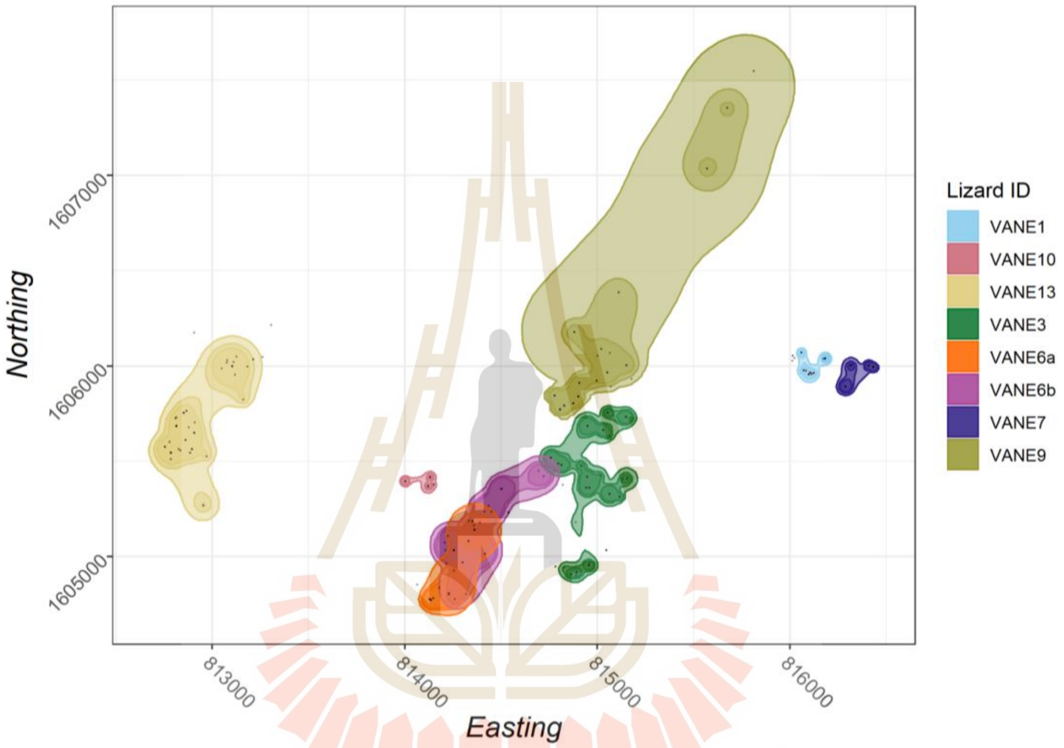

Figure 6.3 Total radio tracked monitor lizard occurrence distributions produced with VHF data.

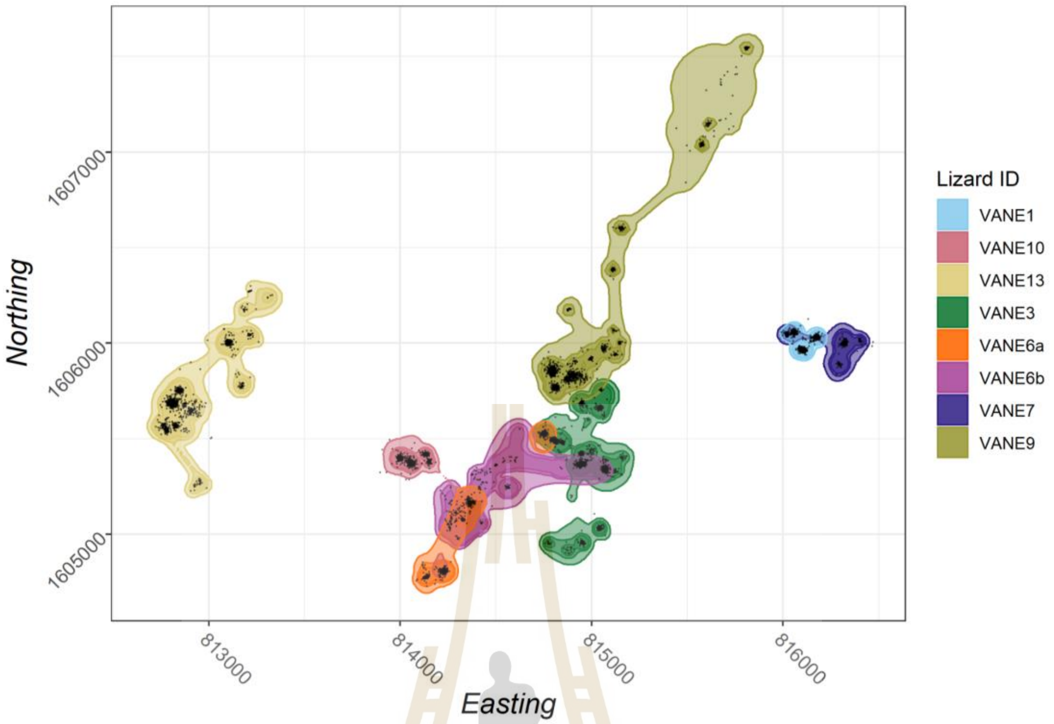

Figure 6.4 Total GPS tracked monitor lizard occurrence distributions produced with GPS <20 m EHPE data.

We compared the average motion variances from the VHF outputs (3.10 ± 1.06 m; range 0.08 to 7.87 m) to the <20 m GPS outputs (2.37 ± 0.71 m; range 0.26 to 6.67 m; Table 6.2; 6.3). The lizards with the highest motion variance were VANE9 (7.87 ± 2.93 m; VHF) and VANE6b (6.67 ± 1.12 m; GPS). The lizards with the lowest motion variance were VANE10 (0.08 ± 0.03 m; VHF) and VANE3 (0.26 ± 0.02 m; GPS). The average lag time between consecutive location fixes was 20.4 hour for the VHF outputs and 1.9 hour for the GPS.

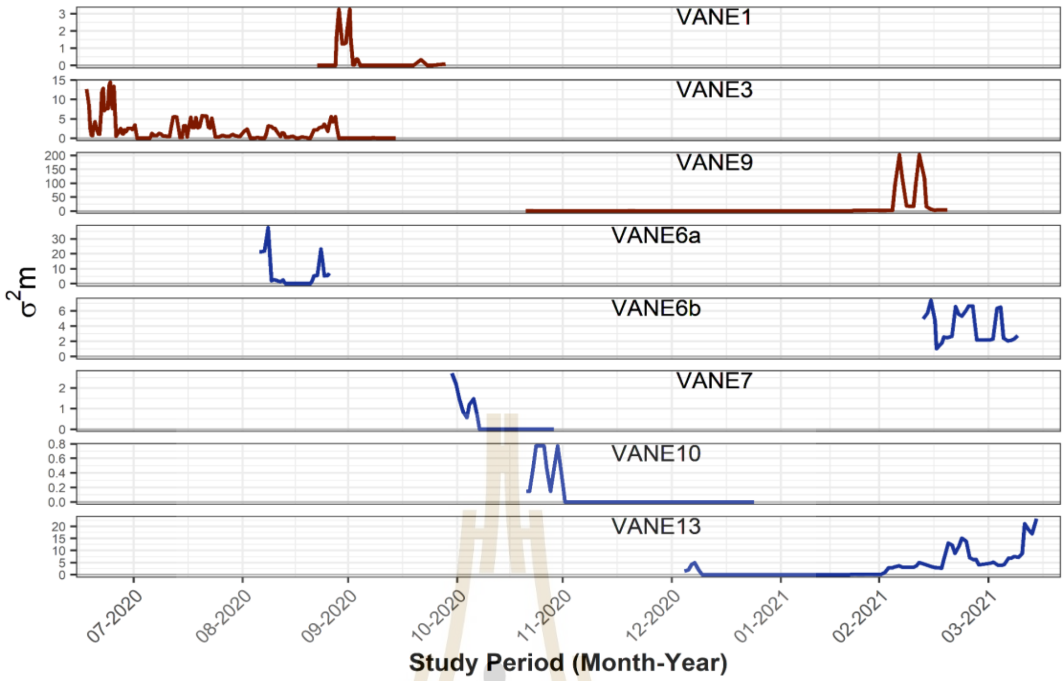

Figure 6.5 Motion Variance of VHF tracked lizards. Red graphs represent female and blue graphs represent male lizards.

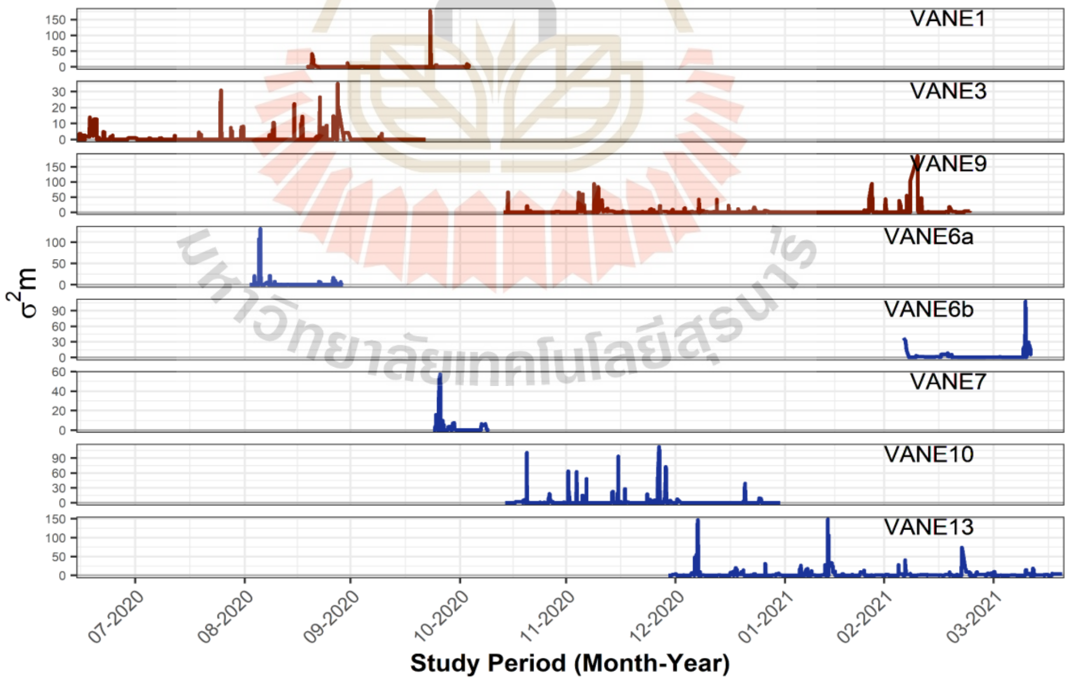

Figure 6.6 Motion Variance of GPS tracked lizards <20 m EHPE. Red graphs represent female and blue graphs represent male lizards.

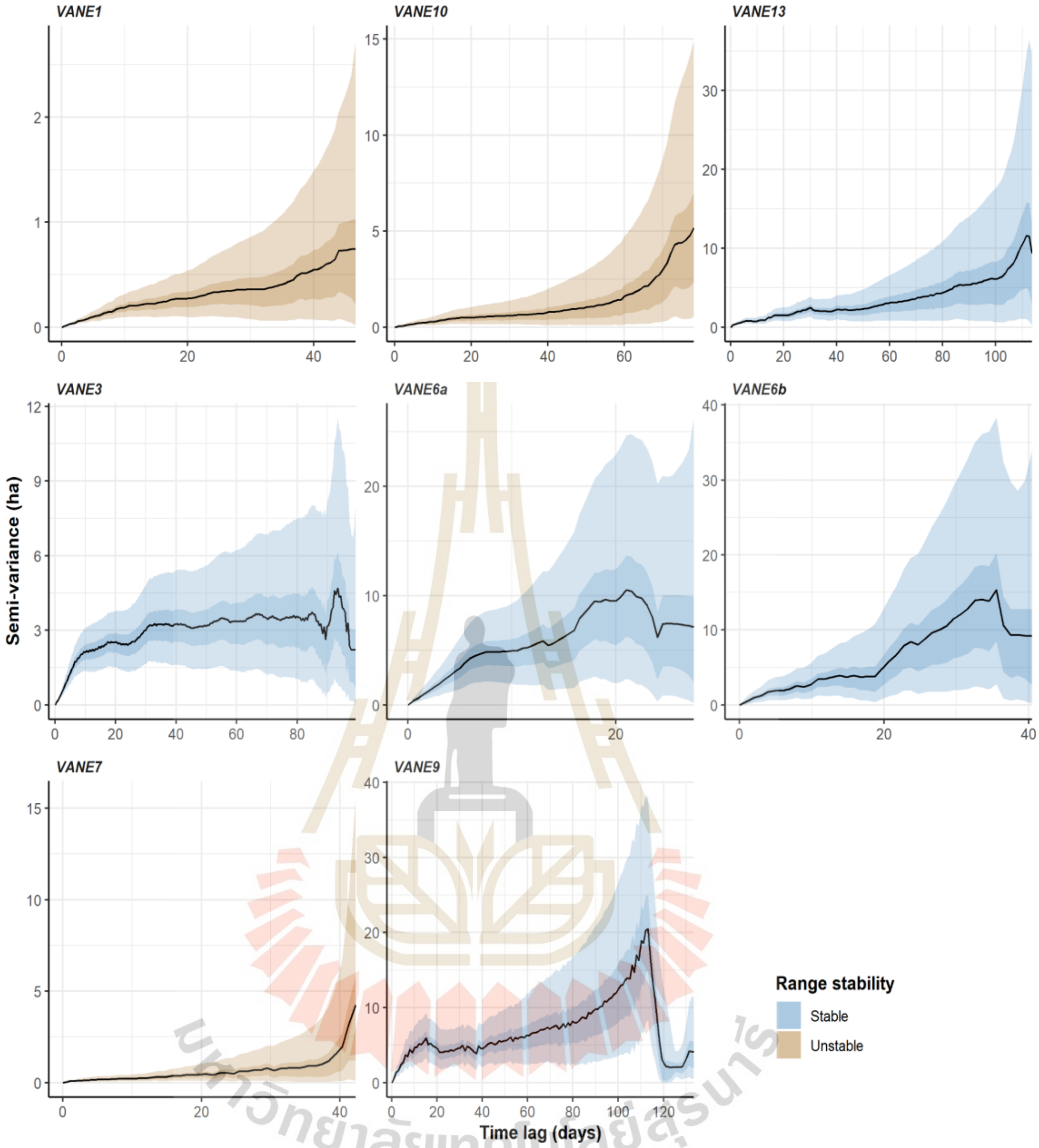

Figure 6.7 Variograms displaying semi-variance (ha) of home range area estimates for each individual's VHF tracking duration. Shaded areas are displaying the 50% and 95% confidence intervals.

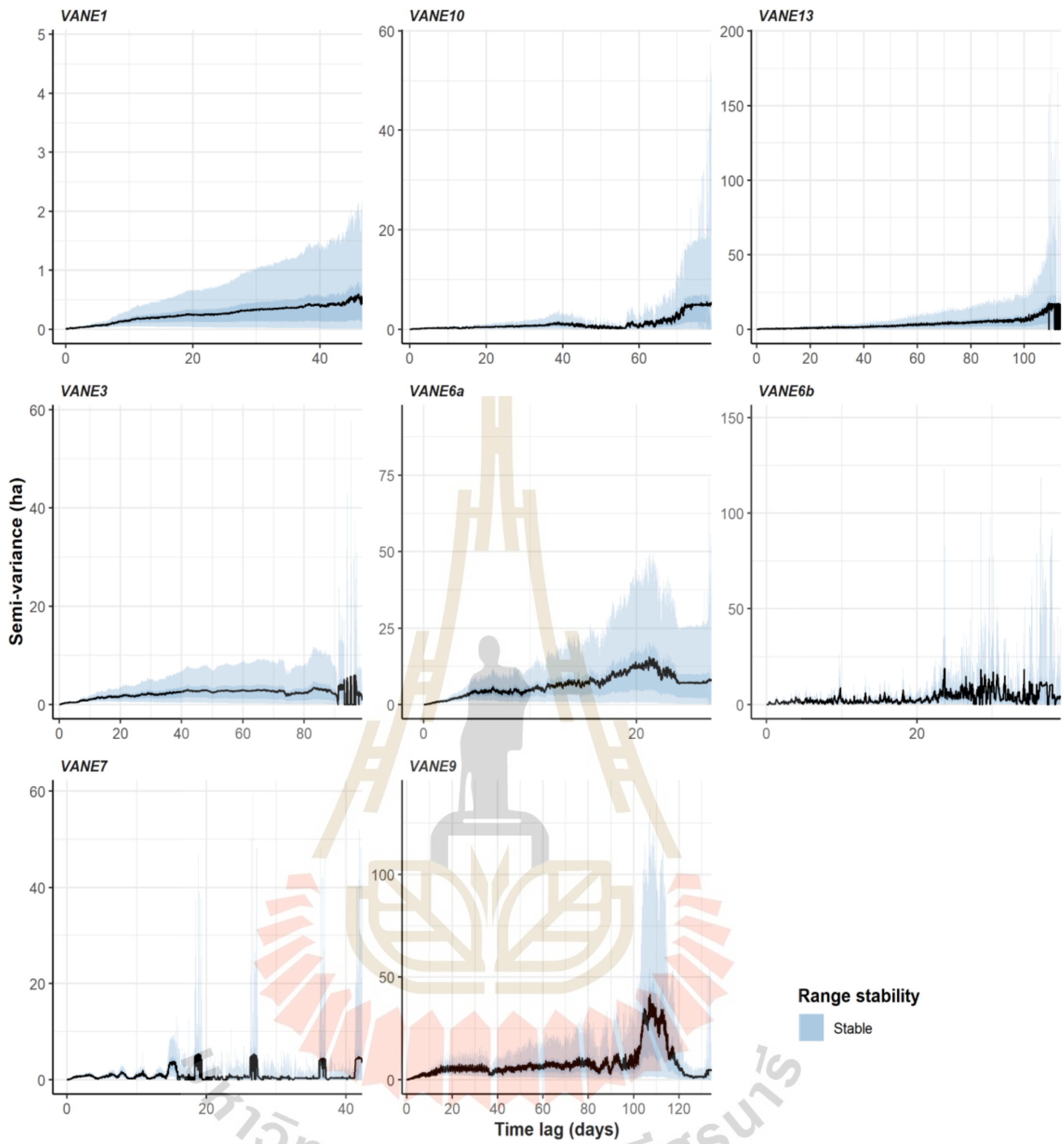

Figure 6.8 Variograms displaying semi-variance (ha) of home range area estimates for each individual's GPS (<20 m EHPE) tracking duration. Shaded areas are displaying the 50% and 95% confidence intervals.

6.4.3 Home range

Based on variograms produced with VHF data, three lizards (VANE1, VANE10 and VANE7), did not meet the range residency assumption for AKDE analysis and were discarded from our sample (Figure 6.7). The mean 95% home range estimates of the remaining individuals were 19.36 ha ± 0.02 with a range from 9.31 to 190.90 ha. The average home range crossing time was 10 ± 1.98 days, with a range from 7.53 to

17.84 days (Table 6.4). The average effective sample size was 9.03 ± 2.82 with a range from 3.59 to 17.53.

Reviewing variograms produced with GPS data (< 20 m EHPE) showed that all individuals met the range residency assumption of AKDE's. The mean 95% home range estimate was 48.15 ± 11.27 ha with a range from 1.39 to 214.9 ha (Table 6.5). The average home range crossing time was 10.98 ± 1.71 days with a range from 3.57 to 16.29. The average effective sample size was 7.28 ± 1.09 with a range from 1.66 to 11.86.

Table 6.4 Autocorrelated Kernel Density Estimate (AKDE) results per individual with VHF data and the movement model used to produce the estimates. Lower and upper confidence intervals are the 95% contour. AKDE estimates are in hectares.

ID	AKDE lower CI	AKDE estimate	AKDE higher CI	Movement Model
VANE1	1.46	7.23	17.51	OU anisotropic
VANE3	18.48	60.32	126.45	OU anisotropic
VANE6a	9.31	46.86	114.15	OU anisotropic
VANE6b	21.96	85.33	190.9	OUF anisotropic
VANE7	1.83	12.13	32.00	OU anisotropic
VANE9	27.54	50.93	81.37	OUF anisotropic
VANE10	2.94	26.9	76.77	OUF anisotropic
VANE13	19.51	39.6	66.69	OU anisotropic

Table 6.5 Autocorrelated Kernel Density Estimate (AKDE) results from GPS (<20 m EHPE) collected data for each individual and the movement model used to produce the estimates. Lower and upper confidence intervals are the 95% contour. AKDE estimates are in hectares.

ID	AKDE lower CI	AKDE estimate	AKDE higher CI	Movement Model
VANE1	1.39	4.18	8.49	OU anisotropic
VANE3	20.23	52.53	99.98	OUF anisotropic
VANE6a	9.80	77.89	215.00	OUF anisotropic
VANE6b	30.86	86.07	169.09	OU isotropic
VANE7	5.86	16.20	31.71	OU isotropic
VANE9	33.42	73.82	129.96	OUF anisotropic
VANE10	3.53	15.78	37.01	OU anisotropic
VANE13	22.01	58.75	113.22	OUF anisotropic

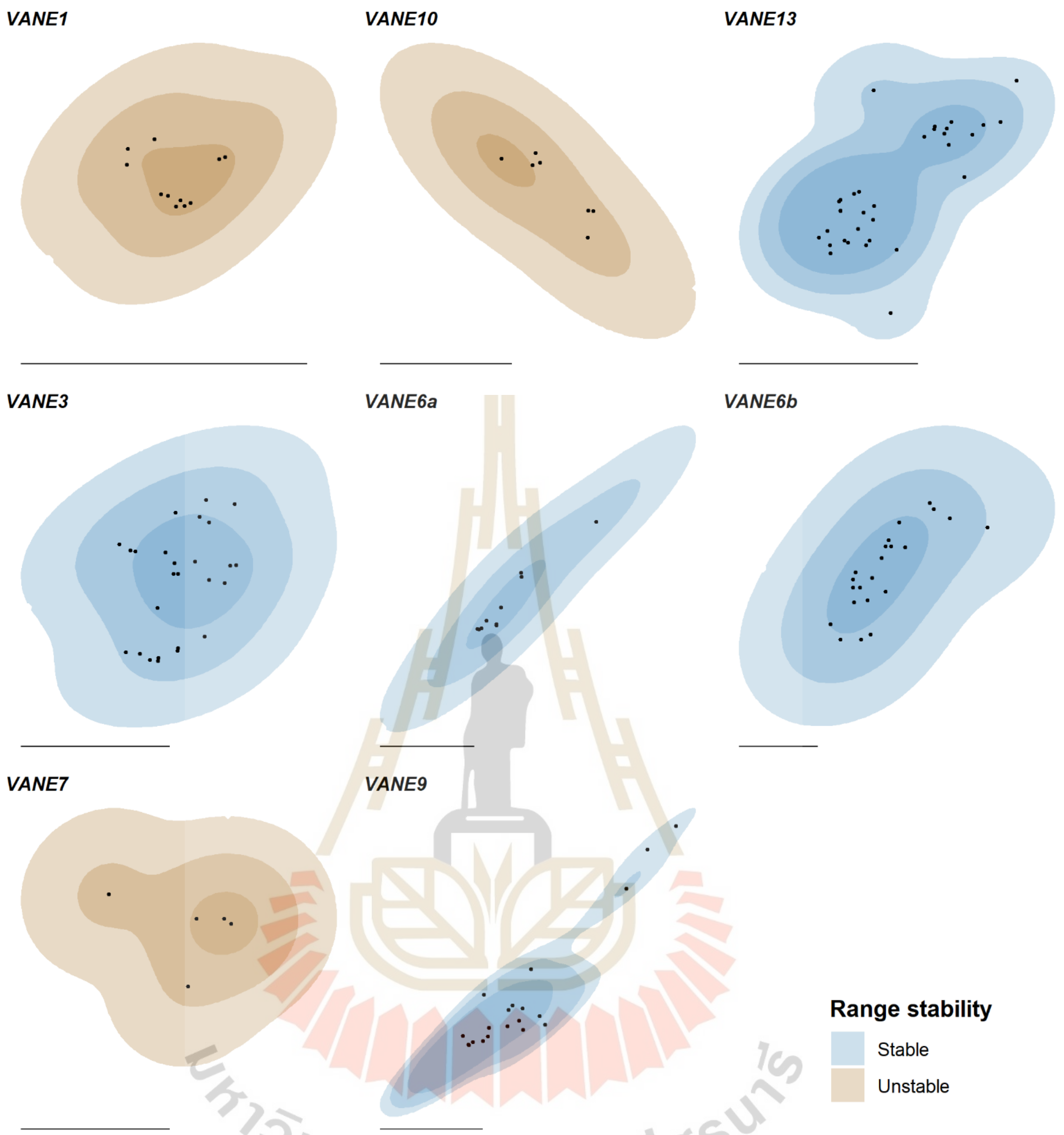

Figure 6.9 Visual representation of the 95% contour AKDE area estimates calculated with VHF data. Scale bars represent 500m.

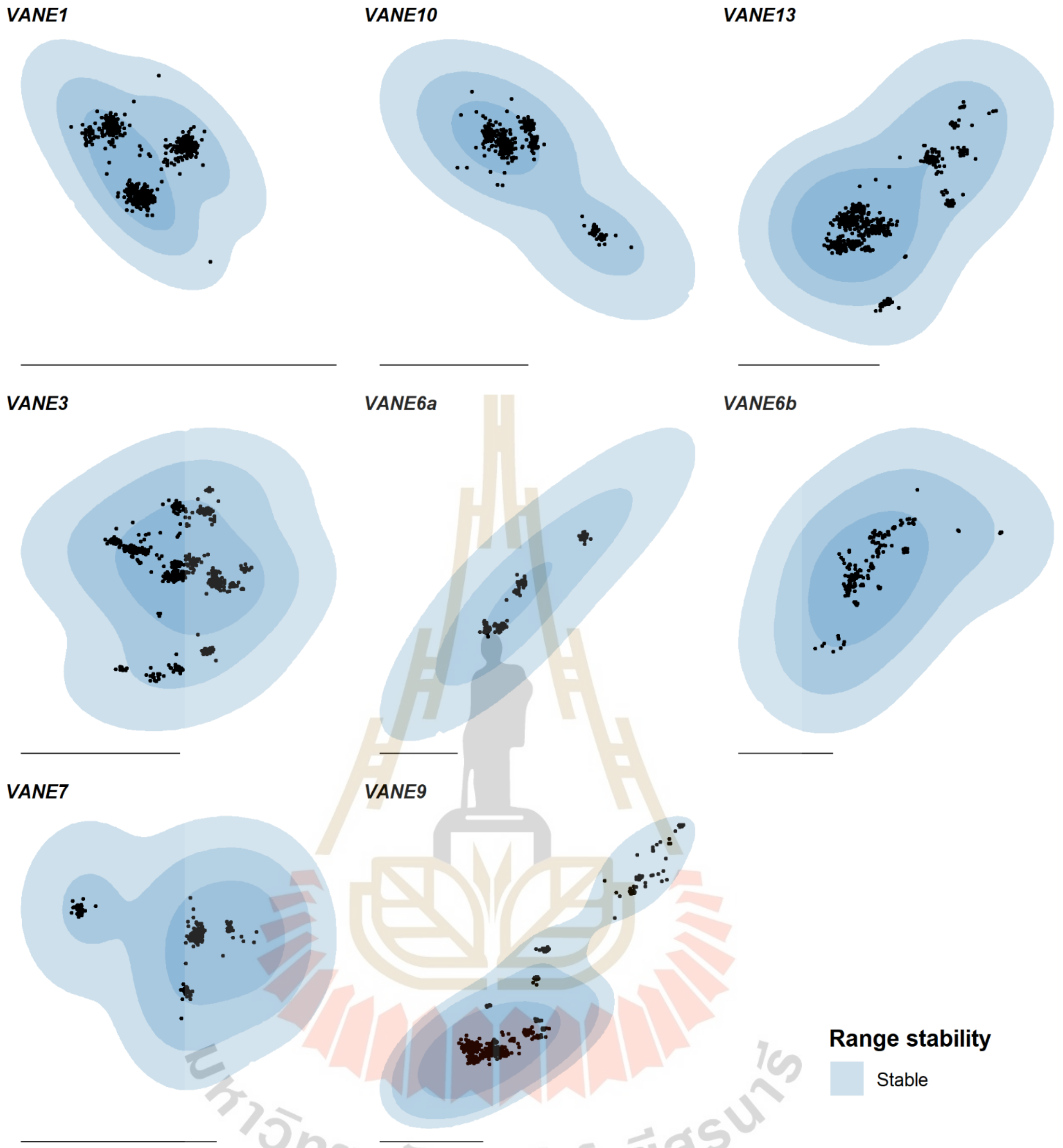

Figure 6.10 Visual representation of the 95% contour AKDE area estimates calculated with GPS data (<20 m EHPE). Scale bars represent 500m.

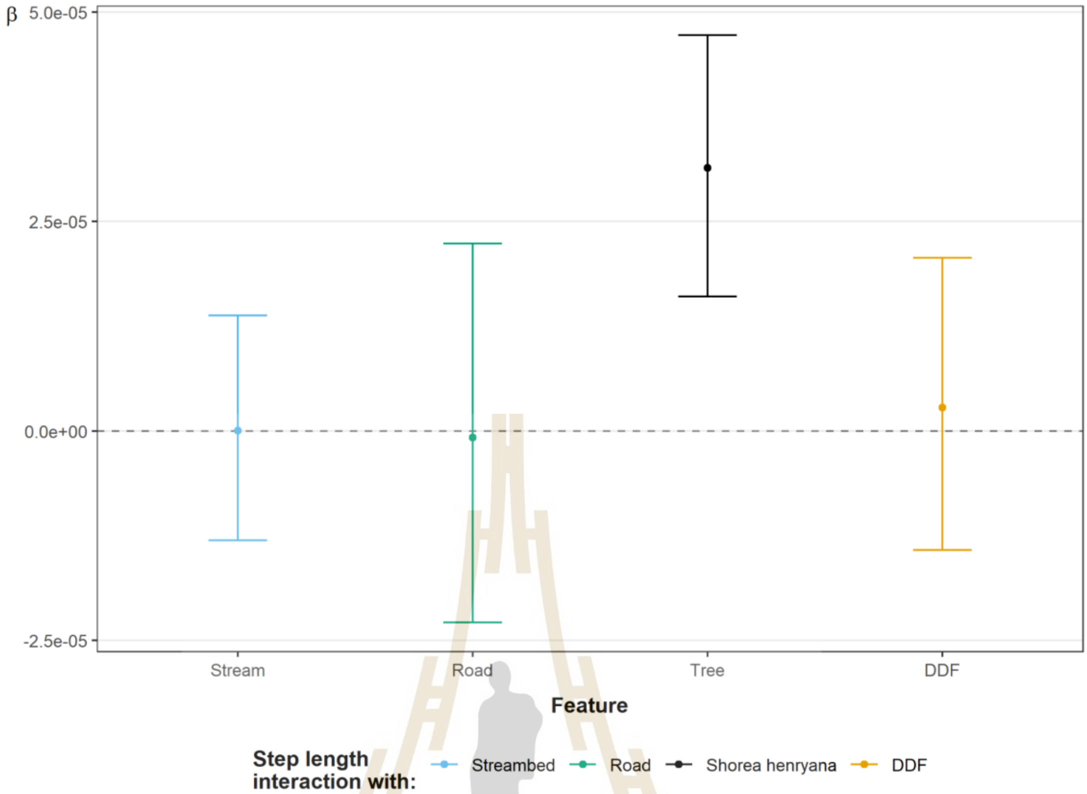

Figure 6.11 VHF derived population level habitat selection for lizards that were tracked within the dry evergreen forest of the core at the Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand. Selection is based on distance to habitat features with positive estimates relating to association. Error bars represent the 95% confidence intervals.

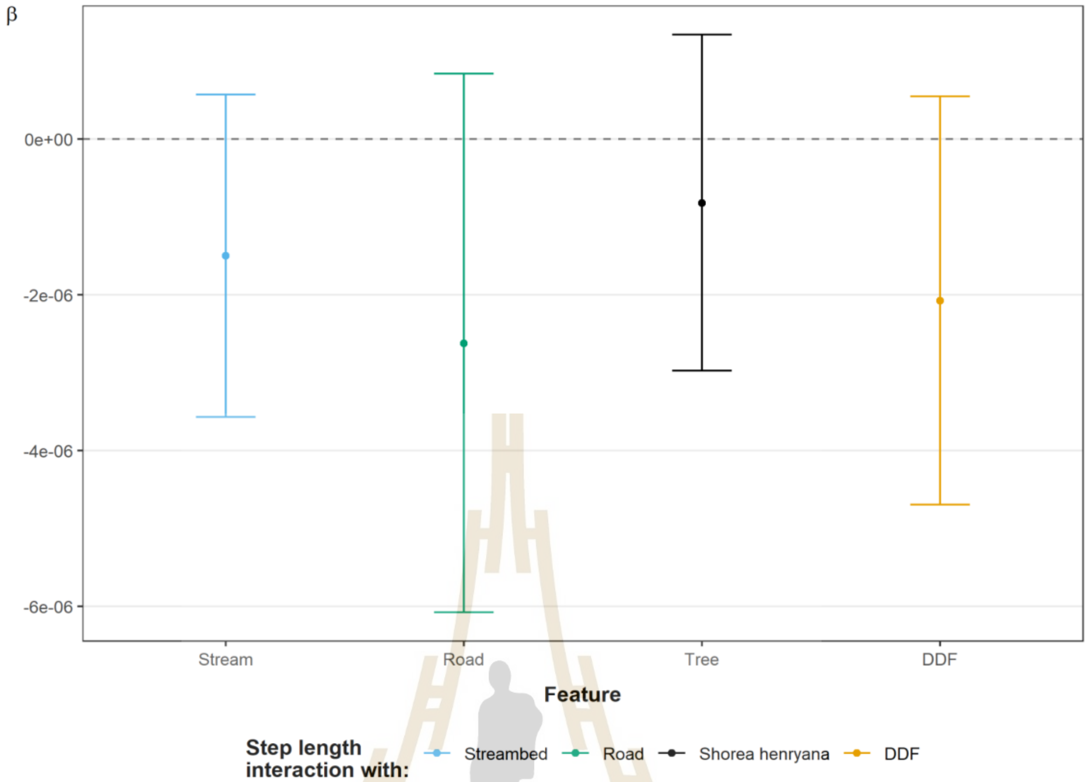

Figure 6.12 GPS derived population level habitat selection for lizards that were tracked within the dry evergreen forest of the core at the Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand. Selection is based on distance to habitat features with positive estimates relating to association. Error bars represent the 95% confidence intervals.

6.4.4 Habitat selection

When conducting ISSF analysis, we focused solely on the lizards within the DEF of the core area (VANE3, VANE6, VANE9 and VANE10), due to the large spatial scale between all individuals. To analyze habitat selection, we modeled step selection between four habitat features: streams, roads, DDF and *Shorea henryana* trees. Due to large differences in the number of location fixes between our datasets we used varying values of step length for each dataset; in all cases the total number of steps was the same. For individual level ISSF we chose to do 200,000 random steps, the step length was programmed at: 400 steps for the VHF data; 200 for the <10 m GPS data; 48 steps for the <15 m GPS data; 20 steps for the <20 m GPS data; 12 steps for the <25 m GPS data and 8 steps for the <30 m GPS data. At the individual level all GPS derived ISSF models found a distinct association of the individual VANE10 to

Shorea henryana trees. The VHF derived models found an association with VANE6 to *Shorea henryana* and avoidance to *Shorea henryana* among the other three individuals. The <20 m GPS derived models suggest an avoidance to *S. henryana* among all individuals except for VANE10 which had an unambiguous relationship.

Due to computational differences between individual and population level ISSF, we opted to use 25,000 random steps for population level analysis. The step length was programmed to: 50 steps for VHF data; 25 steps for <10 m GPS data; 5 steps for <15 m GPS data; 3 steps for <20 m GPS data; 2 steps for <25 m GPS data and 1 step for <30 m GPS data. The VHF derived model suggests an association of *V. nebulosus* to the *Shorea henryana* tree and unambiguous relationship between the other three covariates. However, when assessing the GPS derived models, only the models from the <10 m GPS dataset had a positive association to *S. henryana*. As the degree of GPS accuracy increased so did the degree of avoidance to all habitat features (Figure 6.27 to 6.31).

6.5 Discussion

6.5.1 Fix success rate

GPS tracking can provide precise spatial and temporal data to a degree far beyond traditional radio telemetry. In this study GPS tracking produced an average lag time of around 30 minutes between each consecutive GPS fix, a significant decrease in the temporal scale when compared to radio telemetry, with an average lag time of 24 hours. The ability to collect unbiased location and behavior data in hard to access habitats, during inclement weather and at all hours of the day is by far the greatest advantage of GPS tracking technology. Improvements in location frequency and lower temporal gaps, allow for fine-scale research questions such as: habitat corridors and selection (Frair et al., 2010; Thirgood et al., 2004), home range and movement models (Kie et al., 2010; Smouse et al., 2010), behavior (Davis et al., 1999) and climate change (Durner et al., 2009). While GPS technology is still relatively expensive compared to VHF transmitters, the tradeoffs are unprecedented: less time in the field, less funding needed for resources, smaller research teams and decreasing human induced bias. As we have shown, using inexpensive GPS loggers (~$50 USD) with VHF transmitters can dramatically increase sample sizes and decrease tracking frequencies. While there are more chances of device failure due to a much more dynamic structure than a radio transmitter, we feel in most scenarios the pros outweigh the cons.

There are a multitude of factors that affect FSR such as: fix attempt interval and frequency (Moriarty and Epps, 2015), species behavior (Cristescu et al., 2015; Mattisson et al., 2010), canopy cover (DeCesare et al., 2005) and topography (Lewis et al., 2007). Our average FSR for successful devices during our study was 48.3%, this is right in the average of most commercially available GPS tracking devices. One review of GPS tracking studies from 2001 to 2010 found the average FSR to be between 46-99% (Frair et al., 2010). However, a more recent review paper of 167 different GPS projects, found the average FSR to be 85% (Hofman et al., 2019). Regardless, obtaining an FSR of 48% with the inexpensive cost of the GPS loggers we used for our project is more than significant enough to implement these devices in future projects.

6.5.2 Home range

Here we assessed the performance of inexpensive commercially available GPS loggers against traditional radio transmitters. We used AKDE analysis to calculate the home range estimates for both detector types during overlapping temporal and spatial scales. When reviewing variograms for the VHF dataset we observed three individuals (VANE1, VANE10 and VANE7) who did not meet the range residency assumptions of the AKDE and therefore were discarded from further analysis. Although when reviewing variograms produced with GPS data we observed varying levels of range residency dependent on the EHPE data subset: at <10 m EHPE only VANE9 met the range residency assumption; at the <15 m EHPE subset three individuals (VANE1, VANE10 and VANE13) did not meet the range residency assumption; at the next three EHPE subsets (<20 m, <25 m and <30 m) all individuals met the range residency assumption. This is an important observation because it means that with GPS collected data (higher frequency) we're able to reach range residency in less amount of time than with traditional detector types. Therefore, the tracking schedule not only the duration plays a large role in what questions can be asked and analyzed later.

We chose to focus on the GPS <20 m EHPE subset for further analysis; since all individuals met range residency and to keep our comparisons standardized amongst our other analyses. The mean 95% home range estimates for our VHF data were 19.36 ha ± 0.02 with a range from 9.31 to 190.90 ha (Table 6.4.). It is important to note that the three nonresident lizards were not included in this estimate. The mean 95% home range estimate for our GPS <20 m EHPE subset was 48.15 ± 11.27 ha with a range from 1.39 to 214.9 ha (Table 6.5). This estimate is significantly larger than the VHF estimate and therefore we calculated the 95% home range estimate again, including the three outlier individuals strictly for intuitive purposes; the 95% home range estimate for all VHF individuals was 41.16 ha ± 9.11 with a range from 9.31 to 190.90 ha. This value is significantly closer to our GPS home range estimates and therefore, we assume the GPS derived outputs are closer to the actual estimates of our study animals than the VHF outputs.

6.5.3 Movement pathways and habitat selection

We evaluated the movement patterns and motion variance of radio-tracked Clouded Monitor Lizards using the dynamic Brownian Bridge Movement Models. Based on the estimated 95% confidence areas, the average area used was 9.59 ± 3.57 ha (VHF models) and 7.78 ± 1.93 ha (<20 m GPS models). There were strong variations in movement patterns and motion variance for each individual lizard, which is why the standard error is so high. For example, the VHF model's mean motion variance was 3.10 ± 2.81 m, with a low of 0.08 ± 0.03 ha and a high of 7.87 ± 2.93 ha; the <20 m GPS model had a mean motion variance of 2.37 ± 1.88 m, with a low of 0.260 ± 0.02 ha and a high of 6.67 ± 1.12 ha (Table 2; 3). As expected, the GPS loggers outperformed the radio transmitters during overlapping temporal periods. When comparing movement models between the two detector types it is not apparent in the VHF models on the pathways and corridors individuals used to get between known location fixes. While the GPS models are very refined and clear-cut on how the animal traversed through the forest to get between locations. Intuitively thinking this is mainly because of the shorter gap between sequential location fixes (24 hour for VHF and 0.50 hour for GPS). Although, when anticipating the fix success rate of devices and the overall trend of device malfunctions, which tend to plague most studies utilizing GPS devices, there is a place in research for radio transmitters. We feel that the choice to use each detector type should really be based on; the question being asked, the study areas features and the species in question. GPS telemetry based devices are extremely beneficial to large scale research questions such as: migration (Hebblewhite et al., 2008), movement corridors of megafauna (Hebblewhite and Merrill, 2008), ecology of wide-ranging species (Thirgood et al., 2004), conservation impacts (Berger, 2004) and modeling the impacts of climate change (Durner et al., 2009).

Although, GPS devices are potentially ineffective, for specific research questions which rely on in-field observations (typically associated with radio telemetry), such as modeling movements against resource selection (Haydon et al., 2008; Moorcroft et al., 2006; Smouse et al., 2010), as demonstrated in our study. We recorded a distinct association between *V. nebulosus* and the *S. henryana* tree during our study period, through radio telemetry. One of the main thoughts with GPS collected data is that fine-scale analysis such as habitat selection and resource use will be easier to pull out with more location fixes (Dalziel et al., 2008; Frair et al., 2010). We used Integrated Step Selection Functions (ISSF) to model occurrence data against specific habitat features, which we believe have an impact on *V. nebulosus* movement. The population level analysis with our VHF data (727 location fixes) estimated a strong positive association of *V. nebulosus* to *S. henryana* and unambiguous relationships to the other three covariates; while the population level analysis with our GPS data (<20 m; 13,512 location fixes) estimated a strong avoidance to all four habitat covariates (Figure 6.11; 6.12). The issue arises because we now have fine-scale location data (~1 location/30 minutes) but our habitat data is extremely coarse and nowhere near the same level of depth as the location data at scale (Frair et al., 2010). For studies that want to use GPS data for fine-scale habitat selection, it's important to utilize online satellite habitat and environmental data to conduct proper analysis, although this requires more demanding coding capabilities (Frair et al., 2010; Hebblewhite and Haydon, 2010).

6.5.4 General discussion

Herein we discuss some of the general issues and suggestions for future projects to account for. We noted an issue with the recorded data on the devices which had not been noted in other publications using these loggers. We purchased our devices from three separate venues and each device, when set on schedule mode, took GPS fixes at the scheduled time intervals but it recorded the time under the Universal Time Coordinated (UTC) +1, while our study site was UTC +7. It is a simple fix to convert the time zones to the proper time post processing but researchers using these devices should make sure to account for variations in devices before they are deployed, to account for potential issues early on.

The igotU GT-120 devices we used are “store on board” GPS loggers, meaning they require a USB cable and computer to access the data, this extra step adds another potential source for device failure. Despite GPS loggers being a commonly used device as a substitute for more expensive GPS transmitters, very few studies have addressed the additional risk for data losses (Cabrera et al., 2016). We recorded three instances when we were unable to access the data (VANE3*, VANE9*, VANE16) on devices we were confident recorded data, at least partially during their deployment. In this event, we were able to use a heat gun to soften and remove the epoxy sealant from our data loggers and access the Surface Mount Device (SMD) chip (memory storage) on the PCB board. We then attempted to desolder the SMD chip and solder it to a known working logger. We were unable to retrieve any usable data from VANE3* and VANE16 (it’s possible we damaged the SMD’s from overheating in our initial attempts) but we retrieved an additional 4433 successful GPS fixes for VANE9*, by using this method.

6.6 Conclusion

This study provides a dynamic assessment on the performance of a novel inexpensive GPS logger, supported by in field implementation. Inferences from the comparison analyses suggests, this technology has the potential to expand our movement repositories for species around the globe without heavily impacting research budgets. The main concern with this device was system malfunctions and gaps within datasets, although this is a considerable concern even with expensive wildlife marketed GPS devices. Building your own GPS device raises new challenges and opportunities for failure but the devices are a fraction of the cost and with that, many more devices can be deployed. Which is needed to make inferences at the population level, which is one of the main flaws within GPS location data currently available.

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6.9 Supplementary Materials

Supplementary material includes:

Figure 6.13. Expected (green) and actual (blue) battery life of GPS loggers during deployments. Lizard IDs marked with asterisks represent second and third GPS deployment cycles.

Table 6.6 The total number of days tracked and the number of fixes at varying levels of EHPE for GPS logger data.

Table 6.7 VHF Tracking Summary.

Table 6.8 GPS Tracking Summary EHPE of <10 m.

Table 6.9 GPS Tracking Summary EHPE of <15 m.

Table 6.10 GPS Tracking Summary EHPE of <20 m.

Table 6.11 GPS Tracking Summary EHPE of <25 m.

Table 6.12 GPS Tracking Summary EHPE of <30 m.

Figure 6.14 Motion Variance of VHF tracked lizards. Red graphs represent female and blue graphs represent male lizards.

Figure 6.15 Motion Variance of GPS tracked lizards <10 m EHPE. Red graphs represent female and blue graphs represent male lizards.

Figure 6.16 Motion Variance of GPS tracked lizards <15 m EHPE. Red graphs represent female and blue graphs represent male lizards.

Figure 6.17 Motion Variance of GPS tracked lizards <20 m EHPE. Red graphs represent female and blue graphs represent male lizards.

Figure 6.18 Motion Variance of GPS tracked lizards <25 m EHPE. Red graphs represent female and blue graphs represent male lizards.

Figure 6.19 Motion Variance of GPS tracked lizards <30 m EHPE. Red graphs represent female and blue graphs represent male lizards.

Figure 6.20 Total radio tracked monitor lizard occurrence distributions produced with VHF data.

Figure 6.21 Total GPS tracked monitor lizard occurrence distributions produced with GPS <10 m EHPE data.

Figure 6.22 Total GPS tracked monitor lizard occurrence distributions produced with GPS <15 m EHPE data.

Figure 6.23 Total GPS tracked monitor lizard occurrence distributions produced with GPS <20 m EHPE data.

Figure 6.24 Total GPS tracked monitor lizard occurrence distributions produced with GPS <25 m EHPE data.

Figure 6.25 Total GPS tracked monitor lizard occurrence distributions produced with GPS <30 m EHPE data.

Figure 6.26 VHF derived population level ISSF.

Figure 6.27 <10 m EHPE GPS derived individual level ISSF.

Figure 6.28 <15 m EHPE GPS derived individual level ISSF.

Figure 6.29 <20 m EHPE GPS derived individual level ISSF.

Figure 6.30 <25 m EHPE GPS derived individual level ISSF.

Figure 6.31 <30 m EHPE GPS derived individual level ISSF.

Table 6.13 Movement model selection and effective sample sizes (DOF area).

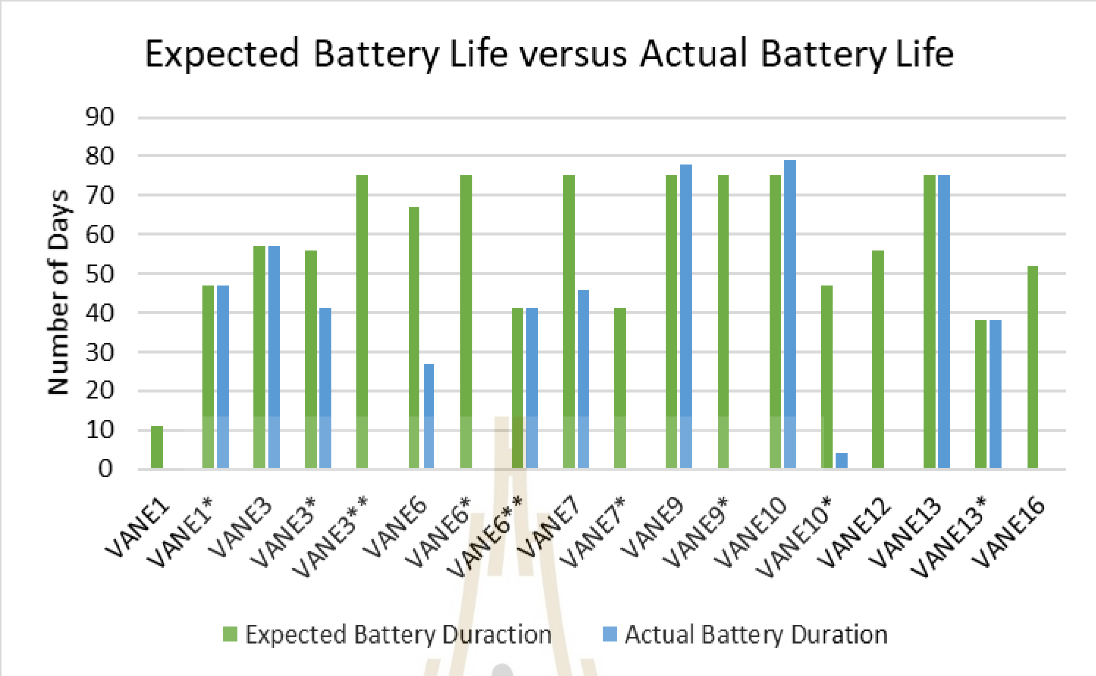

Figure 6.13 Expected (green) and actual (blue) battery life of GPS loggers during deployments. Lizard ID's marked with asterisks represent second and third GPS deployment cycles.

Table 6.6 The total number of days tracked and the number of fixes at varying levels of EHPE for GPS logger data.

ID	Days tracked	Fixes (<5m)	Fixes (<10m)	Fixes (<15m)	Fixes (<20m)	Fixes (<25m)	Fixes (<30m)
VANE1	47	2	86	425	1182	2426	3725
VANE3	98	22	634	2316	4504	6309	7825
VANE9	77	2	89	533	1804	6224	9172
VANE10	79	3	75	401	1368	2872	4484
VANE11	112	2	102	583	1784	3613	5641
VANE6	127	4	98	436	1179	2170	3274
VANE7	42	0	9	59	252	583	985

Table 6.7 VHF Tracking Summary.

ID	Data points	Days tracked	Lag-time (hours)	Relocations	Motion Variance	90%	95%	99%
VANE1	66	46.47	17.16 ± 1	11	0.37 ± 0.11	0.47	0.75	1.67
VANE10	79	78.03	24.01 ± 0.38	7	0.08 ± 0.03	0.23	0.45	1.10
VANE13	111	113.18	24.69 ± 0.72	33	3.16 ± 0.5	8.49	14.04	27.33
VANE3	201	98.94	11.87 ± 0.38	26	2.08 ± 0.21	5.14	8.27	16.15
VANE6a	54	27.03	12.24 ± 0.4	10	6.92 ± 1.52	3.92	6.82	13.91
VANE6b	39	39.81	25.14 ± 2	22	3.97 ± 0.4	11.35	14.99	22.09
VANE7	43	41.72	23.84 ± 0.61	5	0.37 ± 0.13	0.64	1.26	2.41
VANE9	133	133.07	24.19 ± 0.48	20	7.87 ± 2.93	8.64	30.21	123.88

Table 6.8 GPS Tracking Summary EHPE of <10 m.

ID	Data points	Days tracked	Lag-time (hours)	Relocations	Motion Variance	90%	95%	99%
VANE1	85	46.05	13.16 ± 2.82	85	0.1 ± 0.01	0.70	0.93	1.38
VANE10	75	77.0	24.99 ± 5.73	75	0.93 ± 0.18	0.89	1.32	2.29
VANE13	102	104.84	24.91 ± 5.66	102	0.11 ± 0.04	0.42	0.63	1.39
VANE3	634	98.77	3.74 ± 0.5	613	0.25 ± 0.05	6.80	12.19	24.56
VANE6a	94	25.62	6.61 ± 1.1	93	1.01 ± 0.21	2.68	5.35	12.97
VANE9	210	132.11	15.17 ± 2.2	209	0.72 ± 0.18	6.95	21.64	61.59

Table 6.9 GPS Tracking Summary EHPE of <15 m.

ID	Data points	Days tracked	Lag-time (hours)	Relocations	Motion Variance	90%	95%	99%
VANE1	439	46.56	2.55 ± 0.27	429	0.37 ± 0.07	0.99	1.38	2.16
VANE10	425	78.12	4.42 ± 0.62	418	1.68 ± 0.36	1.22	1.95	4.84
VANE13	602	112.54	4.49 ± 0.34	593	1.72 ± 0.21	8.74	16.09	32.37
VANE3	2394	98.78	0.99 ± 0.1	2159	0.23 ± 0.02	5.45	8.33	15.05
VANE6a	412	27.01	1.58 ± 0.13	396	0.6 ± 0.09	2.38	4.49	12.13
VANE6b	43	35.47	20.27 ± 7.39	43	8.77 ± 1.95	20.39	27.17	43.12
VANE7	64	27.13	10.34 ± 4.7	64	3.36 ± 1.07	2.38	3.93	8.74
VANE9	1127	134.24	2.86 ± 0.18	1071	1.34 ± 0.19	5.94	12.18	50.81

Table 6.10 GPS Tracking Summary EHPE of <20 m.

ID	Data points	Days tracked	Lag-time (hours)	Relocations	Motion Variance	90%	95%	99%
VANE1	1219	46.63	0.92 ± 0.06	1155	0.97 ± 0.23	1.55	2.05	3.13
VANE10	1368	78.91	1.39 ± 0.13	1290	2.02 ± 0.26	1.91	2.92	6.45
VANE13	1784	113.56	1.53 ± 0.08	1726	2.84 ± 0.25	7.33	11.78	23.79
VANE3	4504	98.9	0.53 ± 0.05	3885	0.26 ± 0.02	7.56	11.48	22.23
VANE6a	963	27.03	0.67 ± 0.04	900	1.08 ± 0.26	2.62	4.00	10.81
VANE6b	214	39.07	4.4 ± 0.76	214	6.67 ± 1.12	12.69	16.77	25.88
VANE7	252	42.31	4.05 ± 1.36	252	3.31 ± 0.65	2.23	3.18	6.09
VANE9	3208	134.24	1 ± 0.04	2915	1.77 ± 0.15	5.76	10.08	48.50

Table 6.11 GPS Tracking Summary EHPE of <25 m.

ID	Data points	Days tracked	Lag-time (hours)	Relocations	Motion Variance	90%	95%	99%
VANE1	2425	46.67	0.46 ± 0.02	2224	1.84 ± 0.73	2.05	2.61	3.83
VANE10	2872	79.09	0.66 ± 0.03	2616	3.06 ± 0.35	2.40	3.35	6.30
VANE13	3613	113.57	0.75 ± 0.03	3435	3.81 ± 0.34	8.19	13.09	27.93
VANE3	6309	98.91	0.38 ± 0.03	5399	0.47 ± 0.1	9.66	13.62	23.65
VANE6a	1660	27.07	0.39 ± 0.02	1524	1.09 ± 0.29	3.53	4.95	9.89
VANE6b	510	40.83	1.93 ± 0.25	509	16.28 ± 2.36	20.60	27.39	40.73
VANE7	582	42.31	1.75 ± 0.44	573	1.69 ± 0.32	3.09	4.04	6.39
VANE9	6224	134.27	0.52 ± 0.02	5438	3.64 ± 0.38	6.62	10.9	27.17

Table 6.12 GPS Tracking Summary EHPE of <30 m.

ID	Data points	Days tracked	Lag-time (hours)	Relocations	Motion Variance	90%	95%	99%
VANE1	3724	46.7	0.3 ± 0.01	3337	1.36 ± 0.43	2.57	3.23	4.70
VANE10	4484	79.16	0.42 ± 0.01	3977	2.12 ± 0.27	2.79	3.81	6.42
VANE13	5641	113.89	0.48 ± 0.02	5306	3.22 ± 0.3	8.81	13.33	26.36
VANE3	7824	98.91	0.3 ± 0.03	6713	0.61 ± 0.11	10.89	14.76	23.57
VANE6a	2356	27.23	0.28 ± 0.01	2150	1.6 ± 0.42	4.85	6.89	13.67
VANE6b	918	40.83	1.07 ± 0.11	916	12.6 ± 1.99	22.69	29.27	44.69
VANE7	984	42.31	1.03 ± 0.24	958	2.54 ± 0.41	3.31	4.40	7.01
VANE9	9171	134.27	0.35 ± 0.01	7858	3.58 ± 0.33	7.87	12.91	33.92

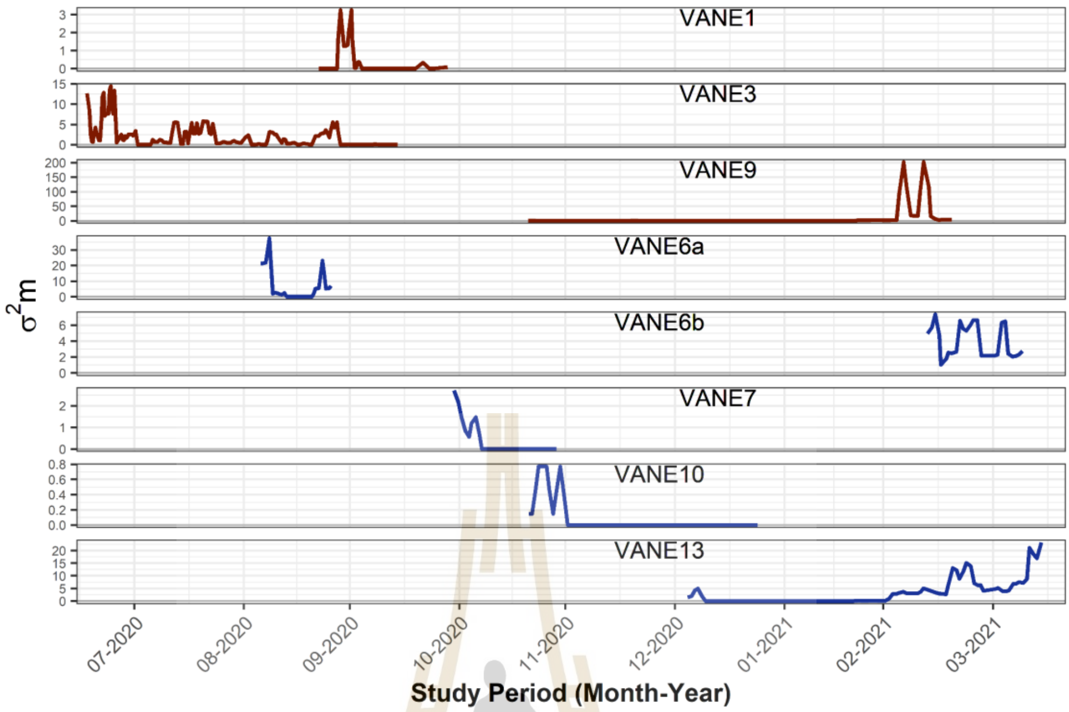

Figure 6.14 Motion Variance of VHF tracked lizards. Red graphs represent female and blue graphs represent male lizards.

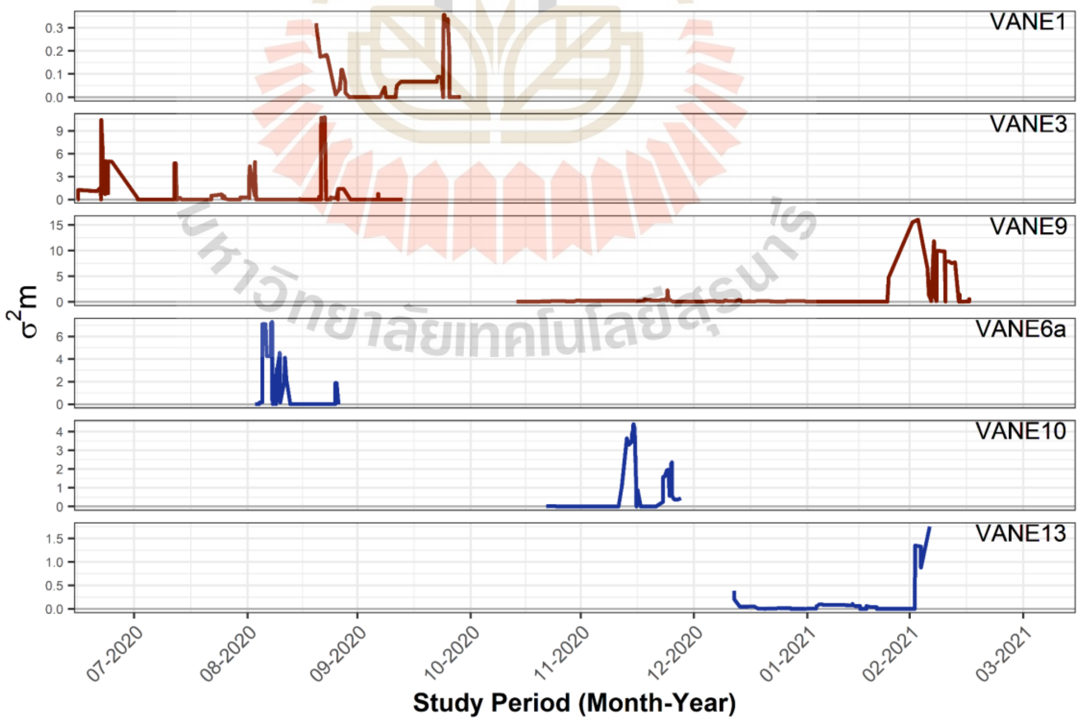

Figure 6.15 Motion Variance of GPS tracked lizards <10 m EHPE. Red graphs represent female and blue graphs represent male lizards.

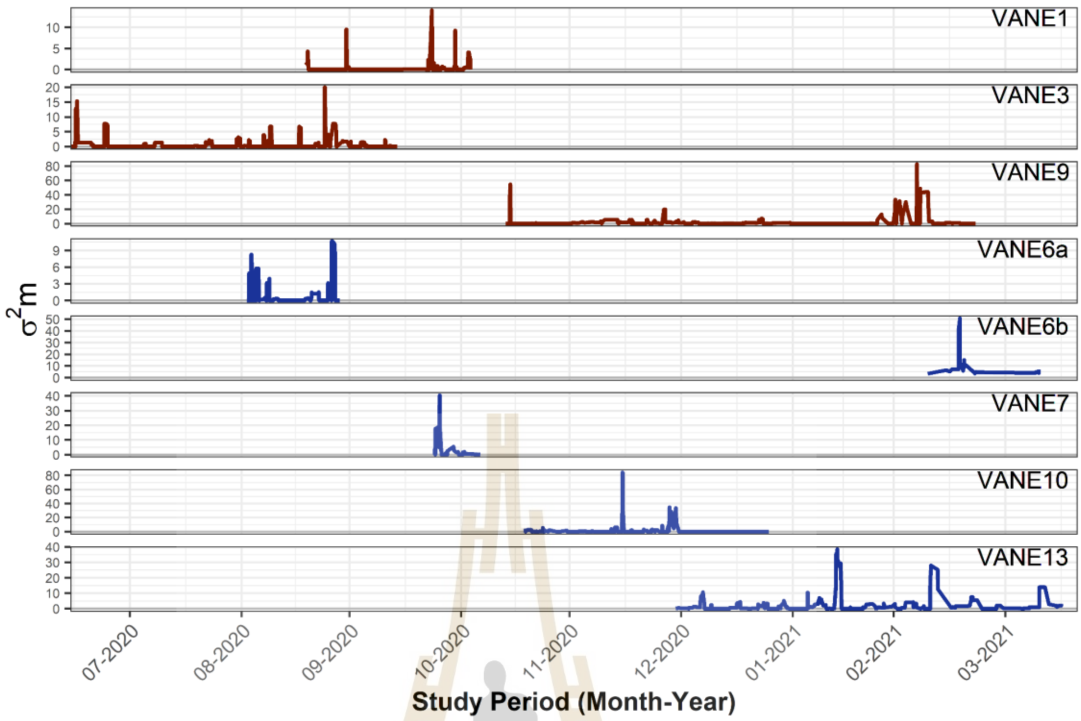

Figure 6.16 Motion Variance of GPS tracked lizards <15 m EHPE. Red graphs represent female and blue graphs represent male lizards.

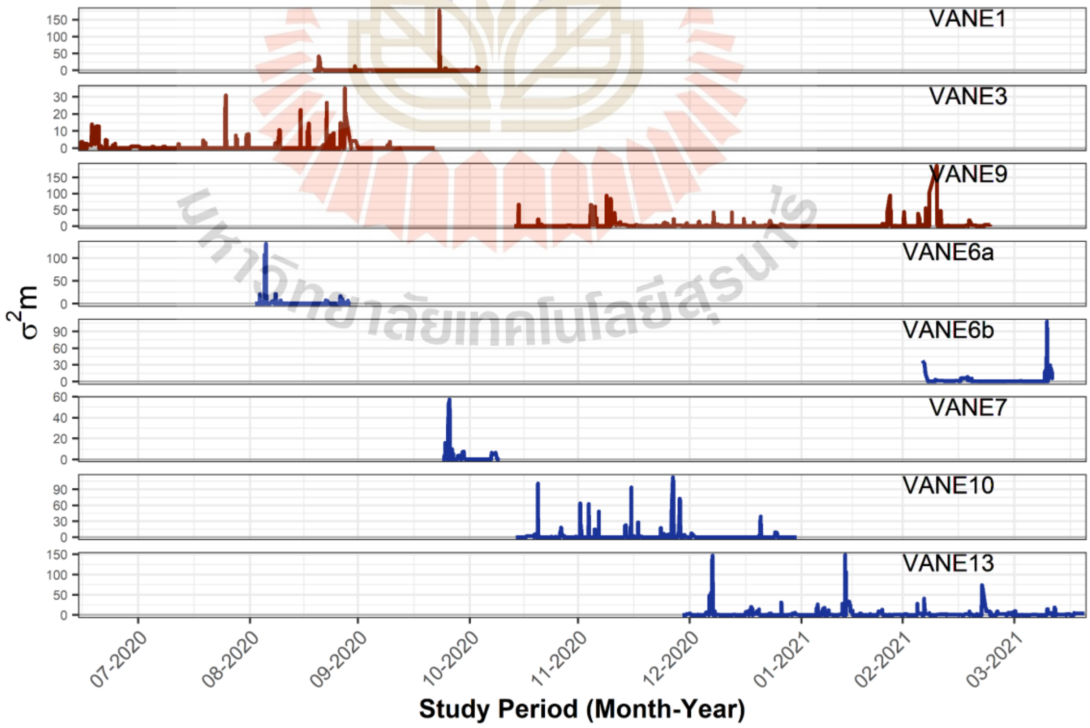

Figure 6.17 Motion Variance of GPS tracked lizards <20 m EHPE. Red graphs represent female and blue graphs represent male lizards.

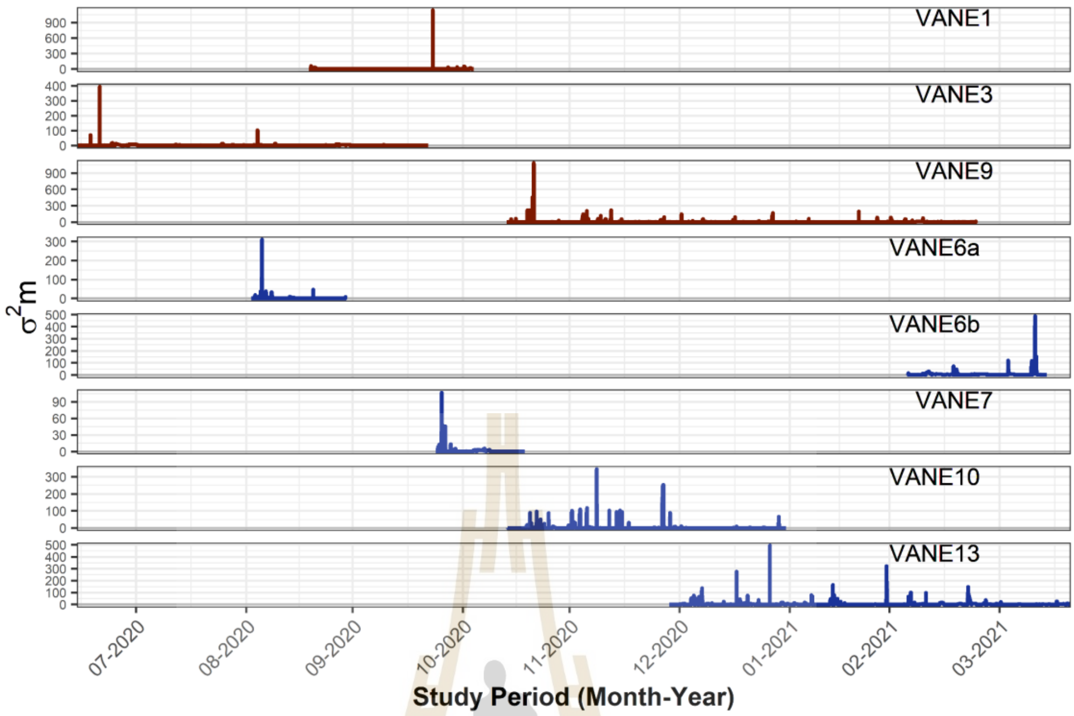

Figure 6.18 Motion Variance of GPS tracked lizards <25 m EHPE. Red graphs represent female and blue graphs represent male lizards.

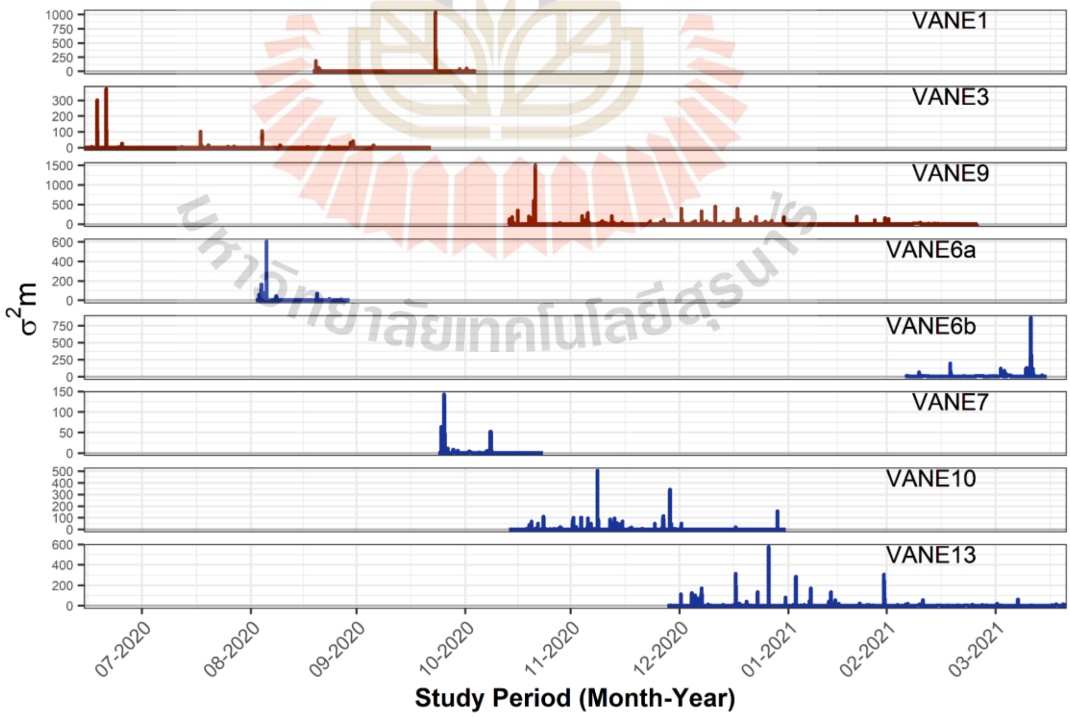

Figure 6.19 Motion Variance of GPS tracked lizards <30 m EHPE. Red graphs represent female and blue graphs represent male lizards.

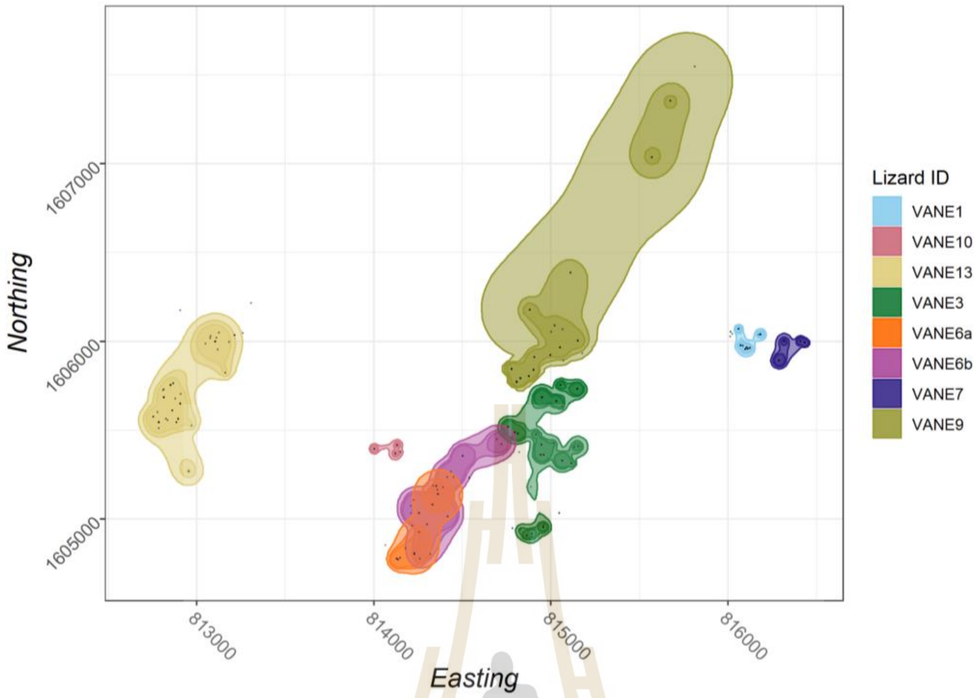

Figure 6.20 Total radio tracked monitor lizard occurrence distributions produced with VHF data.

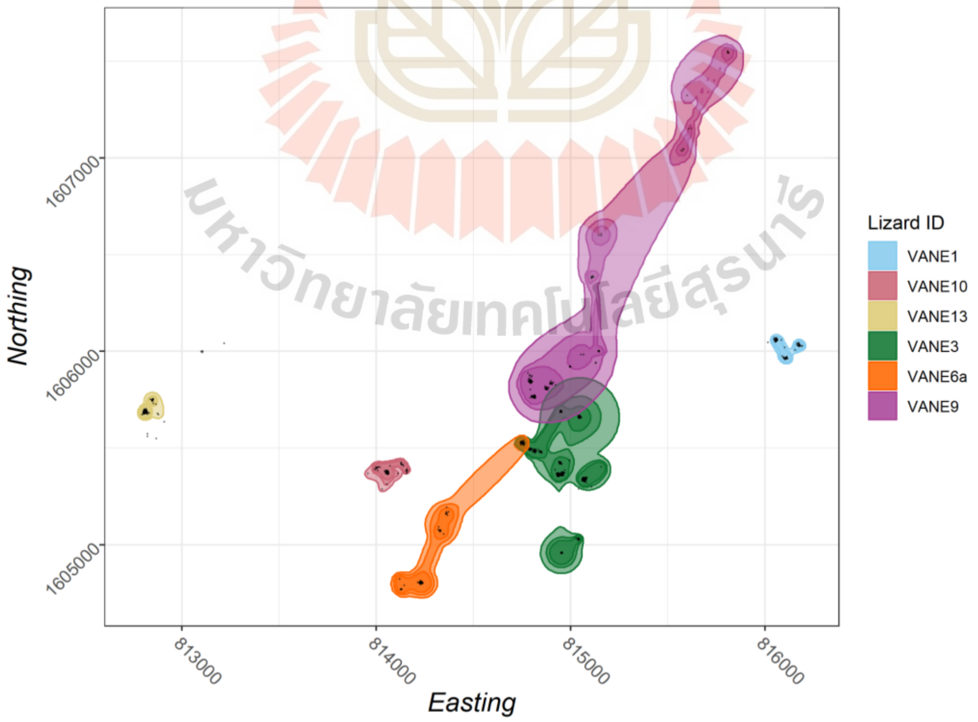

Figure 6.21 Total GPS tracked monitor lizard occurrence distributions produced with GPS <10 m EHPE data.

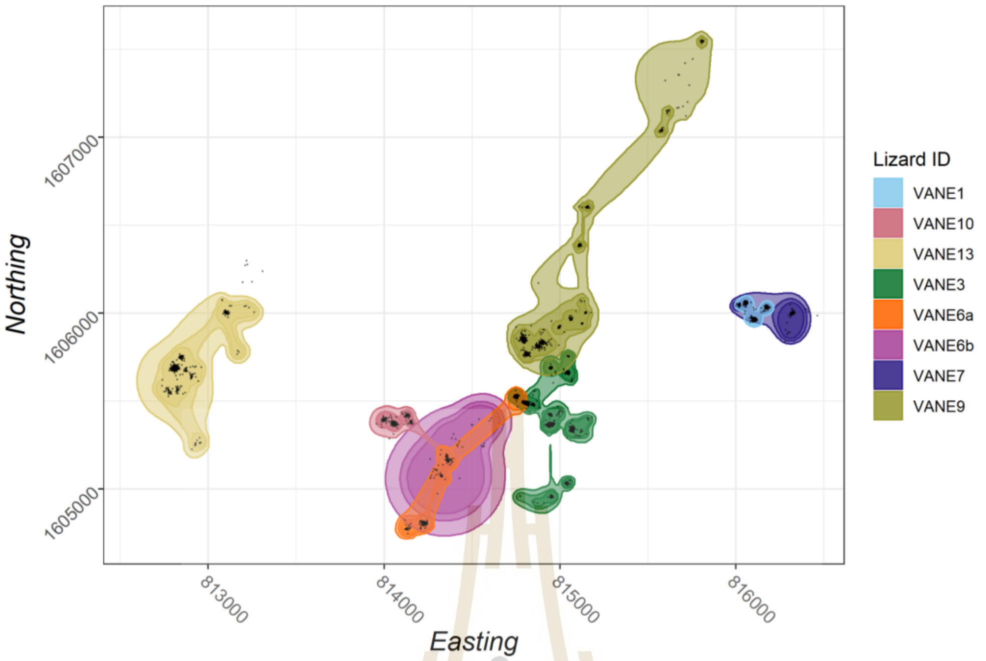

Figure 6.22 Total GPS tracked monitor lizard occurrence distributions produced with GPS <15 m EHPE data.

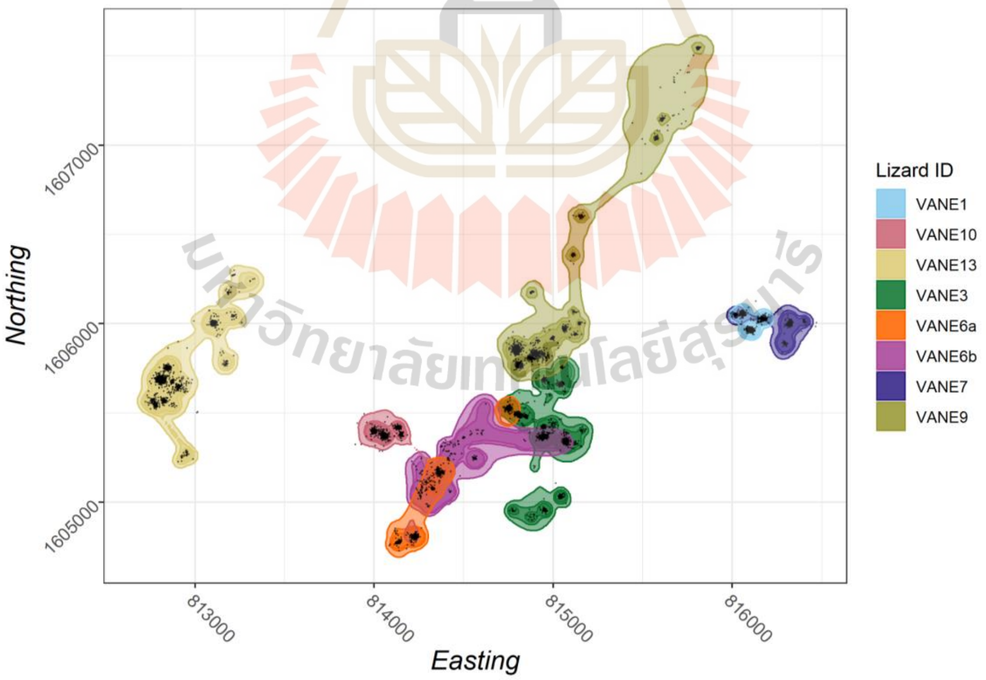

Figure 6.23 Total GPS tracked monitor lizard occurrence distributions produced with GPS <20 m EHPE data.

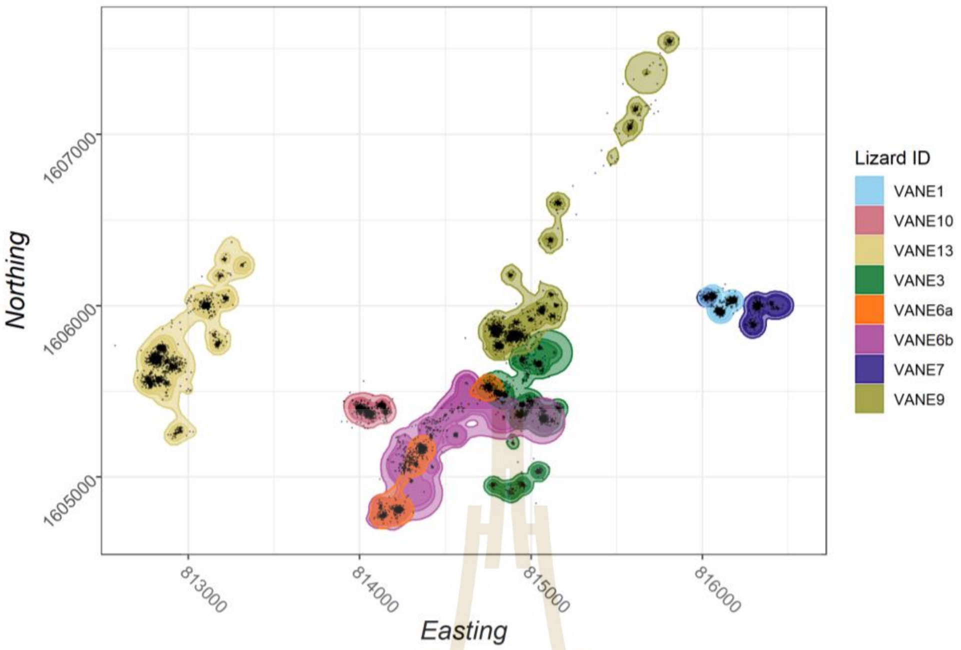

Figure 6.24 Total GPS tracked monitor lizard occurrence distributions produced with GPS <25 m EHPE data.

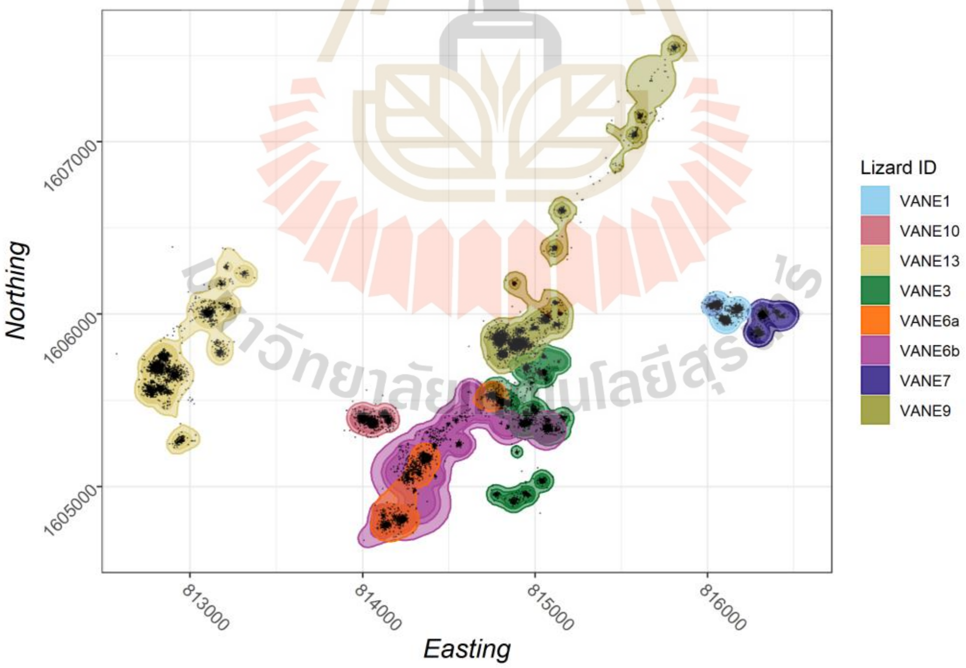

Figure 6.25 Total GPS tracked monitor lizard occurrence distributions produced with GPS <30 m EHPE data.

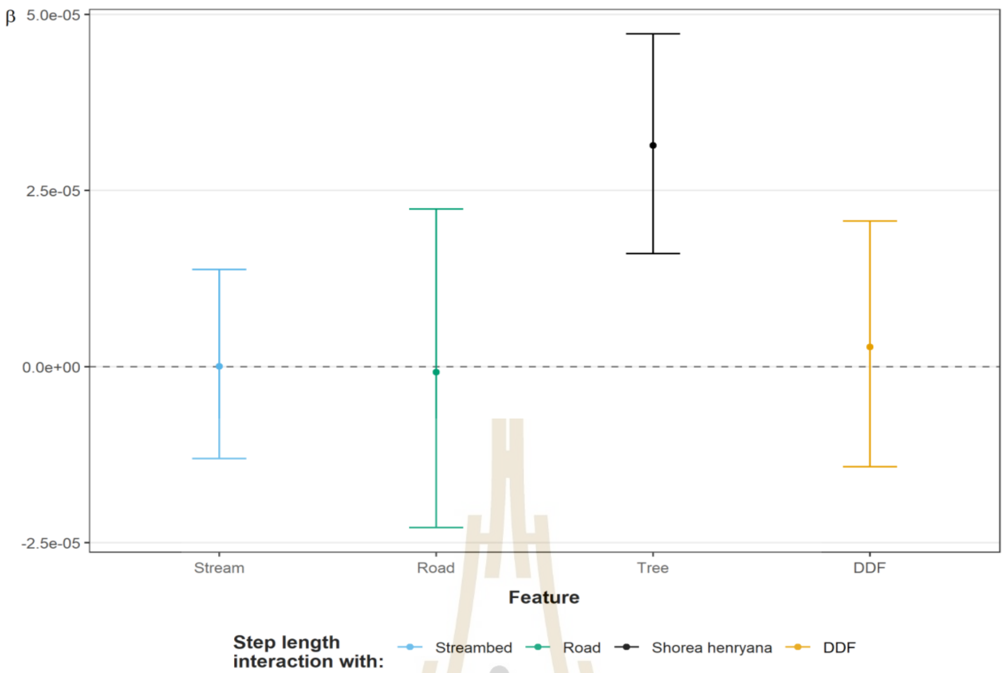

Figure 6.26 VHF derived population level ISSF.

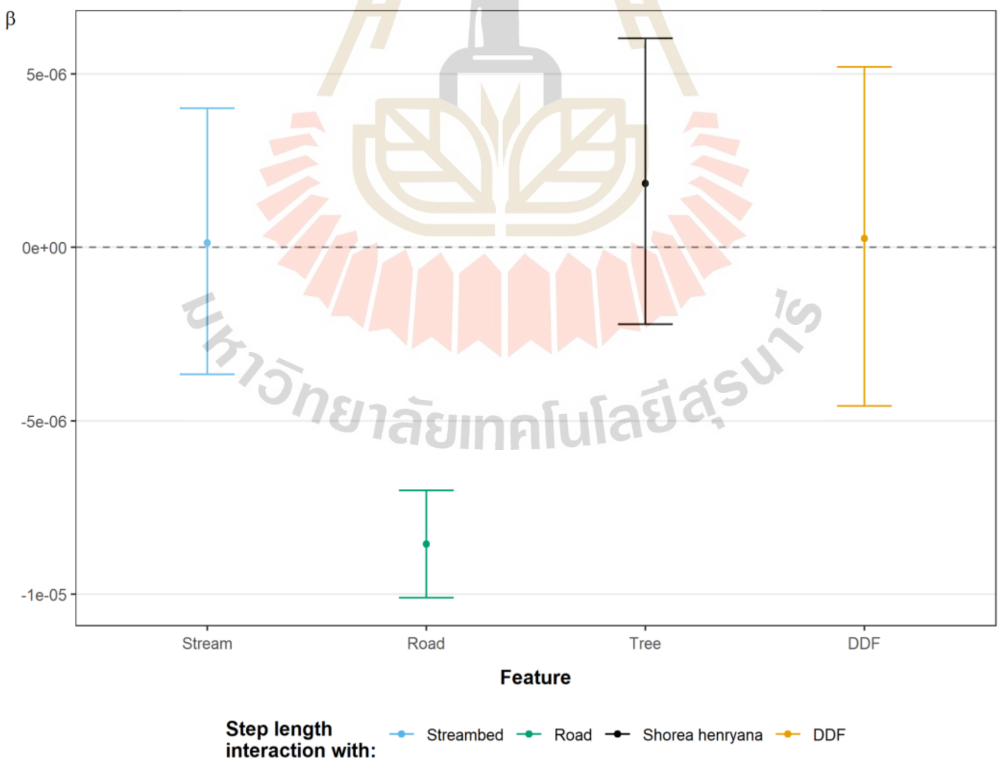

Figure 6.27 <10 m EHPE GPS derived individual level ISSF.

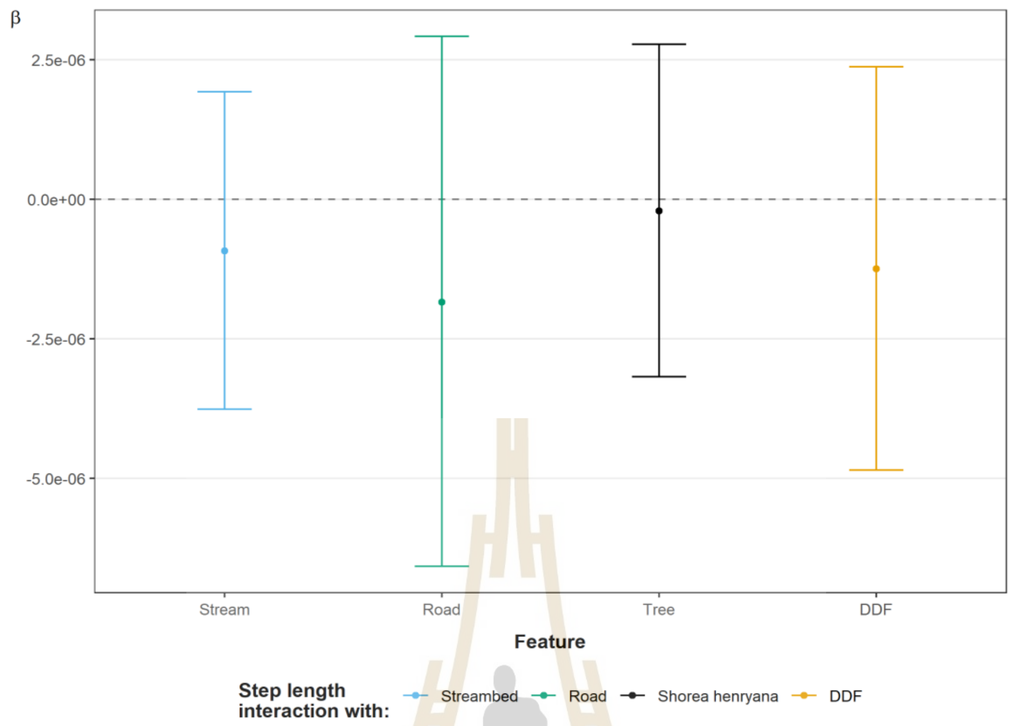

Figure 6.28 <15 m EHPE GPS derived individual level ISSF.

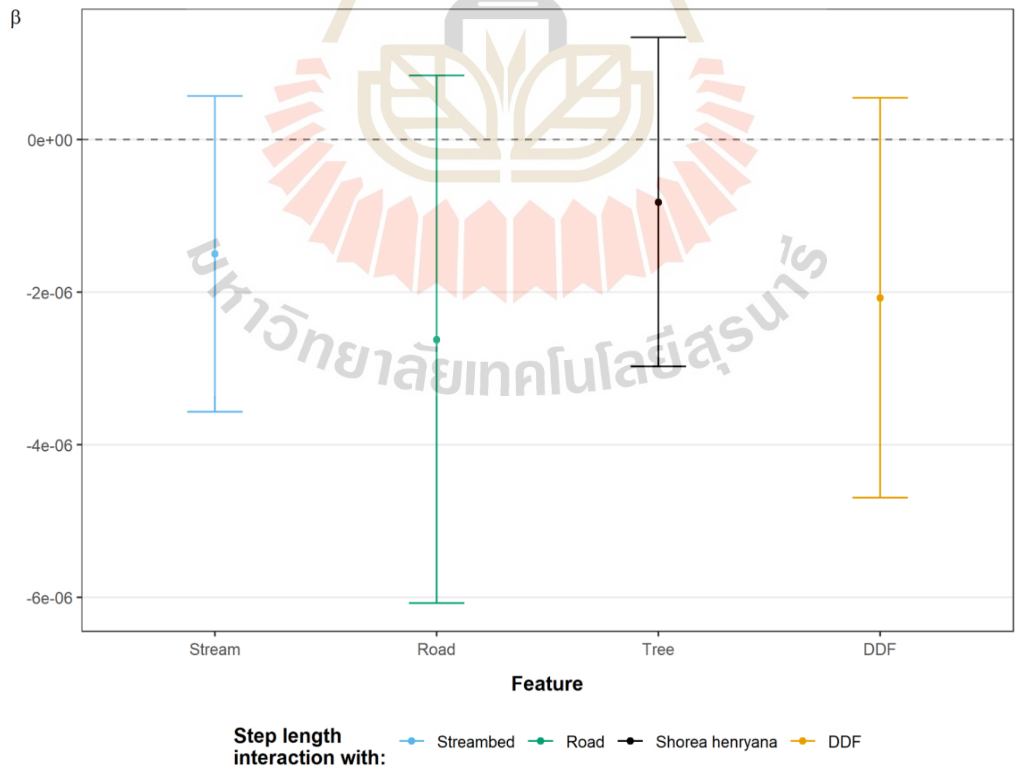

Figure 6.29 <20 m EHPE GPS derived individual level ISSF.

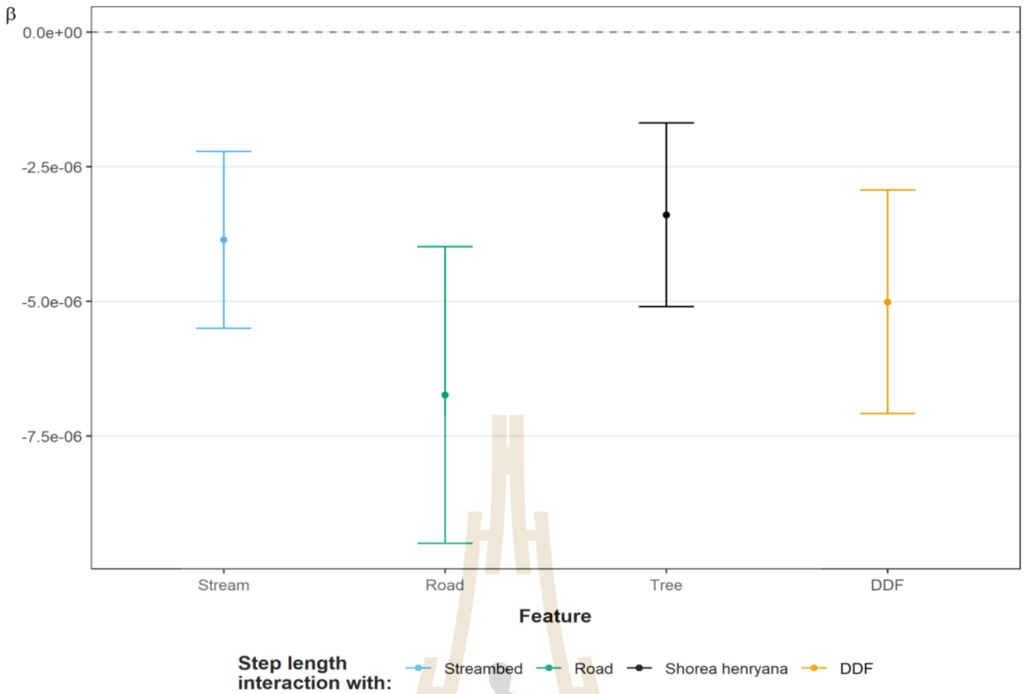

Figure 6.30 <25 m EHPE GPS derived individual level ISSF

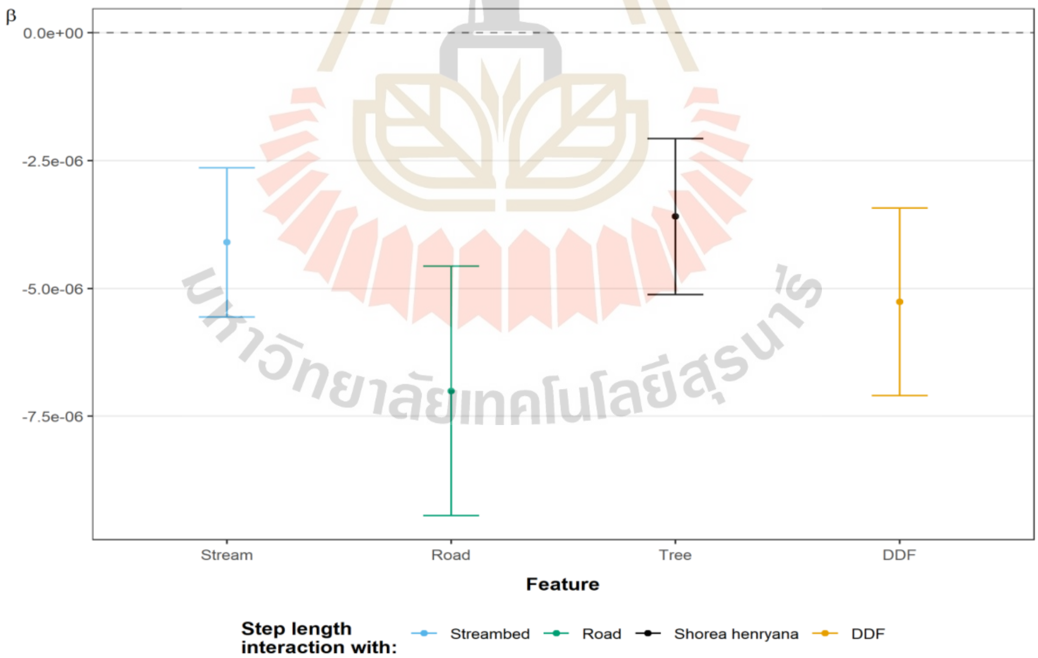

Figure 6.31 <30 m EHPE GPS derived individual level ISSF.

Table 6.13 Movement model selection and effective sample sizes (DOF area).

ID	AICc	dRMSPE (m)	DOF	Movement models
VANE1	0	35.60802	5.165658	OU anisotropic
VANE1	1.752933	26.48646	9.655393	OUF anisotropic
VANE1	41.81944	26.69298	3.980657	OU isotropic
VANE1	43.53405	16.70447	8.162023	OUF isotropic
VANE1	211.9835	5.064967	31.49241	OUf anisotropic
VANE1	225.6514	0	33.5931	Ouf isotropic
VANE1	7372.103	10.70874	140.9542	IID anisotropic
VANE10	0	80.70121	3.24198	OU anisotropic
VANE10	1.671917	54.45628	7.048955	OUF anisotropic
VANE10	86.11632	133.5017	2.425383	OU isotropic
VANE10	87.7387	89.8034	5.719368	OUF isotropic
VANE10	308.7104	7.556151	46.19862	Ouf anisotropic
VANE10	435.9706	19.35517	45.28546	Ouf isotropic
VANE10	7248.524	0	1367	IID anisotropic
VANE13	0	106.1249	6.202448	OUF anisotropic
VANE13	9.314854	110.3801	5.892872	OU anisotropic
VANE13	20.65138	114.366	6.030601	OUF isotropic
VANE13	24.54405	115.6722	5.906689	OU isotropic
VANE13	535.47	0	86.06203	Ouf anisotropic
VANE13	612.9245	9.793968	99.79136	Ouf isotropic
VANE3	0	86.61922	6.493115	OUF anisotropic
VANE3	6.652889	83.44639	6.698717	OUF isotropic
VANE3	176.6058	105.2273	4.247319	OU anisotropic
VANE3	178.5961	102.7228	4.326124	OU isotropic
VANE3	829.6622	0.218466	141.5143	Ouf isotropic
VANE3	830.4758	0	131.8878	Ouf anisotropic
VANE6a	0	207.2117	2.049407	OUF anisotropic
VANE6a	46.48016	257.8985	1.728466	OU anisotropic
VANE6a	88.09435	0	26.69257	Ouf anisotropic 1

Table 6.13 (Continued).

ID	AICc	dRMSPE (m)	DOF	Movement models
VANE6a	169.5499	315.3386	2.09865	OUF isotropic
VANE6a	197.1503	393.7318	1.630745	OU isotropic
VANE6a	245.9608	42.52066	25.6892	Ouf isotropic
VANE6b	0	138.0398	5.78516	OU isotropic
VANE6b	1.307333	137.1572	5.881982	OUF isotropic
VANE6b	4.55176	131.4026	5.741305	OUF anisotropic
VANE6b	116.4341	35.47484	40.51811	OUf isotropic
VANE6b	1418.614	0	213	IID isotropic
VANE7	0	41.62667	5.857272	OU isotropic
VANE7	1.846875	28.35177	9.530555	OUF isotropic
VANE7	5.73401	26.15529	9.23476	OUF anisotropic
VANE7	59.14707	0	24.48782	OUf isotropic
VANE7	1756.31	18.21504	251	IID isotropic
VANE9	0	89.76123	8.810572	OUF anisotropic
VANE9	123.9398	103.5201	7.147069	OU anisotropic
VANE9	329.5432	163.6956	6.934364	OUF isotropic
VANE9	396.9289	167.9464	6.200132	OU isotropic
VANE9	1057.628	0	146.3323	OUf anisotropic
VANE9	1577.195	30.13254	145.678	OUf isotropic

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Publications

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