Conservation of a socio-ecological system:
Indigenous hunting communities and bearded pigs in Malaysian Borneo

By

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Abstract

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In a telecoupled world, people and ecosystems are intricately linked across vast spatial scales. Consumption patterns, disease, and other factors on one side of the world often reverberate powerfully to shape landscapes, socio-cultural practices, and wildlife distributions in far-removed locales. These new realities require sustainability to be fundamentally achieved at global scales in order to have lasting sustainability for people and wildlife at local and regional systems. To consider these themes, my collaborators and I study a socio-ecological system of Indigenous hunting communities and bearded pigs, a cultural keystone species, in Malaysian Borneo. In Chapter 1, we build an intellectual framework that considers the ways that telecoupling unfolds in Sabah and Sarawak, driving oil palm expansion, deforestation, and social change. In Chapter 2, we carry out single-season, single-species occupancy models for bearded pigs that show the association of both socio-cultural factors (e.g. ethnicity and hunting accessibility) as well as environmental factors (e.g. protected area status and elevation) on bearded pig distributions across Malaysian Borneo. In Chapter 3, we document ways that oil palm plantations and urbanization have changed bearded pig hunting practices among Indigenous Kadazandusun-Murut (KDM) hunters in Sandakan District, Sabah. We also describe the ways that some hunting motivations, such as meat provision and gift-giving, have endured despite widespread changes in land-use. In Chapter 4, we investigate intergenerational hunting knowledge transfer within KDM hunting communities, also in Sandakan District, Sabah. Almost two-thirds of respondents had not, or were not intending, to pass on their hunting knowledge to their children. Moreover, many respondents reported low hunting interest among the younger generation, suggesting diminished importance of hunting practices in the future among KDM communities in Sabah. Together, our findings highlight the salience of social practices and Indigenous knowledge for bearded pig distributions in Malaysian Borneo. Our results also raise important questions about the nature of conservation values and human-wildlife interactions in a world in which hunting practices, and connection to nature more broadly, are in decline. Ancient socio-ecological links—including hunting, recreation, and other social practices—highlight profound connection points for long-term sustainability of human cultures, biophysical landscapes, and wildlife communities.

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Chapter 1. Introduction

LIFE IN A TELECOUPLED WORLD

Life is complex in our globalized world. Humans and other organisms exist on a planet that is increasingly "telecoupled", or connected across large scales of space, economies, environments, and systems (Liu et al. 2013). Telecouplings include forces such as disease, trade, tourism, migration, technology transfer, and transnational land deals (Hull & Liu 2018). Socio-ecological processes in one location can be mediated by institutional and governance forces that shape land use in another location (Eakin et al. 2014). For example, many Vietnamese workers tap rubber trees in Laos and send a portion of their income back to Vietnam, representing a significant transnational telecoupling relationship (Baird & Fox 2015). Multi-layered telecoupling relationships also stretch across continents, such as the complex foreign aid relationships between countries such as Japan and Finland with social-hydrological relationships in rural Ethiopia (Chignell & Laituri 2016). Telecoupling relationships also link local wildlife to global markets, such as through tourism that draws visitors from Europe and Asia to the Beagle Channel in Argentina to see charismatic seabirds (Raya Rey et al. 2017). Lessons from telecoupling remind us that traditional boundaries are more fluid than ever, and that sustainability fundamentally exists not at local or regional delineations but at the global scale (Hull & Liu 2018). Nowhere have these boundaries transformed more quickly than in Malaysian Borneo.

PALM OIL MARKETS, LAND-USE CHANGE, AND SOCIO-CULTURAL PRACTICES IN MALAYSIAN BORNEO

Sabah and Sarawak, which together comprise Malaysian Borneo, are characterized by the lowland and hill rainforests that stretch across their landscapes (Gaveau et al. 2014). These forests are rich in terrestrial biodiversity across many taxa (Newberry et al. 1992, Momose et al. 1998, Chung et al. 2000, Hamer et al. 2005, Bernard et al. 2013, Evans et al. 2016, Mohd-Azlan 2018, Samejima & Hon 2020). In parts of Sarawak, soil and topographic variation support some of the most diverse tree communities in the Old World (Lee et al. 2002, Ashton 2005, Ashton 2010). Tree communities play an important role in driving ecological processes in Borneo, not only due to their role in niche differentiation but also due to El Niño-related droughts that lead to mast fruiting events (Curran et al. 2004). Mast fruiting events, in turn, create resource pulses that influence the movement, foraging, and reproduction of a number of vertebrate species, such as the Bornean crested fireback (*Lophura ignita*) and bearded pig (*Sus barbatus*) (Curran & Leighton 2000, Granados et al. 2019).

Within the context of this ecological backdrop, a telecoupling relationship between regional land-use change and transnational palm oil markets has led to large-scale environmental transformation in Malaysian Borneo. Telecoupling is a relatively recent framework that considers "flows of information, energy, matter, people, organisms, and other things such as financial capital and goods and products around the globe" (Hull & Liu 2018). Global demand for palm oil, led by India, China, and the European Union, has created an immense market for palm oil production in Malaysia (USDA 2021). As a result, plantation industries—led by oil palm plantation expansion—have been the leading driver of deforestation in Malaysian Borneo

between 1973-2017 (Gaveau et al. 2016, Gaveau et al. 2019). Gaveau et al. (2016) documented 57-60% conversion of forest loss to industrial plantations (mainly oil palm) in Malaysian Borneo between 1973-2015. Forest loss has been particularly high in lowland areas (here defined as < 1000 m elevation), with over 21,000 km² of lowland forest lost in both Sabah and Sarawak between 1973-2010 (Gaveau et al. 2014). Due to extensive land-use change over the last several decades, the dominant land cover types in Sabah and Sarawak today are intact forest, logged forest, and industrial plantations (primarily oil palm, but also acacia and rubber) (Gaveau et al. 2014, Gaveau et al. 2016).

Figure 1. Forest cleared for oil palm expansion in Sarawak, Malaysian Borneo.
Photo by: Mattias A Klum / National Geographic. Photo used with written permission from the photographer.

Biodiversity losses due to oil palm expansion are well-documented, providing clear evidence that oil palm plantations support fewer species than forests for a variety of taxa (Fitzherbert et al. 2008, Brühl & Eltz 2010, Fayle et al. 2010, Edwards et al. 2010, Aguilar Leon 2020). In addition to species loss, there is also evidence that oil palm plantations reduce food chain length as compared to forests, with important implications for trophic ecology (Wilkinson et al. 2021). Given these profound ecological and conservation impacts, increasing attention is focused on the biodiversity implications of oil palm expansion as it moves across the tropics and takes hold in Africa and Latin America (Prescott et al. 2016, Alonso-Rodríguez et al. 2017, Payán & Boron 2019). While the repercussions of oil palm expansion across the globe are appropriately under scrutiny for biodiversity and other biophysical patterns, much less attention has been given to the influences of oil palm on socio-cultural factors. Some studies

have examined the implications of oil palm for socio-economic outcomes (e.g., Rist. et al. 2010, Lee et al. 2020, Santika et al. 2021); however, less commonly investigated are the associations between the biophysical dimensions of oil palm expansion and socio-cultural practices (e.g. hunting, medicinal plant use, recreation, etc.) associated with oil palm-driven changes in land use, labor, and law. Telecoupling dynamics—such as disease, tourism, and transnational certification (Hull & Liu 2018)—may be linked to oil palm expansion, raising important questions about how oil palm shapes not only biophysical landscapes across the tropics, but also socio-cultural landscapes. As greater insights are put forward on the connections between environmental and social dynamics (Brashares et al. 2014, Kremen & Merenlender 2018, Gould et al. 2020), more tools and lenses are available to connect oil palm to social processes.

Borneo is an optimal stage on which to observe land-use change connections to social processes. Home to dozens of Indigenous groups with unique languages and cultural practices (Sillander 2016, Wan et al. 2015), and at a confluence of global commodity supply chains for palm oil and timber (Brookfield et al. 1995, Alonso-Fradejas et al. 2016), Borneo is at the epicenter of land-use effects on social identity and cultural practices. Land grabs by powerful state and corporate actors have diminished the traditional land and resources for agriculture or hunting, pushing many Indigenous peoples to urbanizing city centers (Bernard & Bissonnette 2011, Cooke 2012, Kurz et al. in review). At the same time, for those who stay in rural areas, new pressures and incentives to participate in a contemporary cash economy can lead to unsustainable hunting or collection of forest products (Bennett et al. 2000). As an inherently social, economic, and political process (Vásquez-León & Liverman 2004), land-use change powerfully shapes, and poses vital questions about, accompanying socio-cultural landscape transformations.

DISSERTATION OVERVIEW

This chapter has presented a theoretical framework that I will draw on throughout the dissertation. In Chapter 2, I will introduce social and environmental factors that are associated with bearded pig distributions across Malaysian Borneo. To do this, I draw on camera data collected by collaborators at 17 field sites across the Malaysian states of Sabah and Sarawak. These sites form a montage of habitats typical of this region - primary lowland forest, primary hill forest, degraded forest, and oil palm plantations (Gaveau et al. 2014, Gaveau et al. 2016). I link bearded pig detections from these sites with a range of social and environmental covariates to quantify their associations with bearded pig distributions. The salience of both social and ecological influences on bearded pig occupancy highlights the importance of context-specific wildlife management policies in Sabah and Sarawak. An integrated management approach is particularly critical for bearded pig recovery from the African Swine Fever outbreak that has swept through at least 10 of Sabah's districts in 2021.

In Chapter 3, I narrow my geographical scope to explore in greater depth some of the socio-cultural influences of hunting practices on bearded pig distributions. Specifically, I examine pig hunting practices among the Kadazandusun-Murut (KDM) community, the most numerous Indigneous ethnic umbrella in Sabah. To explore KDM-bearded pig interactions, I use data that collaborators and I collected from KDM hunters in Sandakan District, Sabah, which is in many

ways a microcosm of the powerful influences of oil palm expansion and urbanization that are reshaping socio-ecological interactions across Malaysian Borneo. I qualitatively and quantitatively explore themes that emerged from 38 semi-structured interviews with former or active KDM pig hunters. Specifically, I examine how hunting motivations, hunting practices, meat consumption, and other factors have transformed or endured amidst patterns of oil palm expansion and urbanization. As in Chapter 2, I recommend context-specific management policies that integrate social and dietary needs of KDM communities while also maintaining sustainable bearded pig populations.

In Chapter 4, I work with the same dataset as in Chapter 3, but again narrow my focus to investigate potential future dynamics in the pig-people socio-ecological relationship, through the lens of intergenerational hunting knowledge transfer in KDM communities. Specifically, I examine the relational dynamics, modes, and recurrence of intergenerational hunting instruction in terms of their own experiences, as well as the values associated, or not, with hunting by the younger generation. I also place these changes in context of the recent outbreak of African Swine Fever (ASF) in Sabah, and discuss the potential for ASF to accelerate the loss of Traditional Ecological Knowledge in KDM communities. Finally, I recommend ways that wildlife managers in Sabah can include participation from KDM youth and protect sustainable offtake of bearded pigs for KDM communities, to preserve biocultural conservation dimensions in a post-ASF bearded pig recovery.

In Chapter 5, I draw out broad implications of Chapter 2-4, synthesizing themes that have emerged across each analysis. Additionally, I connect these themes to frameworks and ideas introduced in Chapter 1, resolving intellectual threads while also proposing novel avenues for future research.

My hope is that this dissertation will clarify links between socio-cultural and biophysical landscapes not only in Malaysian Borneo, but also more broadly around the world. The reciprocal relationships that, and their best, sustainably bind human societies to ecosystems are also connected to the relationships that unite us with one another as humans, within our intricate, transforming, astonishingly created natural home.

Chapter 2. Socio-ecological factors shape the distribution of a cultural keystone species (bearded pig, *Sus barbatus*) in Malaysian Borneo

ABSTRACT

Biophysical and socio-cultural factors have jointly shaped the distribution of global biodiversity, yet relatively few case studies have quantitatively assessed the relative influence of each of these types of influences for a given system or species. The extent to which socio-cultural factors (e.g., value systems, recreation, natural resource use) shape wildlife distributions holds important implications for ecological theory as well as for wildlife management. Drawing on a dataset of 321 total camera traps across 17 field sites in Sabah and Sarawak, Malaysian Borneo, we fit three single-year, single-species occupancy models, incorporating three socio-cultural covariates and six environmental covariates, to identify the factors most strongly correlated with the occupancy of the bearded pig, a cultural keystone species currently undergoing local extinctions in Sabah, Malaysia due to African Swine Fever (hereafter, ASF). Top models for each of the three years included socio-cultural covariates, and the top models for two of the three years included a mix of socio-cultural and environmental covariates. Predicted average probability of occupancy (psi$\pm$SE) for bearded pigs across study sites was 0.85$\pm$0.05 in 2010, 0.66$\pm$0.10 in 2012, and 0.71$\pm$0.08 in 2014. Taken together, these results suggest that context-specific management of bearded pig populations, considering regional racial-ethnic composition, hunting accessibility, and environmental characteristics, is required in Malaysian Borneo. Our results also provide an important baseline of predicted bearded pig site-use from data collected before the outbreak of African Swine Fever, which spread quickly throughout much of Sabah in 2021 and has caused local bearded pig extinctions in some areas. More broadly, our results provide quantitative evidence highlighting the importance of multiple dimensions of socio-ecological systems for understanding factors that influence wildlife distributions.

INTRODUCTION

A deeper understanding of the dynamics linking human cultural practices and wildlife is fundamental to a more nuanced understanding of the overlaps between socio-cultural and biophysical landscapes. Such knowledge is essential for sustainable management of socio-ecological systems that accommodate both human needs and wildlife persistence (Kays et al. 2016). Socio-cultural factors influencing wildlife distributions have been analyzed in a less quantitative manner compared to biophysical factors. Yet, countless socio-cultural factors—such as ethnic identity, culturally-distinctive hunting practices, armed conflict, recreation, feasts, traditions, and value systems—have been shown to have far-reaching implications for wildlife distributions and conservation efforts (e.g., Heberlein & Ericsson 2006, Wong et al. 2009, Riley 2010, Gaynor et al. 2016, Kurz et al. in review). As such, social and cultural affinities, tolerances, and other biases require more attention as important predictor variables, alongside ecological variables, for determining wildlife occurrence (Karanth et al. 2009). A primary challenge has been to incorporate these types of factors in a quantitative manner. Recently, these covariates have begun to move beyond broader indices of human disturbance or footprint (e.g. Barber-Meyer et al. 2013, Linkie et al. 2013) to include more nuanced, culturally-

shaped metrics, such as hunting accessibility, social carrying capacity for development, or religious practices (e.g., Bettigole et al. 2014, Stahlecker et al. 2017, Deith & Brodie 2020).

While the availability of new, more sensitive socio-ecological metrics are increasing, few robust case studies have leveraged the social and environmental data needed to quantify their relative influence on species distributions. Moreover, presence-absence data are needed from species that are feasible to detect, which often (although not always) favors larger-bodied species. As a result, the dependent variable in case studies to date has been estimated occupancy values for large, charismatic mammals or birds (e.g. Karanth et al. 2009, Stahlecker et al. 2017). These species are often readily observable with camera traps (O'Brien & Kinnaird 2011) or other forms of surveying, and also frequently hold special importance to a wide range of cultural groups (Clucas et al. 2008, Festa-Bianchet 2017).

The bearded pig, *Sus barbatus*, is an ideal species to such an occupancy modeling effort that considers social and ecological covariates. The species is adaptable to a variety of habitat types, including multiple forest types, mixed-use landscapes, and elevational gradients (Love et al. 2018, Luskin & Ke 2017, Davison et al. 2019), allowing for comparisons across a gradient of ecological features. In Borneo, which forms the bulk of its range (Ke & Luskin 2019), the bearded pig is also the most favored terrestrial game species for non-Muslim indigenous groups, accounting for 54-97% of wild meat in these communities (Bennett et al. 2000, Chin 2001, Puri 2005). The species also plays a central role in a variety of Indigenous ceremonial practices and celebrations (Janowski 2014). Additionally, high detection rates have been reported for bearded pigs (Bernard et al. 2013, Mohd-Azlan et al. 2019), making existing data well-suited for occupancy modeling. [However, given the long-distance movements for which the bearded pig is known (Caldecott & Caldecott 1985), detections of bearded pigs at adjacent cameras cannot be considered independent, as individual animals are likely to be detected on multiple cameras. Therefore, occupancy model results should be interpreted as site use intensities (Mills et al. 2020).] Finally, as the bearded pig is an IUCN-listed Vulnerable species (Luskin et al. 2017), it is important to understand the ecological and social correlates of pig distributions in order to develop plans for sustainable management.

Here, we integrate socio-cultural and environmental covariates to quantify their collective influence on the distribution of a cultural keystone species, the bearded pig. Specifically, we compile socio-cultural covariates, collected from published datasets, and environmental covariates, collected from the Earth Engine Data Catalog, across a range of sites in Malaysian Borneo. We determine the best-fitting single-season occupancy models across different sets of sites for three study years when large amounts of camera data were opportunistically available (2010, 2012, and 2014), and compare the prevalence of socio-cultural and ecological correlates in top models. Using these results, although our analysis is not set up as a change-over-time study, we broadly discuss results across years. We use our top model for 2014 to model occupancy for some of the primary land cover types characteristic of Malaysian Borneo: large protected areas with intact primary forest, fragmented areas with secondary forest, and oil palm plantations. We also estimate average bearded pig occupancy values for each year and describe patterns in occupancy estimates.

Our results show the salience of socio-cultural factors for bearded pig distributions in all top models, as well as the influence of environmental factors in most top models. Our findings also provide area-specific baseline information of bearded pig occupancies before the outbreak of African Swine Fever in Sabah in 2021. Taken together, we discuss the implications of these findings for management of this ecologically dominant, socially central game species in Borneo. We also discuss the broader significance of quantifying social, cultural, and ecological covariates and understanding their importance in shaping wildlife distributions.

METHODS

Study region and data collection

We opportunistically collated bearded pig detections from 18 camera trap surveys conducted in 2010, 2012, and 2014 across the Malaysian Bornean states of Sabah and Sarawak (Figure 1). These surveys consisted of a total of 321 cameras, accounting for 38,017 camera days and 3,613 bearded pig detections. Original camera surveys were designed for multi-species mammal detections and were therefore suitable for detecting bearded pigs, one of the most common mammals in many camera surveys (e.g. Bernard et al. 2013, Mohd-Azlan et al. 2019). Within each year, we spatially filtered camera locations to ensure at least 1km between camera stations. Some studies used paired cameras at each sampling location; for these datasets, we used a random number generator to randomly select one camera from the pair (i.e., "A" or "B") for our analysis.

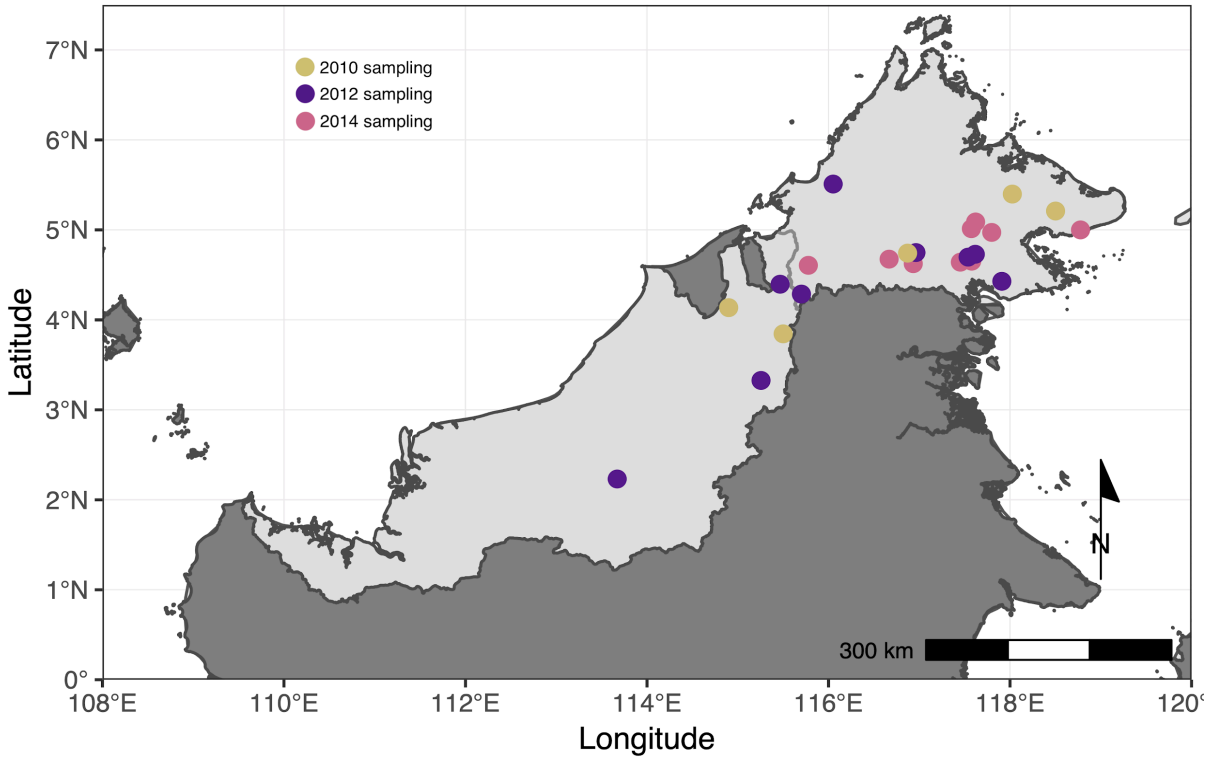

Figure 1. Location of 17 wildlife camera surveys conducted in 2010, 2012, and 2014.

Camera trap surveys were carried out within protected areas (e.g. state parks, national parks, protection forest reserves, wildlife sanctuaries, virgin jungle reserves) and non-protected areas (e.g. forest remnants, oil palm plantations). Human hunting pressure across the study area varied considerably, and our survey data included low and high hunting accessibility areas (Deith & Brodie 2020). Camera trap surveys were carried out across primary forest (lowland and montane), previously logged secondary forest (lowland and montane), and closed-canopy oil palm plantations (Miettinen et al. 2012). Together these habitat types make up the vast majority of non-urban land cover in Sabah and Sarawak (Miettinen et al. 2016).

Occupancy modeling approach

We chose covariates that we hypothesized would be strong predictors of bearded pig occupancy (Table 1). We removed highly correlated continuous covariates until Pearson's correlation among all pairs showed r coefficients of less than 0.7 (Zuur et al. 2009, R Core Team 2019). Environmental covariates were extracted using data sources in the Earth Engine Data Catalog. The environmental covariates included were: distance to water, distance to forest edge, protected area status, elevation, slope, and tree cover (Table 1).

Table 1. Social and ecological covariates included in occupancy models.

Model covariate	Hypothesized relationship Occupancy
Hunting accessibility	—
KDM or Iban Indigenous Racial-ethnic group	—
Hunting accessibility*Racial-ethnic group	—
Distance to water	—
Distance to forest edge	+
Protected area status	+
Elevation	+
Slope	—
Tree cover	+

For the social covariate of racial-ethnic group, we used published census data to calculate the proportion of the total district population composed of the predominantly Christian, bearded pig hunting ethnic group in each state: the Kadazandusun-Murut peoples in Sabah and the Iban peoples in Sarawak (Bennett et al. 2000, Malaysian Department of Statistics 2011, Kurz et al. in review). To incorporate hunting accessibility into our models, we used a published hunting accessibility value that estimates hunting pressure across Malaysian Borneo at 90m spatial resolution, based on fine-scale habitat complexity and hunter densities (Deith & Brodie 2020). While our hunting accessibility metric accounts for the relative human population in a given

area (Deith & Brodie 2020), it is unable to capture the proportion of the local population engaging in hunting in that area. By including the proportion of Indigenous pig-hunting population in each district (including the interaction between this proportion and hunting accessibility), we attempted to incorporate the influence of local pig-hunting cultural practices into our models. The social covariates included in the models were: hunting accessibility, proportion of population of predominant pig hunting ethnic group, and the interaction of the two (Table 1).

We studied a focal species of interest (the bearded pig) using a collection of opportunistic camera data from different geographic areas and timeframes (i.e., few multi-season studies at the same locations). We carried out single-species, single-season occupancy models for 2010, 2012, and 2014 (Davidson 2020). As bearded pigs are known to make long-range movements (Curran & Leighton 2000, Luskin and Ke 2018), we did not consider pig detections at adjacent cameras to be independent. Therefore, models are reflective of intensities of pig site use rather than true occupancy and should be interpreted as such (sensu Mills et al. 2020). We ran models using the package 'unmarked' (Fiske & Chandler 2011) in R version 3.6.0 (R Core Team 2019). We then used the 'dredge' function (Bartoń 2009) in R version 3.6.0 to identify top models (R Core Team 2019). We assumed population closure for each occupied site over the course of the sampling year (Rota et al. 2009). Top models were determined using Akaike's Information Criterion, and models within a delta AIC of 2 were considered to be competing models (Ainley et al. 2006). In addition to obtaining the estimated occupancy across our study areas from the occupancy model, we used the top model in 2014 to predict bearded pig occupancy across all of Sabah and Sarawak.

RESULTS

Estimated occupancy and detection of bearded pigs across study area

Our results suggest a high occupancy by bearded pigs across most forested areas studied in Sabah and Sarawak. Predicted average bearded pig occupancy (psi$\pm$SE) across study areas included in occupancy models was 0.85$\pm$0.05 in 2010, 0.66$\pm$0.10 in 2012, and 0.71$\pm$0.08 in 2014. Estimated bearded pig detection probability (p$\pm$SE) during a 7-day survey period was 0.43$\pm$0.01 in 2010, 0.29$\pm$0.01 in 2012, and 0.36$\pm$0.02 in 2014. The areas with the highest predicted bearded pig occupancy were the Lower Kinabatangan Wildlife Sanctuary, Sabah (0.91$\pm$0.04), Maliau Basin Conservation Area, Sabah (0.93$\pm$0.04), Tawau Hills Park, Sabah (0.92$\pm$0.05), and Pulong Tau National Park, Sarawak (0.95$\pm$0.05). With the exception of the Lower Kinabatangan Wildlife Sanctuary, (which is highly fragmented and mainly surrounded by oil palm plantations), these areas of high pig occupancy are all large, protected continuous forest blocks. The areas with the lowest predicted bearded pig site usage were Crocker Range National Park, Sabah (0.50$\pm$0.10), Gunung Mulu National Park, Sarawak (0.44$\pm$0.15), forest surrounding Sapulut, Sabah (0.27$\pm$0.12), and forest surrounding Ulu Temburong National Park, Sarawak (0.55$\pm$0.10) (note: national park location in Brunei, but surrounding forest in Sarawak). Two of these areas are large protected areas at substantial elevation (exceeding 1000 m in parts) and two are unprotected forests near villages. Predicted occupancy values for the top model in 2014, extrapolated across Sabah and Sarawak, were high for most areas (Figure 2).

Socio-cultural and environmental factors associated with bearded pig site use

For each year analyzed, both socio-cultural and environmental covariates were present in most models ranking within two AICc units of the top model (Table 2). Distance to forest edge and tree cover were present in models within two AICc units of the top model, but were not present in the top model for any year. Distance to water was not present in any models within two AICc units of the top model for any year (Ainley et al. 2006).

The top model for each study year included at least one socio-cultural covariate that was significantly correlated with bearded pig occupancy (Table 3). Environmental covariates were significantly correlated with bearded pig occupancy in top models for two of the three study years. Among socio-cultural covariates, hunting accessibility was significantly positively correlated with pig occupancy in 2010, but significantly negatively correlated with pig occupancy in 2012 (Table 3). (Both of these results should be considered in relation to the other covariates in the top model for those years.) However, Indigenous pig-hunting population proportion was significantly negatively correlated with bearded pig occupancy in both 2010 and 2012. Elevation was positively correlated with bearded pig occupancy in both 2010 and 2012. Other model covariates in top models significantly influenced pig occupancy in only one year.

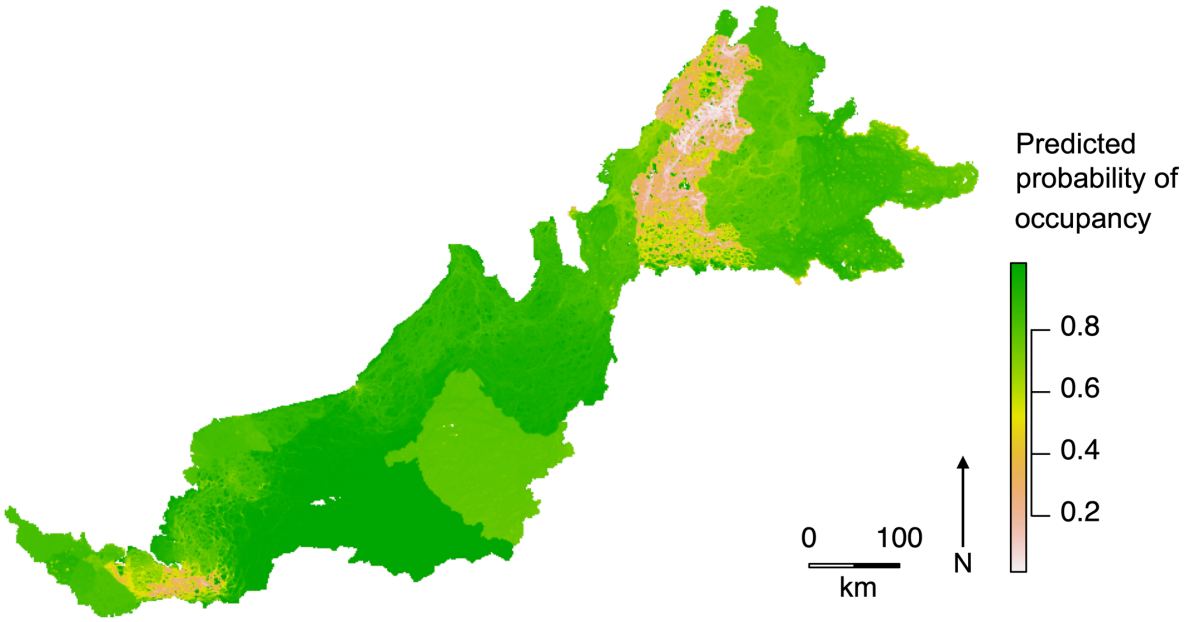

Figure 2. Predicted bearded pig occupancy (defined as site use) across Sabah and Sarawak, based on top model from 2014 data.

Table 2. Model results within <2 ΔAIC of the top model for each year in the study.
[Covariate abbreviations are: Int. = Intercept; Elev. = Elevation; Indig. = Proportion of district population composed of predominantly pig-hunting KDM or Iban racial-ethnic group;
Access. = Hunting accessibility; Treeco. = Percent tree cover; PAs. = Protected area status;
Slp. = Slope; Dist.FE = Distance to forest edge]

Model	N	W	-2LL	AICc	ΔAIC
2010					
Int. + Elev. + Indig. + Access.	5	0.112	-1185.9	2382.3	0.00
Int. + Elev. + Indig. + Access. + Indig.*Access.	6	0.097	-1184.9	2382.5	0.29
Int. + Elev. + Indig. + Access. + Treeco. + Indig.*Access.	7	0.077	-1184.0	2383.0	0.76
Int. + Elev. + Indig. + Access. + Treeco.	6	0.060	-1185.4	2383.5	1.25
Int. + Elev. + Access.	4	0.049	-1187.8	2383.9	1.64
2012					
Int. + Elev. + Indig. + Access. PAs. + Slp.	7	0.150	-1087.1	2189.2	0.00
Int. + Elev. + Indig. + Access. + PAs. + Slp. + Indig.*Access.	8	0.149	-1085.9	2189.2	0.01
Int. + Indig. + Access. + PAs. + Slp. + Indig.*Access.	7	0.097	-1087.5	2190.1	0.87
Int. + Indig. + Access. + PAs. + Slp.	6	0.091	-1088.7	2190.2	1.00
Int. + Elev. + Indig. + Access. + Slp. + Indig.*Access.	7	0.065	-1087.9	2190.9	1.68
2014					
Int. + Indig. + Access. + Indig.*Access.	5	0.117	-570.4	1151.5	0.00
Int. + Dist.FE + Indig. + Access. + Indig.*Access.	6	0.094	-569.4	1151.9	0.43
Int. + Elev. + Indig. + Access. + Indig.*Access.	6	0.084	-569.5	1152.1	0.66
Int. + Dist.FE + Indig. + Access. + PAs. + Indig.*Access.	7	0.061	-568.7	1152.8	1.30
Int. + Elev. + Indig. + Access. + PAs. + Indig.*Access.	7	0.052	-568.8	1153.1	1.61
Int. + Indig. + Access. + PAs. + Indig.*Access.	6	0.046	-570.1	1153.3	1.85

Table 3. Coefficient estimates and standard error for the top models from each year of the study. Significant relationships ($p < 0.05$) between covariates and bearded pig occupancy are listed in bold. [Covariate abbreviations are: Elev. = Elevation; Indig. = Proportion of district population composed of predominantly pig-hunting KDM or Iban racial-ethnic group; Access. = Hunting accessibility; PAs. = Protected area status; Slp. = Slope].

2010			2012			2014		
Coefficient	*Estimate*	*SE*	*Coefficient*	*Estimate*	*SE*	*Coefficient*	*Estimate*	*SE*
(Intercept)	0.836	0.498	(Intercept)	1.628	0.945	(Intercept)	1.004	0.565
Elev.	**0.004**	**0.001**	**Elev.**	**0.002**	**0.001**			
Indig.	**-6.649**	**3.273**	**Indig.**	**-3.428**	**1.056**	Indig.	3.373	3.447
Access.	**2.161**	**0.730**	**Access.**	**-1.218**	**0.384**	Access.	0.821	0.557
						Indig.*Acc.	**-5.932**	**2.993**
			PAs.	**1.454**	**0.626**			
			Slp.	**-0.075**	**0.029**			

DISCUSSION

Influence of socio-cultural factors

Our results provide robust, quantitative evidence of the strong correlations between socio-cultural factors and occupancy of a large-bodied, wildlife game species. Socio-cultural covariates were present in the top occupancy model for each year, highlighting the salience of cultural practices—in this case, hunting—on wildlife distributions. While conceptual models of socio-ecological systems are becoming increasingly common (e.g. Lischka et al. 2018), and urban ecology has embraced human demographics and cultural practices in wildlife distribution assessments (e.g. Alberti et al. 2003, Kumar et al. 2019), we assert that it is critical to normalize more fully the integration of socio-cultural practices into wildlife ecology and conservation. In our study context, social landscapes and ecological landscapes share important intersections. Deith & Brodie (2020) show that landscape characteristics are tightly associated with hunter movements (together comprising "hunting accessibility") across Malaysian Borneo. Our results build on this link by showing that hunting accessibility is also strongly associated with bearded pig distributions across Malaysian Borneo. More broadly, these findings suggest that multidirectional links between social and ecological systems are likely to shape wildlife distributions in a variety of contexts globally.

Notably, hunting accessibility was the only covariate to appear in all top models (within 2 ΔAIC) for each study year. Similarly, three other covariates—elevation, proportion of indigenous pig-hunting groups, and the interaction between proportion of indigenous pig-hunting groups and hunting accessibility—appeared in most top models across study years. The consistency of these patterns indicate agreement among competing models of the association of these covariates with bearded pig occupancy.

Ethnic identity and hunting practices

The association of ethnic population proportion with bearded pig occupancy in two of three years highlights the relevance of social identity, cultural practices, and socio-geographic factors on wildlife distributions. Robust cultural traditions have important implications for conservation value formation (Van Houtan 2006), and ethnicity shapes wildlife utilization patterns across the globe (Hunt & Ditton 2002, Amador et al. 2015, Kurz et al. in review). However, little research quantitatively links ethnicity with wildlife outcomes. In 2010 and 2012, the negative correlation between the KDM and Iban proportion of the population and bearded pig occupancy suggests that hunting by these groups may play a role in reduced occupancy by pigs in some areas.

In our study region, ethnic identification is also tightly linked to religion, leading to additional cultural implications for bearded pig hunting. The vast majority of Kadazandusun-Murut (KDM) and Iban communities predominantly identify as Christian, and the vast majority of Malays identify as Muslim (Malaysia Department of Statistics 2011). These tight ethno-religious identifications add an additional layer of group identity to pig hunting practices and dietary choices — wild pork is highly favored by Christian KDM and Iban communities in Sabah and Sarawak (Bennett et al. 2000, Kurz et al. in review), but actively avoided in Muslim communities in Malaysia generally (Yusof et al. 2012). In fact, food practices rooted in religion and ethnicity

are so strong in our study area that a “pig line” has been recorded in Sarawak between Muslim fishing communities along the coast and Christian pig-hunting communities in the interior (Bolton et al. 1972). While ethno-religious traditions have been linked to harvest of wild animals and plants (e.g., Wadley et al. 1997, Golden & Comaroff 2015, Pieroni & Sõukand 2019), relatively few studies have explored these connections. The strong ethnic and religious factors influencing wild pig consumption in Sabah and Sarawak make a compelling case for the wider relevance of these identities to wildlife consumption patterns generally.

Shifting patterns of hunting accessibility on bearded pig occupancy

As sites differed for each study year, we hypothesize that density differences of bearded pigs among sites could be a reason for the switching influence of hunting accessibility across years and sets of sites. The dependent variable in our models was occupancy, which does not directly account for pig densities. Bearded pigs have a number of population states of varying densities under different environmental conditions (Caldecott et al. 1993), presumably resulting in varying levels of resilience to hunting pressure. In areas with plentiful food resources and high pig densities, bearded pig resilience to hunting could be high; indeed, during resource-rich mast fruiting periods, female bearded pigs can give birth to 10-30 piglets in a single year (Luskin & Ke 2018). While reports of mast fruiting are increasingly scarce in Malaysian Borneo, oil palm plantations provide year-round food subsidies to bearded pigs in many areas (Love et al. 2018, Davison et al. 2019, Kurz et al. in review). Therefore, the relationship between high bearded pig densities and hunting accessibility deserves further study. For example, in 2010 our top model showed a positive correlation between hunting accessibility and pig occupancy, potentially due to high bearded pig densities in the 2010 study areas. Meanwhile, in other areas bearded pig populations may reach a threshold of hunting pressure, with pig occupancy declining with increasing hunting pressure. For example, the top model in 2012 showed a negative correlation between hunting accessibility and pig occupancy. Alternatively, the negative association between hunting accessibility and occupancy seen in 2012 could indicate high levels of bearded pig occupancy in more remote areas, e.g. protected areas with low hunting accessibility, which were positively associated with bearded pig occupancy in the same year. Additionally, given that top models across years had different combinations of covariates, a particular covariate cannot be compared directly to the same covariate in another year (i.e. the sign and coefficient of a given covariate is relative to the other covariates in that model).

In 2014, the significant negative interaction between hunting accessibility and proportion of indigenous pig-hunting population may indicate that, as the proportion of Indigenous pig-hunting population increases and hunting accessibility increases, these covariates are more negatively correlated with bearded pig occupancy than would be expected. That is, Indigenous pig-hunting populations living in high-accessibility hunting areas could have a ‘more than the sum of their parts’ influence on bearded pig occupancy, perhaps due to the robustness of hunting practices by Indigenous communities in favorable hunting areas. However, the inconsistency of significant interactions across years indicates that these trends could be highly context-specific and suggests that this hypothesis deserves further study.

Context-specific management of bearded pigs in Malaysian Borneo

Our results support context-specific management of bearded pigs in Sabah and Sarawak, Malaysian Borneo. In general, average estimated occupancy values (psi±SE) for bearded pigs were high: 0.85±0.05 in 2010, 0.66±0.10 in 2012, and 0.71±0.08 in 2014. These occupancy estimates are closer to occupancy values reported for the wide-ranging Eurasian Wild Boar, *Sus scrofa* (0.82 ± 0.12 SE) (e.g., Thapa et al. 2017) than those reported for rarer species such as the Bawean warty pig (0.59 ± 0.06 SD) (Rode-Margono et al. 2020). The variation in correlation of demographic, environmental, and hunting accessibility covariates with bearded pig occupancy across years and study sites highlights the range of factors that can shape bearded pig occupancy. Additionally, the large range of average predicted occupancy across field sites (0.27 - 0.95) suggests a range of management needs for bearded pig populations, which are known to have shifting movement patterns and growth rates in different population states (Caldecott et al. 1993). Bearded pig natural history fits many characteristics of a generalist species—e.g., dietary flexibility, broad habitat use, and high dispersal ability (Luskin & Ke 2017, Davison et al. 2019)—yet the species still seems to require forested cover for behaviors such as nesting, wallowing, and tree rubbing (Love et al. 2018). As such, managing for contiguous areas of forest is likely important, particularly in areas threatened with deforestation and containing low predicted occupancy. Some of the areas of lowest predicted occupancy in our study are found outside formally protected areas and may require management interventions to ensure sustainable bearded pig populations. Moreover, our results from the top model in 2012, showing a positive relationship between bearded pig occupancy and protected areas, suggest a continued role for national parks and other protected conservation areas in sustainable bearded pig conservation. Large, protected national parks may also be one of the last opportunities for conserving the unique migratory ecology of bearded pigs, which are thought to historically have traveled for hundreds of kilometers tracking supraannual mast fruiting bounties (Caldecott & Caldecott 1985). Large tracts of protected forest are likely the only places remaining with sufficiently high masting activity (Granados et al. 2019), low hunting levels, and low oil palm fruit subsidies that together allow for long-range bearded pig nomadic movements.

Finally, our results point to a need to manage for both human- and pig-related needs. This negative association between pig-hunting cultural groups and bearded pig occupancy for two of the study years should be considered in management decisions about sustainable offtake levels of bearded pigs. At the same time, rather than suggesting that hunting practices by these groups should be discouraged, the differences in model results across years and areas suggest that context-specific management of bearded pig populations may be more appropriate than one-size-fits-all solutions. Indeed, nuanced solutions will be critical so that Indigenous communities in Sabah and Sarawak can continue to sustainably hunt bearded pig populations, as they have for millennia (Harrisson et al. 1961, Medway 1964). For integrated biocultural conservation goals, it is critical to preserve the cultural importance of bearded pig hunting for indigenous groups while also limiting hunting to sustainable levels for bearded pig populations (Kurz et al. in review). Our results highlight the tensions and challenges of these twin goals. However, robust pig occupancy estimates across most of our study sites and high

bearded pig reproductive capacity (Luskin & Ke 2017) also suggest that balancing these goals is possible.

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Chapter 3. Transformation and endurance of Indigenous hunting: Kadazandusun-Murut bearded pig hunting practices amidst oil palm expansion and urbanization in Sabah, Malaysia

ABSTRACT

Land-use change and political-economic shifts have shaped hunting patterns globally, even as traditional hunting practices endure across many local socio-cultural contexts. The widespread expansion of oil palm cultivation, and associated urbanization, alters land-use patterns, ecological processes, economic relationships, access to land, and social practices. In particular, we focus on the socio-ecological dynamics between Kadazandusun-Murut (KDM) hunters in Sabah, Malaysian Borneo, and native bearded pigs (*Sus babatus;* Malay: "babi hutan"), the favored game animal for non-Muslim communities throughout much of Borneo. We conducted 38 semi-structured interviews spanning over 50 hours with bearded pig hunters, asking them about contemporary hunting practices, changes in hunting practices, and patterns of meat consumption. Amidst widespread land use change, primarily driven by oil palm expansion, respondents reported substantially different characteristics of hunting in oil palm plantations as compared to hunting in forests. Additionally, 17 of 38 hunters—including 71% (10/14) of hunters who started hunting before 1985, compared to 26% (6/23) of hunters who started hunting in 1985 or later—mentioned that bearded pigs are behaving in a more skittish or fearful way as compared to the past. We also documented shifts in dietary meat consumption among our respondents between rural and urban contexts, as well as urbanization-related reductions in hunting frequency. However, despite these substantial changes in hunting practices, numerous KDM motivations, hunting techniques, and socio-cultural traditions have endured over the last several decades. Oil palm has stimulated new hunting practices that differ from those in forests, and has potentially contributed to altered bearded pig behavior due to increased hunting accessibility. Simultaneously, urbanization has led to changes in dietary patterns, as well as shifted schedules and time availability for hunting. We also note the striking endurance of long-standing KDM pig hunting practices and traditions. We recommend policies that allow flexible, location-specific management approaches to ensure fair access to the dietary and social benefits of bearded pig hunting, while preserving the critical conservation needs of bearded pig populations and habitat. This is particularly important given the recent confirmed outbreak of African Swine Fever (ASF) in numerous forests and districts within Sabah.

INTRODUCTION

Hunting has been called "the master behaviour pattern of the human species…which puts motion and direction into the diagram of [hu]man's morphology, technology, social organization, and ecological relations..." (Laughlin 1968). In addition to the provision of meat, a typical hunting event includes, among other behaviors, searching for prey, pursuing animals, killing and butchering one or more animals, transporting carcasses, distributing meat among households or markets, and communicating ecological information throughout and following the hunt (Laughlin 1968, Puri 2005). Correspondingly, a great number of physical, cultural,

social, and ecological dynamics are linked to hunting practices: hunting is, in short, one of the most fundamental and enduring of human-wildlife relationships.

Land use change and hunting are intimately linked. For example, land conversion increases access to wildlife habitats and often leads to dramatic and unsustainable levels of hunting (e.g., Parry et al. 2007, Abernethy et al. 2013, Harrison et al. 2016). Furthermore, land conversion has been shown to influence hunting practices and techniques in a variety of socio-cultural contexts (Wightman et al. 2002, Luskin et al. 2014). The many and varied modes through which land use changes interact with hunting practices call for greater understanding of the links between socio-ecological systems, social practices, food security, and the sustainability of wildlife populations (Bassett 2005, Brashares et al. 2014). Drawing on a case study of these integrated dynamics, we investigate the ways that oil palm expansion, urbanization, and ancillary socio-cultural factors have been tied to the transformation and endurance of pig hunting practices in Sabah, Malaysia.

Historical and contemporary bearded pig hunting practices in Borneo and Sabah

The bearded pig (*Sus barbatus*, Bahasa Melayu - *"babi hutan"* : "forest pig") is a large, nomadic Suid species native to Sundaland and deeply woven into the socio-ecological fabric of Borneo (Puri 2005, Luskin & Ke 2018). Bearded pig hunting is a deeply embedded social practice in many Indigenous communities in Borneo, who have hunted and consumed bearded pigs for over 40,000 years (Harrisson et al. 1961, Medway 1964). For example, for the Penan Benalui in East Kalimantan, hunting is the most regularly occurring economic activity and a central organizing activity in Penan society (Puri 2005). Some traditional hunting techniques are also tied to nomadic movements of bearded pigs (e.g. Banks 1949), which are thought to periodically move long distances up to 650 km in large herds of up to 300 individuals (Pfeffer 1959, Davies & Payne 1982, Caldecott et al. 1993). Bearded pig meat has been shown to account for 54-97% of wild meat by weight in Indigenous Bornean societies (Bennett & Sompud 2000, Chin 2001, Puri 2005), for whom wild meat can contribute to as much as 36% of meals (Bennett & Sompud 2000). Thus, bearded pig is the most heavily-consumed terrestrial game animal for Indigenous, non-Muslim communities throughout Borneo, and is also widely considered the clear favorite type of wild meat among many of these communities (Bennett & Sompud 2000, Chin 2001, Puri 2005, Janowski 2014).

Bearded pig hunting also carries significant implications for spirituality, recreation, gift-giving, and social practices in many Indigenous Bornean communities (Harrisson 1965, Wadley & Colfer 2004, Janowski 2014). More broadly within Malaysia, pigs and pig hunting are situated at intersections of religion, ethnic identity, and geography. In Malaysia, a multicultural society politically controlled by ethnic Malays, one of the many socio-religious delineations between Malay Muslim elites and other ethno-religious groups is the consumption of pig meat: many Malay Muslims find pigs and pork highly objectionable—to the point that *"babi"* ("pig") is an insult (Yusof 2012). In contrast, other groups, including ethnic Chinese minorities, consume pork in large quantities (Neo 2011). The prominence of religious food practices has a dramatic influence on patterns of pork consumption in Malaysia (Chua 2012), to the extent that a "pig line" has even been described in Sarawak, delineating predominantly Muslim coastal fishing

communities from primarily non-Muslim inland communities who are nutritionally dependent on wild pig meat (Bolton et al. 1972). Similarly, ethno-religious dynamics shape hunting practices and influence which species are targeted for hunting in Indonesian Borneo (Wadley et al. 1997).

Bearded pig hunting today takes place within a general context of habitat loss and heterogeneous management policies across its range. Luskin & Ke (2019) estimated significant (20% or more) habitat loss and range reduction from 1990-2010 in each of the three largest historical regions of bearded pig habitat: Peninsular Malaysia, Sumatra, and Borneo. This decline in habitat was driven by agriculture-related habitat fragmentation (primarily due to oil palm and rubber plantations), leading to the recent re-listing of the bearded pig as a Vulnerable species in the International Union for Conservation of Nature and Natural Resources Red List (Luskin et al. 2018). While habitat loss is readily quantifiable via tools such as remote sensing and geographic information systems, shifting human-pig interactions, hunting patterns, and related effects on bearded pig populations are more challenging to track and map. Furthermore, a patchwork of multiple legal frameworks regulates hunting across the bearded pig range. Hunting of the species is permitted in some form across bearded pig range countries (Indonesia, Malaysia, and Brunei), with restrictions varying by jurisdiction and including measures such as hunting permits, no-hunting protected areas, and native hunting clauses (Brunei Wildlife Protect Act 1984, Indonesia Act No. 5 of 1990, Sabah Wildlife Enactment of 1997, Sarawak Wildlife Protection Ordinance 1998). Law enforcement capacity also varies by region (Bennett & Sompud 2000, Luskin et al. 2014, Lintangah et al. 2015).

In Sabah, it is legal to hunt bearded pigs and sell the meat with appropriate licenses from the Sabah Wildlife Department (Sabah Wildlife Enactment of 1997). [Note: as of early 2021, hunting licenses remain frozen due to movement control orders related to the COVID-19 pandemic and due to mitigating the spread of the African Swine Fever (ASF) outbreak in Sabah (Chan 2021, The Borneo Post 2021, The Star 2021).] Hunting of bearded pigs in Sabah is widespread in many rural areas, and bearded pig meat remains an important food resource for many human communities (Bennett & Sompud 2000, Mojiol et al. 2013), including those adjacent to oil palm plantations (Wong et al. 2012). Oil palm plantations have shaped bearded pig ecology by reducing the area available for some behaviors (e.g. limited wallowing and nesting sites in plantations), altering demographics (e.g. increasing the proportion of young pigs in plantations), and changing activity patterns (e.g. shifting pigs to nocturnal activity patterns in plantations) (Love et al. 2018, Davison et al. 2019). Research has also shown how bearded pigs benefit from crop-raiding in oil palm plantations (Love et al. 2018, Davison et al. 2019), and has hypothesized that this behavior could potentially increase their populations near oil palm plantations (Luskin et al. 2017, Love et al. 2018, Davison et al. 2019).

These findings raise questions about how bearded pig responses to forest-oil palm mosaics might affect hunting practices. Despite the historical and contemporary prominence of these hunting and dietary relationships—in Sabah, most notably within KDM communities that depend most heavily on bearded pigs—there has been little published research on these practices and how they have been reshaped by the socio-economic and environmental changes

brought about by oil palm expansion. Furthermore, case studies and syntheses, both regional and global, are needed to elucidate how relationships between human societies and natural resources change in response to factors such as land-use change and political-economic forces (Lambin & Meyfroidt 2010).

Economic, environmental, and social processes of oil palm expansion in Sabah

Sabah has been on the frontlines of the oil palm boom since the late 20th century. This transformative process is noteworthy for its deep roots in globalized commodity chains, through which oil palm became highly valued as a "global flex crop" useful for food, fuel, and personal care (Alonso-Fradejas et al. 2016). By the 1960s, Borneo had been identified as a major resource frontier, providing more tropical timber than anywhere else in the world by the late 1970s (Brookfield et al. 1995). With timber extraction helping pave the way for oil palm expansion, Malaysia emerged as the global leader in palm oil production in the 1970s (FAOSTAT 2020). By the early 1980s, oil palm had become Sabah's most important cash crop, fueled by high profitability and the diversity of commercial applications for palm oil (Bernard & Bissonnette 2011). Oil palm plantation area in Sabah reached over 1.7 million hectares (6,867 sq. miles) by 2015; 68% of this total area was converted to oil palm within five years of forest clearance (Gaveau et al. 2016). As of 2015, roughly 24% of Sabah's total land area was covered by oil palm or pulpwood plantations (Gaveau et al. 2016).

These large-scale economic and land-use changes resulted in profound shifts in socio-ecological relationships in Sabah. In significant part, Sabah became a particular manifestation of the 'global land grab' in which large tracts of land were allocated to a small number of business, bureaucratic, and political elites (Cramb & Curry 2012). Indeed, some have argued that this socio-environmental shift represents an extension of colonial legacies of territorialisation, with large plantation corporations taking a capitalist role analogous to their imperialist land-control forbearers and shaping labor relations and livelihood options across the state (Bernard & Bissonnette 2011, Cooke 2012). While oil palm smallholdings became popular and often profitable options for some Sabahans with access to land (Cooke 2012), most labor and management in the vast stretches of industrial oil palm plantations began coming from outside of Sabah. For example, by the late 1990s, 95% of workers on Federal Land Development Authority (FELDA) plantations in Sabah were migrants from the Philippines or Indonesia (Bernard & Bissonnette 2011). As a result, this migrant labor force, consisting of both legal and illegal workers, has become a mainstay of Sabah's plantation economy (Kelly 2011). For their part, Sabahans often take administrative posts within oil palm companies, or move to urban areas for relatively well-paying jobs in manufacturing and retail. For those Sabahans remaining in rural parts of the state, disputes over land allocation and ownership have reduced access to both croplands and forests in some areas, reducing food security and restricting accessibility to non-timber forest resources (Bernard & Bissonnette 2011). Due in large part to the vast areas already gazetted for timber production and oil palm plantations, new land for oil palm "either has to encroach on claimed but untitled lands on which customary rights have been established or excised from existing government forest reserves" (Cooke 2012).

Oil palm expansion, urbanization, and bearded pig hunting among Kadazandusun-Murut (KDM) hunters in Sabah

In this paper, we argue that the socio-ecological processes of oil palm expansion and urbanization in Sabah have profoundly shaped—and continue to shape—hunting practices within the influential Kadazandusun-Murut ethnic group (or "KDM", the common shorthand for this community in Sabah). The KDM make up roughly a third of the *Bumiputera* population (literally translated to "sons of the land," used in Malaysia to refer to Malays and Indigenous ethnic minority groups) within the state of Sabah, and over 20% of the total population of Sabah (Malaysia Department of Statistics 2011). Within Sabah, the KDM peoples are considered among the *Orang Asal*, or Indigenous Peoples of Malaysia. In this study, we investigate the particular ways that KDM bearded pig hunting practices have been preserved or changed in the face of the environmental, economic, and social changes that have come with oil palm expansion and urbanization. Specifically, we interviewed KDM hunters in Sandakan District, Sabah, to assess persistence and change in their hunting practices, perceptions of bearded pig behavior, meat and fish consumption patterns, hunting motivations, and hunting techniques. We discuss ways our findings shed light on the relationships between oil palm expansion, urbanization, and hunting, and connect our results to potential biocultural conservation opportunities that encompass both KDM social practices as well as bearded pig conservation.

METHODS

Study Area

We conducted our study in Sandakan District (5.840415, 118.116757), located along the eastern coast of Sabah, Malaysian Borneo (Figure 1). Sandakan is the third most populous district in Sabah, with a population of 396,290 in the 2010 census (Malaysia Department of Statistics 2015). Between 2000 and 2010, the population of the district grew by 13.6% (Malaysia Department of Statistics 2015). Most land area in Sandakan district is covered by industrial plantation agriculture (Gaveau et al. 2014). The Sandakan economy is also supported by numerous factories and industrial uses, including oil terminals, oil refineries, glue factories, a shipyard, and wood-based factories (Sabah State Government 2014). Of the Malaysian citizen population of Sandakan (constituting 63% of the total population), 71% identify as *Bumiputera* (Malay, Kadazandusun, Bajau, Murut, and other Bumiputera), 25% are of Chinese descent, 0.4% are of Indian descent, and 3.5% are from additional racial-ethnic groups (Malaysia Department of Statistics 2015).

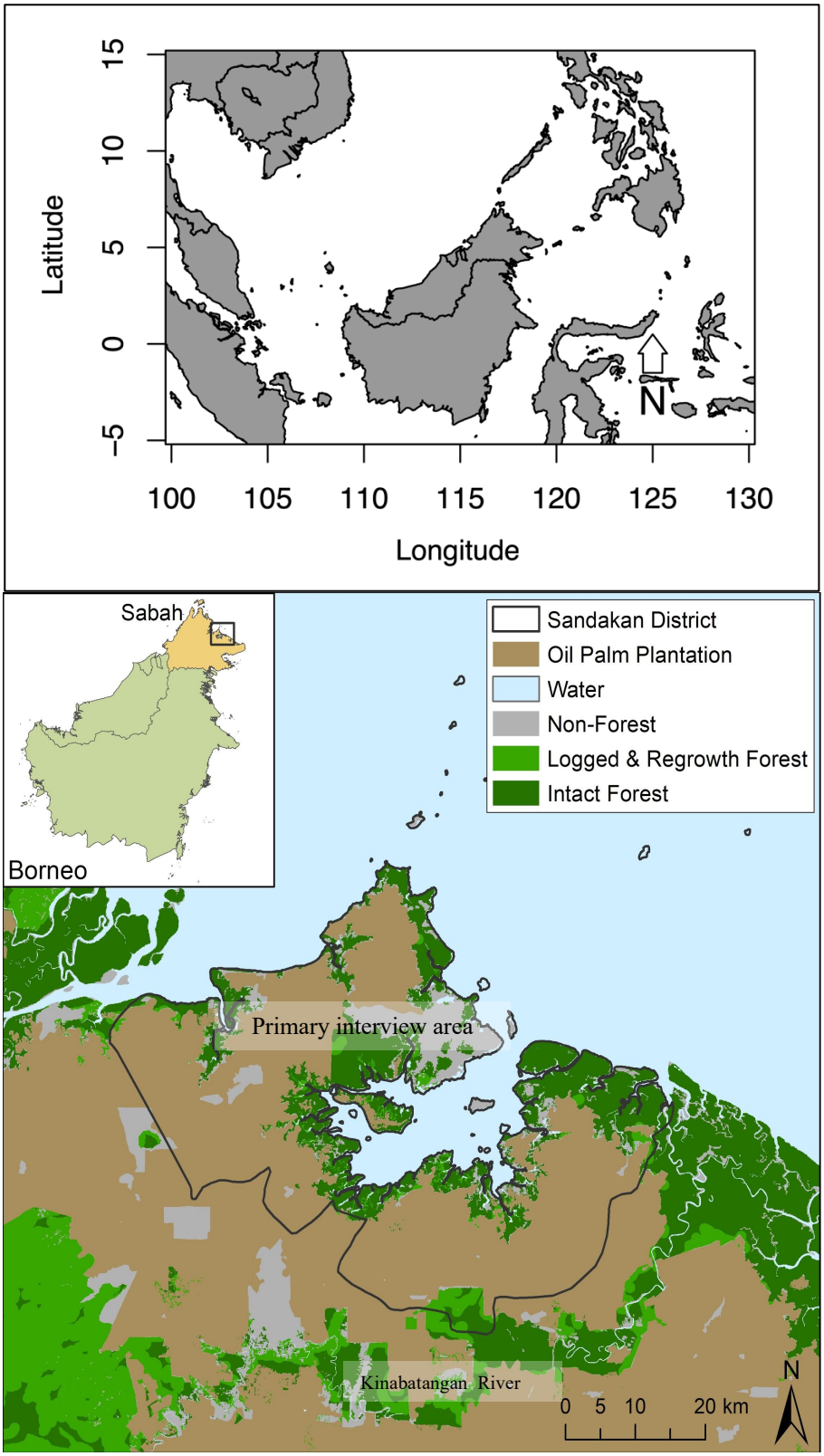

Figure 1. (Top) View of part of Southeast Asia region. (Bottom) Map of the study area: Sandakan District, Sabah, Malaysian Borneo.

Data collection

We conducted 38 in-depth, semi-structured interviews with Kadazandusun-Murut (KDM) bearded pig hunters in 2019 in Sandakan District (Figure 1). Our interview protocol was approved by the Committee for Protection of Human Subjects at the University of California, Berkeley (Protocol number: 2019-04-12096), by the Sabah Biodiversity Council (Ref. No. JKM/MBS.1000-2/2 JLD.9 (59)), and by the Sandakan Municipal Council (Ruj.MPS100-48/001/0000/035). All hunters interviewed were men. Although women in some Bornean communities play significant roles in the various cultural practices associated with bearded pig consumption, we did not encounter any women engaged in hunting over the course of our study.[1] More broadly, hunting has historically been associated with men in Indigenous Bornean societies (Alexander & Alexander 1994, Thambiah 2016). We defined a "hunter" as someone who had hunted bearded pigs twice per year or more, on average, for a span of at least five years of their lifetime. A hunter did not need to be hunting regularly at the time of the interview to be included in our study. We identified hunters through our existing social and professional networks, and we relied on referral ("snowball") sampling, by which respondents connected us with other hunters. While this strategy did not provide us with a representative pool of the KDM hunting community in Sandakan District, it promoted trust and helped identify a set of highly knowledgeable respondents (e.g. Luskin et al. 2014). When potential respondents were in a village (*kampung*) setting, we sought and received permission from the village chief before proceeding with interviews. Before conducting an interview, we asked each participant for his verbal consent to participate in the research. To protect the privacy of respondents, we did not record their names or any audio.

Two (JB, VTJ) or three (DK, JB, VTJ) authors conducted each interview, primarily in Bahasa Melayu (supplemented only occasionally with English if respondents were comfortable and chose to speak in English). Both primary interviewers (JB, VTJ) spoke fluent Bahasa Melayu, and one of the primary interviewers (VTJ) was a local Sabahan. Each interview lasted from 0.5 - 2.5 hours, and took place in a location chosen by the respondent. Respondents were normally interviewed individually, but occasionally social norms and relationships led to respondents being more comfortable with an interview in a small group (i.e. 2-3 individuals). Our survey consisted of basic demographic information (e.g. age group, home village/city, education level, work information) and questions about their hunting practices (See Supplementary Material for interview guide in English and Bahasa Melayu). We asked hunters to compare their hunting practices in oil palm plantations and forest. We also asked hunters about perceived changes in: their bearded pig hunting practices, the influence of their job on hunting, their hunting locations, and bearded pig behavior. Respondents were also asked about differences in their animal protein consumption patterns in village and urban contexts, hunting motivations, hunting techniques, hunting narratives, and hunting success. Most of the questions asked were open-ended, but we also asked closed questions about specific topics in order to gather information about certain categories of interest. To avoid asking for sensitive information and

[1]Women in some communities in Sarawak, however, play significant roles by consuming pig meat, participating in discussions of pig hunts, and feeding domesticated pigs (Janowski 2014). Women in our study area in Sabah participate in preparation and consumption of bearded pig meat at meals and community feasts.

making our respondents uncomfortable, we did not ask whether they had obtained the appropriate licenses for hunting or sale of bearded pig meat. We did not compensate respondents for participating in the study.

To quantify meat and fish consumption patterns, we asked respondents how many times in the previous week they had eaten: bearded pig meat, deer meat, any other kind of wild meat, wild fish from rivers, wild fish from the sea, and domestic chicken, domestic pig, or other domestic meat. We asked respondents to share their consumption patterns for both village (*kampung*) and city (*bandar*) settings, as many respondents had spent significant time living in each setting. To quantify hunting success, we asked respondents how many hunting trips for bearded pig, on average, were successful out of four attempts.

To quantify bearded pig hunting motivations, we asked hunters to rank common motivations from several categories: subsistence food provision (*makan*), sale for money (*jual*), recreation (*hobi*), pest control (*kawalan perosak*), gift (*hadiah*), or other (*lain-lain*). To quantify the frequency with which different hunters used different techniques, we asked respondents to indicate yes (*ya*) or no (*tidak*) to whether they had ever used the following common hunting strategies: dog and spear (*anjing dan tombak*), spear only (*tombak sahaja*), dogs and gun (*anjing dan senapang*), gun on foot (*senapang sahaja [kaki]*), drive hunt with gun (*senapang sahaja [kereta]*), snare (*jerat*), trap (*perangkap*), homemade bomb (*bom babi*), and other (*lain*).

Respondent characteristics

Hunter ages ranged from 26 - 72 years, with a mean age of 47 years. Most hunters had attended school until Form 1-5 (corresponding to 13-17 years of age), a few had received their Sijil Pelajaran Malaysia (Malaysia Certificate of Education, equivalent to a US high school degree), and a small minority of respondents had attended university or institute programs. Respondents worked in a variety of fields, including the oil palm industry (smallholder and industrial), police and government service, the clergy, semi-professional hunting, forestry, farming, rideshare driving, and various forms of self-employment. Twenty-seven out of 36 respondents who answered said they had worked in oil palm agriculture at some point, whether as small holders or in industrial oil palm plantation roles.

Data analysis

To investigate whether hunting practices have changed due to the expansion of oil palm plantations in Sandakan District, we compared hunting techniques used by hunters who started hunting earlier and later in the process of oil palm expansion in Sabah. We calculated the approximate year each hunter began hunting, based on their current age and the age they began hunting. We separated hunters into two categories: those who began hunting before 1985, and those who began in 1985 or later. We chose 1985, as extensive oil palm expansion in the Sandakan district occurred throughout the 1970s, resulting in an oil palm-dominated landscape by the late 1970s and 1980s (Norwana et al. 2011, Gaveau et al. 2016). To test for differences in hunting techniques used between these two categories of hunters, we then conducted a Fisher's exact test in R version 3.6.0 (R Core Team 2019).

Qualitative data were analyzed via inductive content analysis (Elo & Kyngäs 2008), in which we started with specific observations of individual hunters and moved to a more general framework of contemporary KDM hunting practices among our respondent pool. We present our findings as a sequence of themes that emerged from the interviews (Dhee et al. 2019). The themes we chose to analyze were related to our guiding questions of (a) how structural political-economic forces shape interactions between KDM hunters and bearded pigs; and (b) how local sociocultural forces shape the KDM - bearded pig socio-ecological system. To protect respondent identities we associated each interview record with a pseudonym, which we reference with each quote presented. Except where noted, excerpts of interviews have been translated into English, with the original Bahasa Melayu quote sometimes included to present respondent insights in their own language and expression.

RESULTS

Differing hunting practices in forest and oil palm plantations

In response to an open-ended question about whether hunting in the forest is different from hunting in oil palm, hunters reported several distinct characteristics of hunting in each environment (Table 1). Most prevalent was the perception that hunting in oil palm plantations was easier overall than hunting in forests, e.g. because it was less tiring than walking in a forest, easier to see or find pigs, or more predictable in terms of knowing exact foraging locations preferred by pigs. Hunting in forests was characterized by a number of hunters as being harder overall than hunting in plantations, and involved walking on foot (often for longer distances). For example, Kunol contrasted the two styles of hunting this way: “In the plantation you know the pig will come eventually – it’s only a matter of time” whereas in the forest “it’s not as certain even if you hunt all day long – because you will need to walk and only if you cross paths with it will you get it – if you do, you do.”

Additionally, five respondents noted a difference between the taste of the meat from pigs in oil palm plantations as compared to forest. Three hunters specifically expressed a preference for the taste of meat from forest. Gompudung commented, “The pig from the forest is much tastier, it’s more fit. If the pig eats oil palm its fat isn’t as sweet. It’s very rare to meet a pig that’s never eaten oil palm.”

Table 1. Salient themes of hunting in forest and oil palm plantations mentioned by hunters in response to an open-ended question about the difference between hunting in the two habitat types.

Characteristics of hunting in forest	# hunters	Characteristics of hunting in oil palm plantations	# hunters
Harder overall (e.g. more tiring, more variable).	8	Easier overall (e.g. less tiring, more predictable).	9
Hunting on foot.	6	More waiting for pigs.	5
Walking farther distances.	5	Easier to find / see pigs.	4
Easier to get more pigs.	2	Predictable places pigs come to forage.	3
		Hunting with a car.	2

Perceived changes in pig behavior over time

In response to an open-ended question about whether they had noticed any changes in bearded pig behavior since they had started hunting, more than half of all respondents (20/38) noted some type of pig behavior change over time (Box 1). In particular, 17 hunters replied that they noticed that pig behavioral responses had become more skittish, wild, or fearful over the years. Among hunters who had started hunting before 1985, 71% (10/14) noted this increased flight response, whereas only 26% (6/23) of hunters who started hunting after 1985 mentioned this behavioral change. Additionally, 5 hunters noted other pig behaviors (e.g. activity patterns) that they perceived to have changed over time. For example, one hunter theorized that pigs change their behavior in response to the schedule of workers in the plantation, suggesting that the pigs came into the plantation after workers had gone home for the day.

Qualitative evidence of changes in pig behavior

"The pigs are more wild and more difficult to track." -Tiansim

"The pigs can smell man; they are getting more wild because they are always getting shot by men." -Sumpi

"In the past pigs did not fear men." -Jempurung

"They don't come at the same times as they did before." -Hendry

"Before they didn't run; now when I turn on a lamp the pigs run everywhere!" -Tamin

"The pigs saw people before and did not run away. It has a sense of who is a hunter and who is not a hunter. Now he is running." -Goruck

"Yes there's a change. The pigs today have already become wild. Pigs today are afraid of men. In the past they wouldn't run from men. It was much easier to hunt pigs in the past." -Gompudung

"In the past pigs only looked, but now they run away. Now the pig has got a high school certificate." -Tinggalung

Box 1. English translations (from Malay) of quotations from respondents who perceived changes in bearded pig behavior over time.

Many hunters reported seeing bearded pig eruptions of scores or hundreds of individuals, although many of these observations were by older hunters. Several hunters in our study described these pig eruptions with awe, fear, excitement, and shock. For example, Sumping said: "I was sitting in a tree when a huge herd of pigs came by. I was so shocked that I didn't even shoot any. I just sat there counting them." Matasing commented, "There are so many pigs that all you can do is just stand and stare until they run away." Other hunters acknowledged

that large herding behavior occurred, but they had not seen large herds and did not know many details about them. Younger hunters typically had never seen or heard of the migrations.

Hunter consumption patterns in village and urban settings

In village settings, 72% of respondents (n = 32) reported consuming bearded pig weekly or more frequently, 31% of respondents reported consuming bearded pig 2-3 times per week, and 22% reported consuming bearded pig 4 or more times per week. More respondents in village contexts consumed bearded pig meat on a weekly basis than any other meat besides domestic chicken (Figure 2). In addition to bearded pig meat, a minority of respondents in village settings reported at least weekly consumption of deer (7.4%) and other wild meat (18%). Other wild meat consumed in village settings varied widely, including Malay civet (*Viverra tangalunga*), common water monitor *(Varanus salvator)*, large flying fox (*Pteropus vampyrus*), Bornean crested fireback (*Lophura ignita*), reticulated python (*Malayopython reticulatus*), and long-tailed macaque (*Macaca fascicularis*).

In city contexts, 50% of respondents (n = 26) reported consuming bearded pig weekly or more often and 38% of respondents reported consuming bearded pig 2-3 times per week, but no respondents reported eating bearded pig meat 4 or more times per week. However, in city settings, more respondents consumed marine fish, domestic chicken, and domestic pork than bearded pig. In city contexts, only 4.3% of respondents reported consuming other wild meat on a weekly or more frequent basis.

Hunting declines due to urbanization and other factors

Seven hunters said they hunted less than before due to job commitments, or factors related to job opportunities and urban life. These factors tied to urbanization included job-related time commitments, lack of energy due to work, and increased travel distance required to hunt. For example, Tiko, who worked as a contractor in Sandakan, said, “In the past you’d always go hunt, now there’s not enough time to hunt.” Gintas noted, “When you live in the city there are no good places to hunt.” Sumpi, a rideshare driver in Sandakan, noting that he hunts on his days off work, commented that he hunts “Less now, there are many estates, the forest is remote and the pigs are far away.”

Hunters also reported hunting declines with respect to other factors. Three hunters specifically mentioned oil palm-driven land use change, and related factors such as the resulting increase of travel time to hunting locations, as a reason for their own reduced hunting frequency. Three hunters also referenced the increased difficulty in finding and / or purchasing ammunition as a reason for reduced hunting.

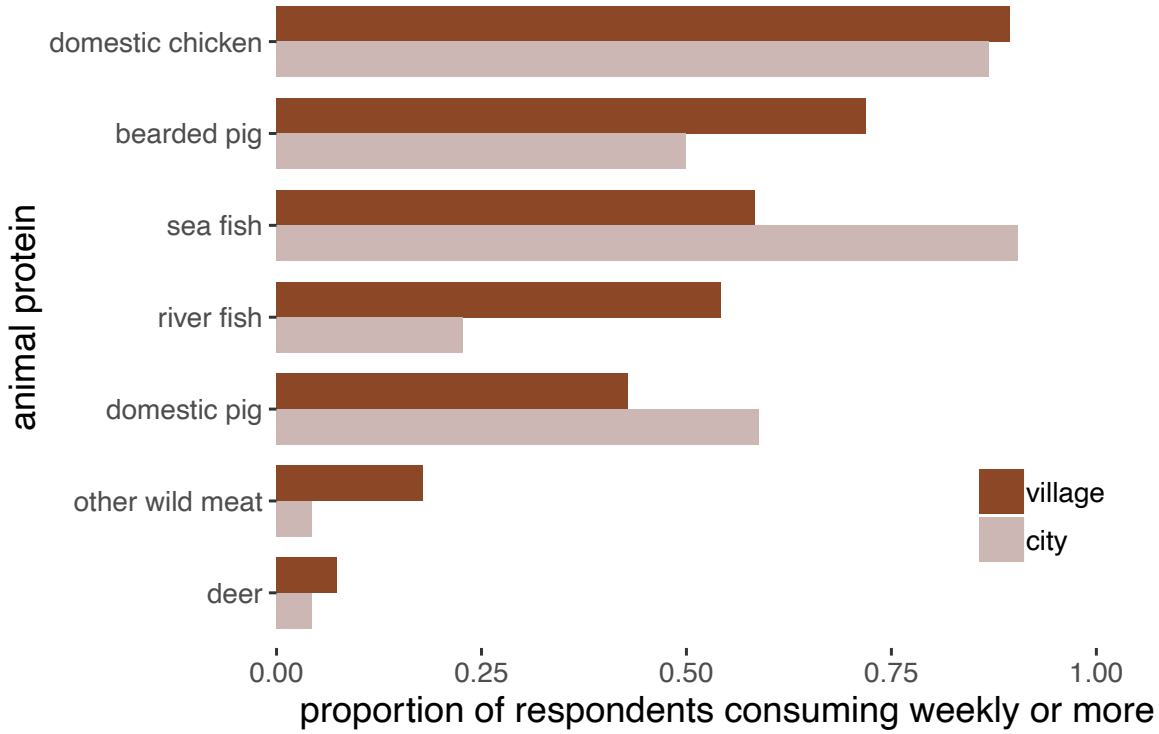

Figure 2. Comparison of animal protein consumption by respondents in village and urban contexts.

Hunting motivations

Food provision was the most commonly cited hunting motivation (36 respondents, 97% of pool); other major hunting motivations cited were pest control (22, 59%), gift giving (20, 54%), and hobby (19, 51%) (Figure 3). Food provision was also the primary hunting motivation for the vast majority of respondents (31 respondents, 85%), followed by sale (2, 6%), pest control (2, 6%), and hobby (1, 3%) (Figure 3).

Some hunters were very clear about the importance of bearded pig meat as a central food source. For example, Matasing said: "It is the main source of food for people who live in the villages" (*"Dia menjadi sumber makanan orang kampung"*). For some hunters, it was important that hunting bearded pig was a way of life. Gasam said that his father taught him: "This is our life. We live in the forest; this is our food." Jempurung responded: "We cannot leave [stop eating] the pig." (*"Kami tidak boleh tinggalkan babi."*) For many respondents, hunting bearded pigs was also regarded as an important form of pest control to limit bearded pig disturbance of oil palm plantations (both industrial and smallholder) and garden crops, such as cassava and durian. Multiple hunters also referenced the importance of sharing bearded pig meat communally at parties, weddings, marriages, Christian events, and other celebrations, and the community expectations that therefore motivated them to hunt. One hunter shared that during certain months "there are many requests" [to supply bearded pig meat], due to seasonal parties and celebrations. Several respondents also mentioned satisfaction in their hunting ability; for example, Sumping said, "Only the village people have what it takes to know what the pig needs" (*"Only the kampung punyai people men know what the babi need bah"*).

Selling bearded pig meat for money was cited as a secondary motivation for hunting among a minority of respondents (10 respondents, 27%), followed by respondents citing other motivations (6, 16%). Respondents expressed mixed perceptions of hunting bearded pig for sale. Some hunters said they never hunted for sale, and felt that selling bearded pig meat was irresponsible because it contributed to pig population declines. Others felt that selling bearded pig meat was unnecessary, even reprehensible, due to the robust KDM cultural practice of gifting the meat. For example, Jempurung captured the sentiment of many KDM hunters towards selling bearded pig meat: "Don't sell it, if people ask just share it." *("Bukan jual lah, kalau orang minta bagi-bagi lah.")* However, for other hunters who sold bearded pig meat regularly or occasionally, the sale was an important source of income. Monthly income from pig hunting was reported to be as high as 5000 MYR (~1,194 US$) in a good month, substantially higher than wages earned in oil palm plantations. Hunters generally reported current bearded pig meat prices to be roughly 10-15 MYR / kilogram, and by contrast reported prices around 3-5 MYR / kilogram around 10 years ago (much lower than current prices, even when adjusted for inflation).

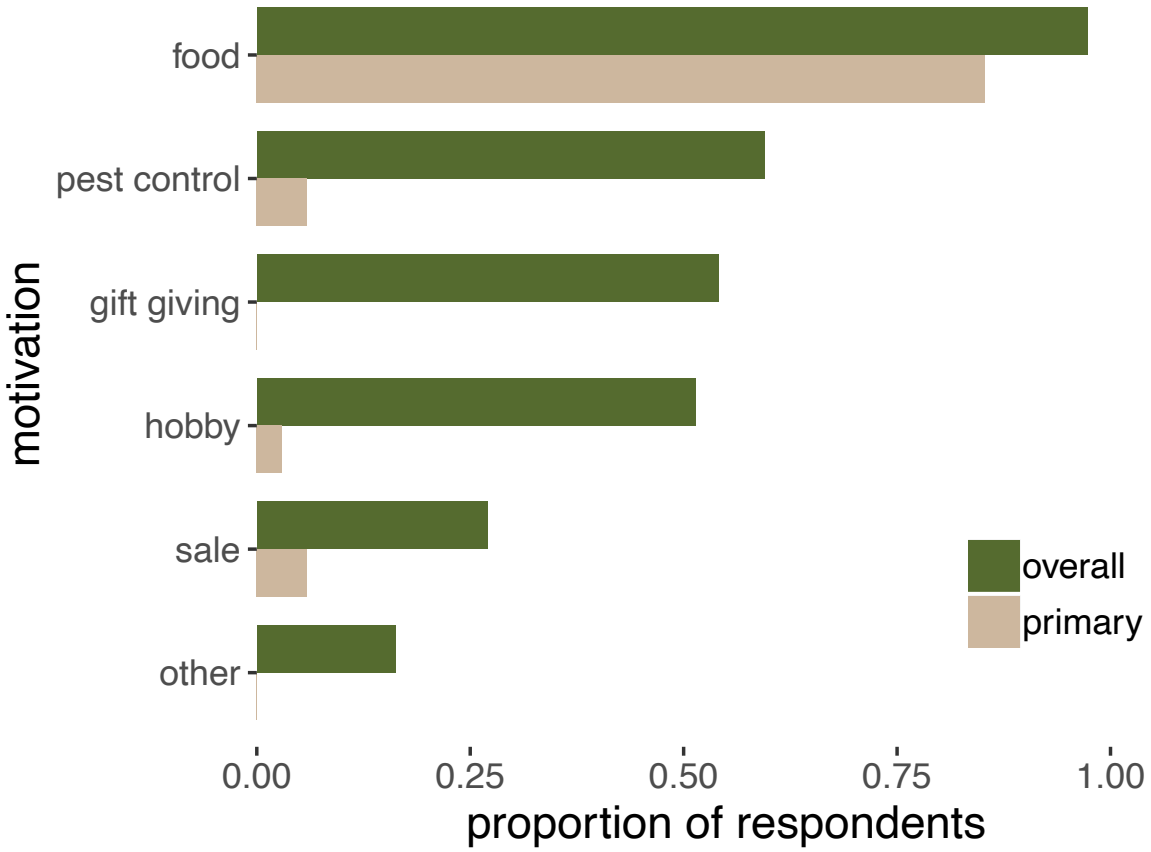

Figure 3. Common motivations of respondents (n = 37) to hunt bearded pig. "Overall" motivations indicate that a motivation was affirmed by a given hunter (regardless of rank order), whereas "primary" motivations indicate that the motivation was listed as the number one motivation for that hunter.

Hunting technique persistence over time

We found no significant difference in hunting techniques between respondents who began hunting before 1985 and those who began in 1985 or later (Fisher's exact test, $p > 0.99$). Overall, the most popular hunting techniques that respondents had used were: (a) on foot with a gun (28 respondents, 83% of respondents); and (b) drive hunts with a gun (25, 75%), although numerous other techniques were also widely used (Figure 4). Hunting with dogs and a spear as well as with snares were also common among our respondents.

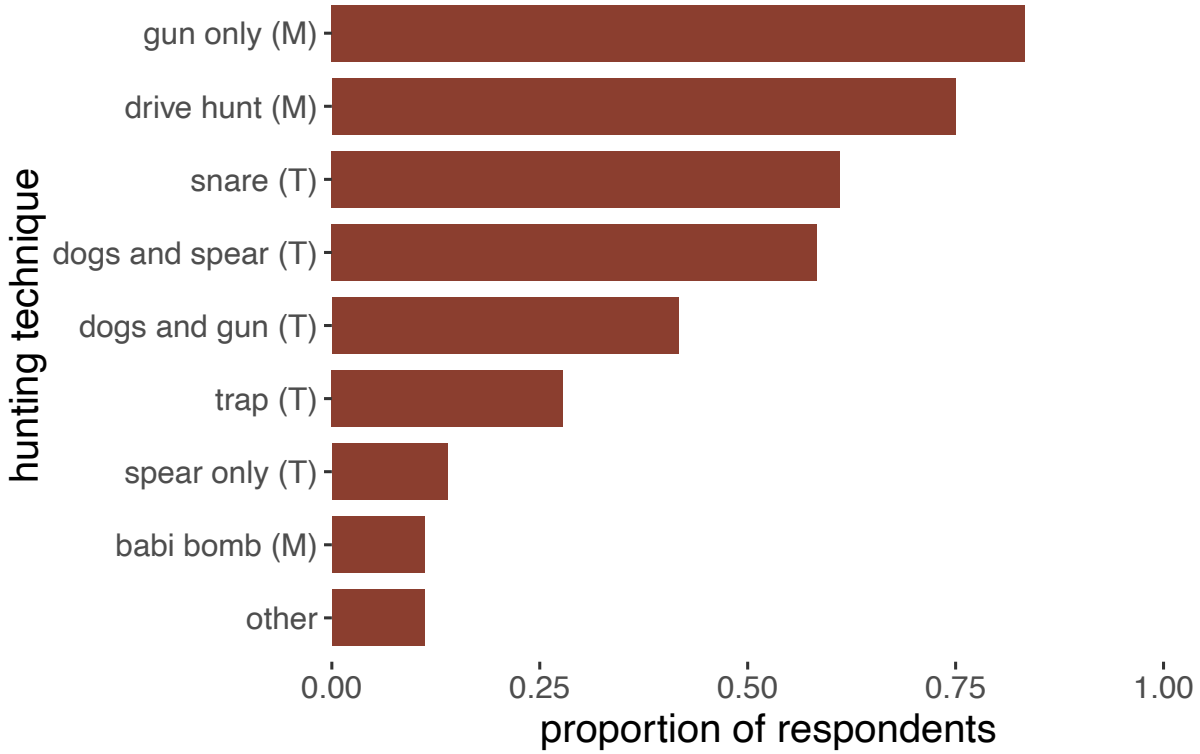

Figure 4. Proportion of KDM hunters within respondent pool (n = 34) who had used a variety of traditional (T) and modern (M) techniques for hunting bearded pig.

Respondents cited a variety of reasons why they preferred different hunting techniques. For some, hunting location was a major factor in the technique used. For example, hunting on foot with a gun was possible in all habitat types, whereas drive hunts were mentioned in connection with oil palm plantations. Other factors dictating the use of different techniques included success rate, effort and cost required, personal preference, and availability of tools such as guns and ammunition. For example, Tamin commented: "Who in the world would use a snare when you have a gun!" (*"Mana ada mahu jerat sudah! Ada senapang."*) Hunting techniques specific to long-distance bearded pig movements were not reported among our respondents.

Hunting success was highly variable, with hunters citing success rates per hunt ranging from roughly 25% to 100%. On average, hunters reported success obtaining a bearded pig on 25% - 50% of hunts. Hunt lengths varied between several hours to a full day or night.

Regulatory factors influencing contemporary bearded pig hunting practices

Hunters were generally aware that regulations existed about hunting bearded pigs, and that permits were required to legally hunt wildlife and sell wild meat. Several hunters shared stories about enforcement of these laws, or referenced permit requirements when explaining their own reasoning about hunting decisions. Sometimes respondents shared specific costs associated with hunting permits, which were considered by some hunters to be expensive. However, despite their general awareness of the regulatory environment around hunting bearded pig and other species, there was inconsistency and confusion in understanding permit requirements and hunting regulations. There was also a shared perception that Wildlife Department and Forestry Department officials, among others, were frequently monitoring forest areas for illegal hunting. For example, Tiko said, "Many of my friends have been fined by the Wildlife Department."

DISCUSSION

We found several lines of evidence indicating that important hunting practices have been reshaped by oil palm expansion and urbanization, as well as results showing that hunting motivations and socio-cultural practices involving consumption of bearded pig meat continue to be robustly expressed in contemporary KDM communities in Sandakan District, Sabah. Respondents indicated several distinct themes differentiating hunting practices in oil palm plantations and forest. Additionally, many hunters—particularly older hunters who started hunting before 1985—perceived changes in bearded pig behavior over time. Hunter dietary patterns also revealed important differences in meat consumption between village and city life. However, hunting motivations and techniques were consistent with past records of hunting practices within Indigenous Bornean communities. Together, these results point to the endurance and transformation of hunting practices within our KDM hunting respondent pool, and suggest a need for hunting that sustain meat provision, socio-cultural practices, and bearded pig populations.

Oil palm expansion drives changes in contemporary KDM bearded pig hunting practices

The different characteristics reported between hunting in oil palm plantations and forests indicate an important shift in contemporary KDM hunting practices. With roughly a quarter of Sabah's land area now under plantation agriculture, mostly oil palm (Gaveau et al. 2016), and the majority of our study area under oil palm agriculture (Figure 1), increasing and shifting hunting practices in oil palm plantations carry important implications for people and pigs across Sabah. For KDM people, the qualities of the pig hunting experience have already changed substantially. Our respondents noted that hunting in oil palm typically involves more waiting for pigs to forage on oil palm fruits at predictable locations, and that they can more easily see and find pigs in the wider, open environment of an oil palm plantation. Respondents also mentioned that hunting in oil palm plantations is typically easier and less tiring, requiring less walking for extended distances as compared to hunting in forests, and sometimes involving

hunting from a car. In Sabah, just two decades ago the vast majority of bearded pig hunting took place in forest contexts and typically on foot with a gun (Bennett et al. 2000), and for millennia across Borneo bearded pig hunting took place in a habitat defined primarily by forests (e.g. Medway 1964). Many village settings in our study area are located adjacent to, or even within, agricultural landscapes, which are disproportionately associated with higher pathogen infection rates and zoonotic disease emergence (Shah et al. 2019, Rohr et al. 2019). The increase in contemporary bearded pig hunting within oil palm plantations therefore raises important concerns about potential public health risks to KDM pig hunters and communities.

Pest control was a common hunting motivation among our respondents, highlighting another major influence of oil palm cultivation on pig hunting patterns. More than half of our respondents cited pest control as a motivation to hunt bearded pigs. Three quarters of our respondents worked in oil palm at some point in their lives, many of them as smallholders and some in industrial oil palm plantations; bearded pigs are often regarded as pests in both settings. Bearded pigs are regarded as pests within oil palm plantations (Meijaard et al. 2018); this is due to their rooting behavior, similar to that of the wild boar, which also damages young oil palm trees in plantations (Jambari et al. 2012, Luskin et al. 2014), with potentially important economic implications. Jambari et al. (2012) recorded pest control of wild boar as an important motivation for oil palm workers hunting for consumption and sale in plantations in Peninsular Malaysia. Our results indicate a similar pattern for pest control as a secondary motivation for pig hunting among our study population of KDM hunters in Sabah. In addition to the other influences of oil palm cultivation on pig hunting, five respondents noted the different taste of bearded pig meat from oil palm and forest, with three expressing a clear preference for pig meat from forest (e.g. noting the meat tasted sweeter, and less smelly, from forest as compared to oil palm plantations). This partiality for bearded pig meat has been reported elsewhere in the literature (e.g. Bennett et al. 2000, Janowski 2014). Taken together, these findings suggest that oil palm expansion is reshaping a variety of environmental, technical, economic, and alimentary aspects of contemporary KDM pig hunting and cultural practices.

Perceived changes in the behavioral ecology of bearded pigs

When asked if they had noticed a change in bearded pig behavior over the last several decades, 17 hunters noted that pigs today are *"wilder"* or *"smarter"* —seemingly more skittish—as compared to the past. Janji, for instance, claimed "In the past they weren't wild, [but] now they are more wild to hunt." *("Dulu tidak liar, sekarang liar diburu"*, where wild means quick to flee or harder to catch). Similarly, Bukarak commented "They are a bit wilder" *("Ada liar sikit"*) and said "It means he [the pig] has an IQ" ("*Bermakna dia ada IQ"*). A number of hunters noted that pigs have become increasingly sensitive to hunter presence, including stimuli such as gunshots, gunpowder smell, and headlamp lights. Hunters explained that the pigs responded to these stimuli by fleeing more readily than in the past (Box 1). Rapid fleeing behavior in response to human hunting has also been recorded in other ungulates, including duikers (Croes et al. 2007), reindeer (Reimers et al. 2009), and red deer (Chassagneux et al. 2020).

Further research could investigate the causes and mechanisms of these changes in bearded pig behavioral ecology. High behavioral plasticity, which has been suggested as an adaptive

response of red deer in Norway (Lone et al. 2015), could be a mechanism, as could evolutionary selection for individuals with elevated flight response. Further research could also investigate whether habitat fragmentation and oil palm expansion is a potential cause of this behavioral shift. Our study area in Sabah has high hunting accessibility (Deith & Brodie 2020), which could elevate the actual or perceived risk to wildlife in the area (Gaynor et al. 2019). Recent ecological evidence from Sabah suggests substantial rates of bearded pig crop raiding in oil palm plantations (Love et al. 2018, Davison et al. 2019), which was widely reported amongst our respondent pool as well. We therefore hypothesize that bearded pigs in many parts of Sabah are employing a "high risk, high reward" strategy of feeding on cross-border oil palm fruit subsidies, providing access to high-fat food resources but also elevating risk due to human hunting in oil palm plantations, potentially causing elevated flight responses in pigs.
Finally, responses from hunters suggest further research should investigate links between oil palm-driven fragmentation and bearded pig nomadic movements. In our study, several older hunters had seen or heard of movements of large herds of bearded pigs, a behavior thought to indicate historical patterns of bearded pig nomadism (Caldecott et al. 1993). Younger hunters, however, had typically not observed this aggregating behavior amongst bearded pigs. This pattern is consistent with speculation of declines of bearded pig nomadism in the literature due to habitat fragmentation (e.g. Luskin & Ke 2018). Moreover, oil palm fruit subsidies to bearded pigs in many areas—as shown with wild boar (*Sus scrofa*) (Luskin et al. 2017)—could reduce or eliminate the ecological basis for bearded pigs to make nomadic movements at all. As has been shown with logging (Granados et al. 2019), we hypothesize that oil palm-driven habitat fragmentation is causing a reduction in bearded pig responses to mast fruiting events, as well as the loss of traditional ecological knowledge of these migrations and hunting practices associated with them. Further research should investigate this hypothesis through social and ecological studies of habitat fragmentation, long-range pig movements, social memory, and traditional ecological knowledge.

Urbanization as a driver of changes in contemporary KDM pig hunting practices
Shifted dietary patterns and reduced hunting tied to urbanization reflected important elements of change in our study. In urban contexts, hunter responses suggested that bearded pig was a favored delicacy but not an indispensable source of food given the widespread availability of wild fish and domestic chicken and pork. While bearded pig was the fourth-most commonly consumed meat source for our respondents in urban contexts, in village contexts bearded pig was the second-most consumed meat source (Figure 2). As urbanization increases in Sabah (Cai 2018), our study suggests that reduction of bearded pig consumption levels in urban contexts may be one way in which reliance on bearded pig meat is lessening in modern times. Additionally, the time commitments related to urban jobs and increased distance from hunting locations resulted in lower hunting for seven of our respondents. The proportion of the Sabah population in gazetted areas of 10,000 people or greater has roughly tripled in the last half century, rising from 16.9% in 1970 to 53.2% in 2005 (Department of Statistics Malaysia 1977, Department of Statistics Malaysia 2010, Yaakob et al. 2010). Urbanization may be weakening not only consumption of bearded pig meat within the KDM community, but also the hunting relationship that has connected people and pigs across Borneo for millennia (Medway 1964, Harrison 1998).

Enduring links between historical and contemporary KDM pig hunting practices

While KDM hunting practices appear to be changing in important ways, motivations and techniques to hunt bearded pigs spoke to enduring links between KDM communities and pigs. The hunting motivations we recorded among KDM hunters in Sandakan district are in step with the outcomes Bennett & Sompud (2000) recorded in Sabah and Sarawak, with meat provision as the primary motivation for bearded pig hunting. Presumably meat provision was also the primary motivation for Indigenous bearded pig hunting across Borneo for millennia, based on archaeological dig sites showing bearded pig bones in sites used for food consumption (Medway 1964). Additionally, Bennett & Sompud (2000) found that wild meat presence in rural villager diets was directly related to the abundance of bearded pigs in the forest, and unrelated to alternative sources of food and income. Thus, bearded pigs were generally hunted if they were locally available, whether or not local communities were directly reliant upon them. Some hunters did not rely on bearded pig meat; however, we also encountered hunters who regarded bearded pig meat as essential to their livelihoods and food security. For example, in describing his motivation to hunt, Gitom said simply: "It's a matter of survival." *("Pasal – untuk survive lah.")* Finally, as there was no significant difference in hunting techniques used by older and younger hunters (i.e. hunters who began hunting before or after 1985), our results suggest that common bearded pig hunting techniques—a blend of modern and traditional techniques (Figure 4)—have likely persisted for at least the last two generations of hunters.

The ceremonial and communal importance of bearded pig meat remained central for the KDM respondents in our study. Weddings, church events, family gatherings, festivals, birthdays, and other celebratory occasions were considered by many hunters to be incomplete without wild meat, typically bearded pig. As Gitom noted: "The bearded pig is our tradition. For celebrations you only use the bearded pig." (Note: Other wild game meat is still used by some; for example, feral buffalo was also mentioned in connection with celebrations. However, bearded pig meat is indeed standard fare at many KDM cultural events.) Barbecued, sautéed, or roasted bearded pig was widely considered a favorite delicacy among our respondent pool, and for many the sharing and consuming of this delicacy constituted a centerpiece of communal celebrations. The significance of bearded pig meat for cultural events is also evident in the high proportion of respondents (54%) who ranked "gift-giving" as a secondary motivation to hunt. Sharing bearded pig meat, in everyday life and in special life events, has been part and parcel of many Indigenous societies in Borneo (Wadley et al. 1997, Chin 2001); our results indicate that this species continues to be a cultural touchstone today.

Regulatory factors influencing contemporary bearded pig hunting practices

State-wide regulations and enforcement may be playing a role in reducing the frequency of KDM hunting of bearded pigs. As Jay shared, *"Sekarang, beli babi jak – sibuk – takut undang-undang"* ("Now, you just buy pig because either you're busy or you're afraid of the law"). Many respondents were aware of hunting regulations, as has been shown for hunters in northern Sabah as well (Wong et al. 2012). Important conservation legislation requiring licenses for hunting bearded pig passed in the 1990s (Sabah Wildlife Enactment of 1997), and enforcement has increased in many areas of the state (e.g. Latip et al. 2015). We hypothesize that the permitting system and/or enforcement of hunting laws could be influencing the frequency of

hunting behavior in Sabah. While our study was not designed to directly understand this relationship, future work addressing the relationship between wildlife law enforcement and KDM pig hunting would be a valuable contribution to understand sustainable biocultural conservation in Sabah. Adding to this dynamic, in 2020, hunting licenses were frozen by the Sabah Wildlife Department due to the Movement Control Order put in place during COVID-19 (Chan 2021, The Star 2021). With the confirmed spread of African Swine Fever to multiple Sabah districts in early 2021, the Wildlife Department has maintained the freeze on hunting licenses and prohibited the selling of *sinalau bakas*, a popular smoked form of wild bearded pig meat (Borneo Post 2021). For biocultural conservation of the KDM - bearded pig socio-ecological system, we recommend that local and state government officials and conservation managers consider flexible and location-specific management approaches. These approaches should include local KDM and other Indigenous peoples to identify and preserve culturally important practices (Bridgewater & Rotherham 2019).

CONCLUSION

Our results speak to both the endurance and reshaping of historical hunting practices among contemporary KDM communities in Sabah, Malaysia. Several important hunting motivations and techniques were maintained amongst our respondents, including meat provision as the primary motivation to hunt and hunting with guns as the primary technique used for bearded pigs. However, our findings also indicate that KDM hunting practices have changed substantially, with oil palm plantations as (a) a more common hunting environment than recorded in the past in Sabah; and (b) a context for reshaped hunting practices by KDM hunters in our study as compared to hunting practices in forest. Additionally, urbanization has led to lowered levels of bearded pig meat consumption and less time for some KDM people to hunt bearded pigs. Our study has shown both the persistence and malleability of Indigenous KDM pig hunting practices. Amidst ongoing oil palm expansion, urbanization dynamics, and broader political-economic changes, environmental governance initiatives should support these cultural traditions while ensuring sustainable bearded pig populations. Through robust collaborative planning and flexible regulation, bearded pig management plans can ensure fair access to the meat provision, socio-cultural benefits, and pest control from sustainable bearded pig hunting, while also ensuring long-term conservation of bearded pig populations, ecological functions, and habitat.

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Chapter 4. Diminishing transfer of bearded pig hunting knowledge among Indigenous peoples of Sabah, Malaysia

ABSTRACT

Human hunting practices are declining in communities across the globe, reflecting shifts in ecological conditions, values and knowledge. In Borneo, Indigenous communities have been hunting bearded pigs for millennia, and bearded pig meat continues to be the most widely consumed wild meat source for many local communities. The degree to which Indigenous hunting knowledge is passed on between generations is critical for preserving traditional ecological knowledge (TEK) as well as for sustainable bearded pig management. These goals are particularly urgent given the recent outbreak of African Swine Fever (ASF) among bearded pig populations in Sabah, Malaysia, which has caused multiple local bearded pig extinctions. To document quantitative and qualitative evidence for shifts in intergenerational hunting of bearded pigs in Borneo, we interviewed 36 Kadazandusun-Murut (KDM) hunters in Sabah, Malaysia. Respondents reported that the transfer of hunting knowledge was deeply relational, with three-quarters of hunters having learned to hunt from a relative, friend, or neighbor. Most respondents obtained knowledge by participating in hunts, where they observed and assisted more experienced hunters. When asked if they had or would transfer their knowledge to their children, 65% of respondents said that they had not or would not pass on their knowledge. These findings suggest that KDM bearded pig hunting practices are threatened, and raise questions about how bearded pigs will be valued—and therefore conserved—in future generations. Preserving Kadazandusun-Murut bearded pig hunting practices in Sabah will require a rebound in bearded pig populations, wildlife management that allows sustainable offtake of bearded pigs for Indigenous communities, and active community participation among Indigenous youth. This case study adds to a growing body of literature documenting declines in traditional ecological knowledge and hunting-related ties to wildlife and landscapes.

INTRODUCTION

Human hunting is in widespread decline globally (Condon et al. 1995, Rambaldi et al. 2007, Schorr et al. 2014). This pattern broadly holds across continents, for subsistence as well as sport hunting (Wexler 2014, Winkler & Warnke 2013). The increasing loss of this behavior—fundamental in human societies for millennia—raises important questions about the nature and future of human-environment interactions in a world with diminished hunting. What layers of meaning connect cultural groups to nature through hunting practices and food provision? What does a loss of hunting knowledge mean for youth and for their connections to their cultural heritage? Finally, what are the implications of declining human-environment links for environmental value formation, and conservation of biodiversity?

Hunting declines shape, and are shaped by, shifting values between generations.

In many places, values that encourage or lead to hunting behavior have declined significantly over the last several decades (e.g. Manfredo & Zinn 1996, Wexler 2014). For example, among Cree women in subarctic Canada, values associated with hunting and Indigenous knowledge declined in the younger generation due to a more sedentary lifestyle, schooling, and the advent

of television (Ohmagari & Berkes 1997). Luz et al. (2015) also recorded a negative relationship between schooling and hunting activity. However, in other cases, hunting values continue to endure, adapt, or even increase with modernizing environmentally-conscious paradigms (Schorr et al. 2014, von Essen 2018). However, the prevailing trend of decline in hunting values and practices speaks to an important transformation of human-environment interactions in the world today.

In Borneo, hunting relationships between people and pigs have had extensive cultural and dietary significance for millennia (Harrison et al. 1961, Medway 1964). In many Indigenous, non-Muslim communities across Borneo, hunting and consumption of bearded pigs (*Sus barbatus*) is common (Bennett et al. 2000, Puri 2005). In fact, 54-97% of wild meat consumed in Indigenous Bornean communities is bearded pig meat (Bennett et al. 2000, Chin 2001, Puri 2005). Additionally, several cultural practices associated with bearded pig consumption, such as gift-giving and celebratory feasts, have endured (Kurz et al. in review). However, oil palm expansion and increased urbanization are resulting in transformations to hunting and dietary practices in Sabah (Kurz et al. in review). This trend, if true across Borneo and other parts of the world, suggests that transformations of hunting and dietary practices could be linked to broader shifts in societal connections to nature. Layers of conservation values have been linked to wildlife harvest, and hunting can be linked to conservation values and funding mechanisms (Heffelfinger et al. 2013, Delibes-Mateos et al. 2014).

To answer this question and investigate changes in intergenerational hunting knowledge, we carried out short, open-ended surveys with Kadazandusun-Murut (KDM) hunters in Sandakan District, Sabah, Malaysia. We asked hunters about: (a) relational dimensions of hunting (who taught them to hunt); (b) modes of hunting knowledge transfer (how they learned to hunt); and (c) frequency of hunting knowledge transfer (whether they would pass on their knowledge to their children). These themes take on particular significance given the recent outbreak of African Swine Fever (ASF) across central, eastern, and interior Sabah (The Borneo Post 2021, Vanar 2021), which has resulted in confirmed bearded pig population crashes in several forest reserves (S. Nathan, pers. comm.). Using the results of these surveys, we draw conclusions about the nature of changes in intergenerational KDM hunting knowledge within our respondent pool, and potential outcomes for KDM hunting practices in the context of post-ASF Sabah.

METHODS

Study Area

Our study context was Sandakan District, on the east coast of Sabah, Malaysia (Figure 1). Sandakan is one of the largest cities in Sabah, with almost 400,000 inhabitants (Malaysia Department of Statistics 2015). Regionally, Sandakan is a key port city, oil industry hub, and center for the industrial palm oil industry (Sabah State Government 2014, Mulok et al. 2015). Of the total population of Sandakan District, 63% of inhabitants are Malaysian citizens and 37% are non-citizens. Among the Malaysian citizenry, 71% are *Bumiputera* (Indigenous "sons of the land") and a large minority (25%) are of Chinese descent (Malaysia Department of Statistics

2015). The land cover of Sandakan district is primarily industrial oil palm plantations, although several tracts of intact forest remain (Gaveau et al. 2014, Figure 1).

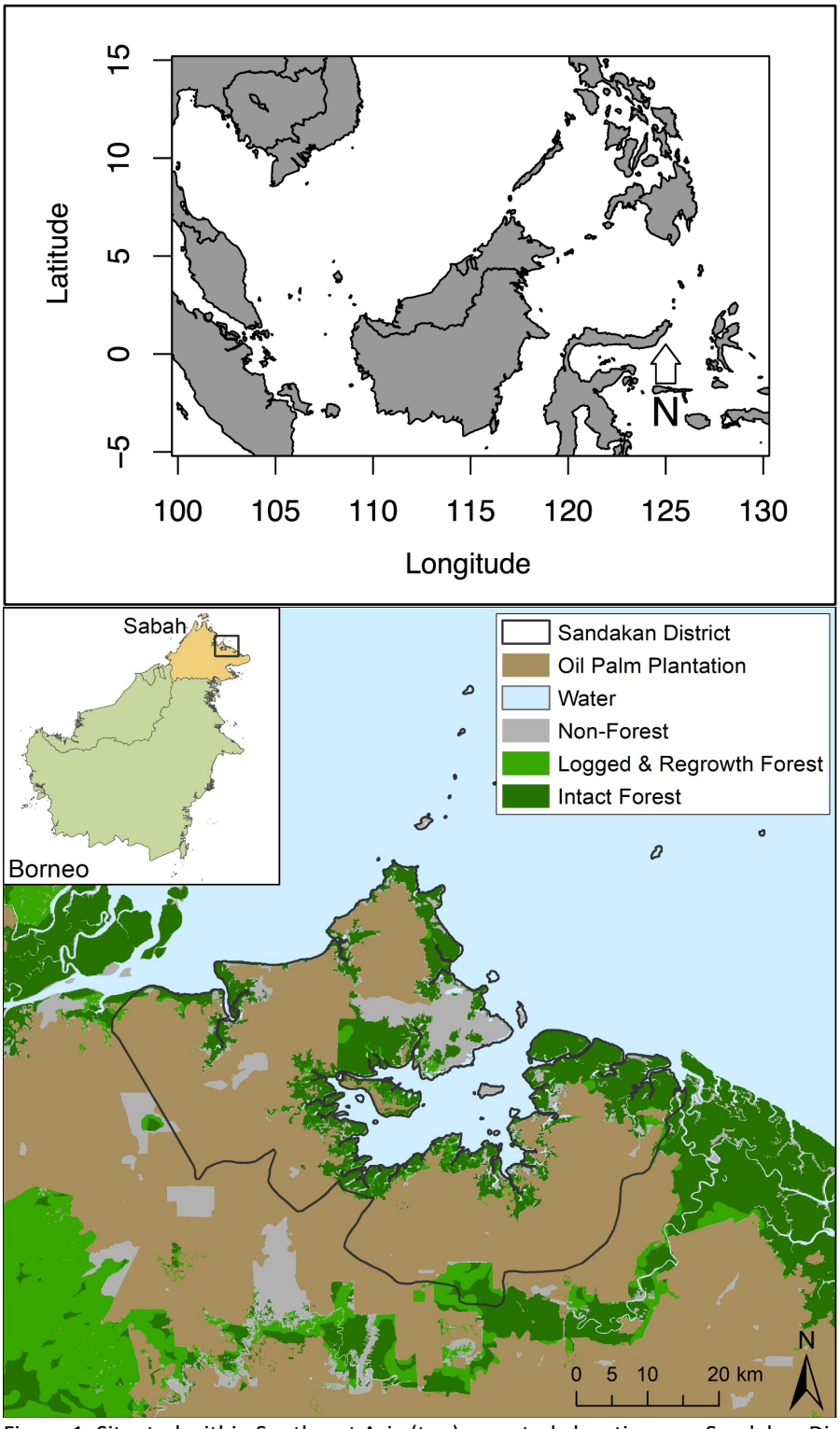

Figure 1. Situated within Southeast Asia (top), our study location was Sandakan District, on the East Coast of Sabah, Malaysia (bottom).

Data collection

We carried out 36 short, semi-structured interviews with bearded pig hunters as part of a larger interview study (Kurz et al. in review). The pool of respondents was all male, which is typical of hunting practices within Indigenous communities in Borneo (Thambiah 2016). We considered a "hunter" to be an individual who hunted bearded pigs at least twice per year on average, for a span of at least five years at any point in his lifetime. To build our respondent pool, we relied on referral sampling, through which hunters connected us with others in their community or network (Luskin et al. 2014). Through this approach, and by obtaining permission from the village chief as appropriate, we developed trust and social credibility with our respondents. We asked each respondent for verbal consent to participate in the study. To safeguard participant privacy we did not record respondent names or any audio from the interviews. We did not provide compensation for participation in the study.

The primary interviewers (JB and VTJ) each spoke fluent Bahasa Melayu (Malay). Interviews were generally conducted in Bahasa Melayu, but occasionally English was used if respondents were comfortable speaking English. Interviews were conducted with either one respondent at a time, or in a small group (2-3 individuals) according to social and communal norms. Interviews took place in a space in which the respondent was comfortable, e.g., an office, church, or village common space. We asked respondents open-ended questions about hunting knowledge transfer from older generations to their generation, knowledge transfer between them and their children, and their perceptions of generational shifts in hunting practices and values (see Supplemental Material for study questions in Bahasa Melayu and English). Taken together, these questions were typically answered in 15-20 minutes or less. For more detailed methods and for information about the broader study, see Kurz et al. in review.

Respondent characteristics

Mean respondent age was 47 years (range: 26-72 years). Of the 36 respondents, 29 responded that they had children. Education levels among respondents varied from attending Form 1 (13 years of age) to university. Respondents were employed in a wide variety of fields, including oil palm agriculture (industrial and smallholding), government forestry positions, police and security work, farming, rideshare driving, the clergy, entrepreneurship, and self-employment. Respondents were interviewed in both village (*kampung*) and urban (*bandar*) settings, with many respondents traveling between both environments for work and family reasons.

Data analysis

We focused our analysis on the relational dimensions, modes, and frequency of intergenerational hunting knowledge transfer. To quantitatively categorize respondent answers within each theme, we relied primarily on manifest coding, i.e. coding of distinctive answers to specific questions (Aberbach & Rockman 2002). For example, in response to the question "Will you / have you taught your children how to hunt?", we recorded the number of hunters who indicated that they had, or planned to, teach their children to hunt, and the number of hunters who indicated that they had not (or would not). We also qualitatively analyzed our data using inductive content analysis (Elo & Kyngäs 2008), identifying and developing themes from individual interviews into a broader framework of generational transfer of hunting knowledge

within our respondent pool (Dhee et al. 2019). To ensure the privacy of respondents, we associated each of the quotations presented with a pseudonym. Most quotations are presented in English, except where we also include the original Bahasa Melayu to reflect the original character and expression of the respondent.

RESULTS

Relational dimensions of intergenerational knowledge transfer

Hunting knowledge transfer within our respondent pool was deeply relational. Three-quarters (27 of 36) of hunters reported being taught to hunt by at least one—and often several—people within their community (Table 1). A wide variety of relationships provided this hunting training, including elders, fathers, uncles, grandparents, neighbors, and friends (Figure 2). Several hunters mentioned being taught by people from more than one relational category (e.g., elders and uncles). For some hunters, learning (or not learning) hunting from a father seemed to take on a special importance. A son's inheritance of the family gun from his father was one indication of this particular relationship. One respondent who did not have the opportunity to learn how to hunt from his father described feeling "very rugi", or a "sense of loss".

Modes of intergenerational hunting knowledge transfer

Respondents identified several modes of intergenerational hunting knowledge transfer. By far the most common mode of knowledge transfer was participation in hunts with more experienced hunters. Many respondents described accompanying older or more experienced hunters on hunts, often at a young age (Table 1). During these preliminary trips, hunters described observing hunting techniques, learning hunting grounds and pig tracks, listening to instructions provided by older hunters, and assisting with various tasks (e.g. carrying equipment, transporting meat back to the village, etc.). After months or years of learning these skills, eventually more experienced hunters would teach newer hunters how to kill pigs themselves, e.g. by teaching them to shoot or set snares.

A minority of respondents reported learning how to hunt by themselves, although often these hunters nonetheless had been taught critical hunting skills or approaches by others. For example, several hunters learned how to shoot from family members or through service in the army or police force, and then applied these skills to hunting bearded pigs.

Transfer of intergenerational hunting knowledge

We identified a clear decreasing trend in intergenerational hunting knowledge transfer among our respondent pool. Of 23 respondents who directly answered the open-ended question, "Will you / have you taught your children how to hunt?", 15 hunters responded that they had not or would not, as compared to 8 hunters who responded that they had or would (Figure 3). In response to the question, "Is hunting important to the younger generation?", 16 respondents said that they thought that hunting was not important to the younger generation. For example, Kunol (Box 1) hypothesized that young people were more interested in mobile phones or alternative food options than in hunting. Three hunters also suggested that increases in hunting regulations made it more difficult for the younger generation to hunt. Another perception was

that increased ties to cities made hunting less accessible for young people than it had been in the past.

Table 1. Salient themes of hunting knowledge transfer reported by respondents in a Kadazandusun-Murut pig-hunting community in Sabah, Malaysia.

Major themes of hunting knowledge transfer	# hunters
Taught to hunt by community (elders, relatives, friends, or neighbors).	27
Perception that the younger generation has less desire to hunt.	16
Did not / will not teach his children to hunt.	15
Started to hunt at age 12 or younger.	11
Started to hunt at age 13-19.	10
Started to hunt at age 20-30.	8
Taught / will teach his children to hunt.	8

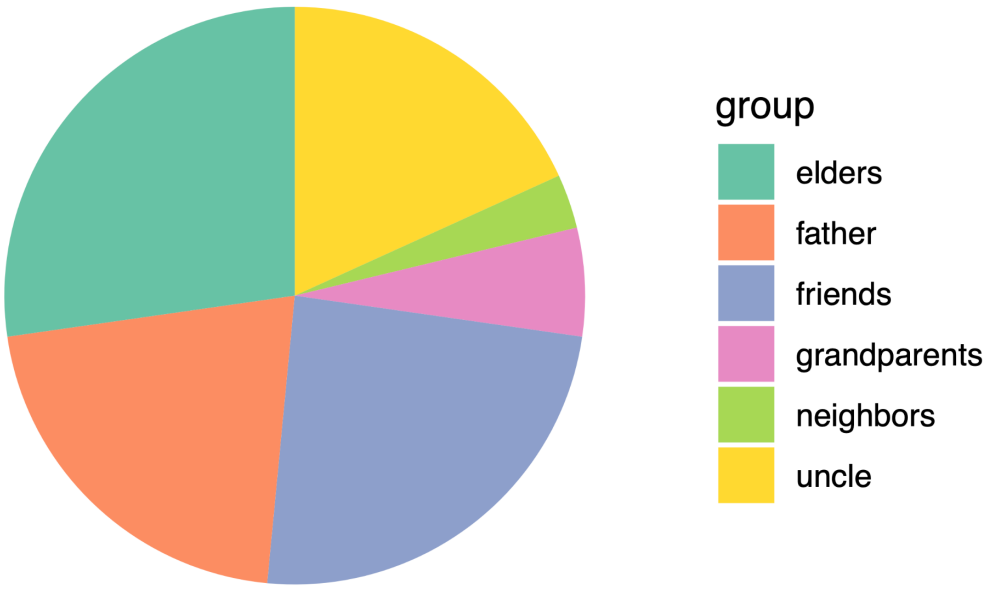

Figure 2. Diversity of community relationships involved in inter-generational hunting knowledge transfer within a sample of Kadazandusun-Murut hunters in Sabah, Malaysia.

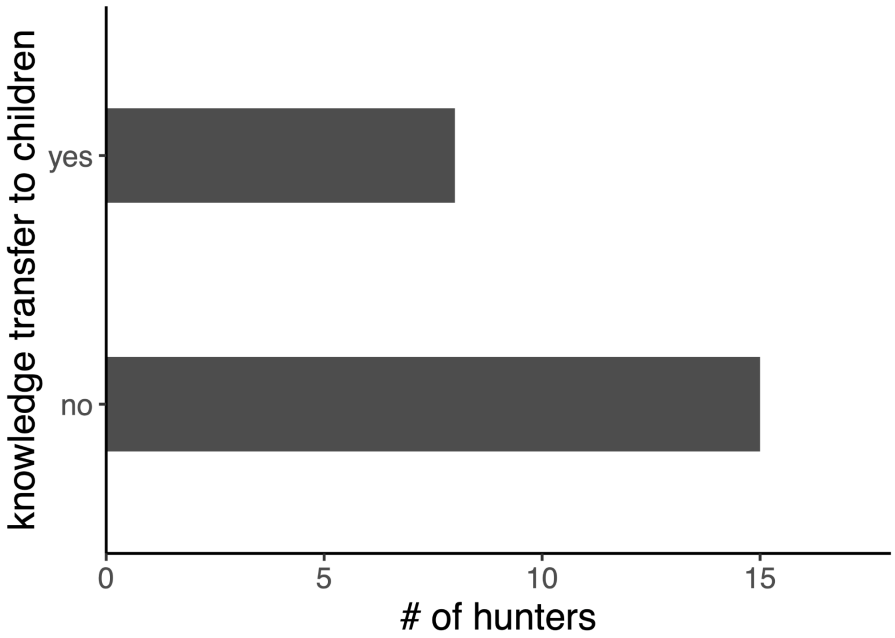

Figure 3. Comparison of hunters who have (or plan to) transfer hunting knowledge to their children, and hunters who have not (or plan not to) transfer hunting knowledge to their children.

Intergenerational dynamics of hunting knowledge transfer

"Maybe they [the younger generation] are not interested - they're more interested in their Mobile Legends [phone game]...They only eat hot dogs, KFC, and McDonald's - that's their food already...They're not interested [in hunting] and they don't know how to get food in the forest." -Kunol

"Most animals today are protected; you can't encourage the youth to poach." -Gitom

"Yes [I have taught my children hunting], because they should continue the traditional village way of life so that the traditions are not lost in the modern era. Moreover, they don't need to 100% work before school. If they don't succeed [at school or work], hunting will give them the basic principles to be independent." -Sumping

"It [hunting] is not necessarily important [to the younger generation]. It's only to find food or if you like it. It's not for most people, mainly for village people." -Yoko

"My elders taught me. I would follow them and then know how to bring along the [hunting] dogs." -Burakak

Box 1. Qualitative evidence of intergenerational hunting knowledge transfer within the respondent pool of Kadazandusun-Murut hunters.

DISCUSSION

Hunting knowledge transfer within the Kadazandusun-Murut respondent pool was mediated through a rich diversity of community relationships. Through these relationships, respondents learned to hunt by active participation in Indigenous bearded pig hunting practices. However, almost twice as many respondents had not, or were not planning to, pass along their hunting knowledge to their children. This steep ongoing dropoff in hunting knowledge within the community is likely to be accelerated by ASF, which has decimated bearded pig populations in our study region.

Importance of community and active participation

Robust community relationships and active participation in the forest were central components of the hunting knowledge passed down to our respondent pool. There was no single relationship that formed the predominant context for knowledge transfer among respondents; rather, respondents referenced a range of community relationships involved in teaching them to hunt. These diverse and close community bonds have been reported in Indigenous hunting societies around the world (Condon et al. 1995, Ohmagari & Berkes 1997). Moreover, regardless of the relationship of the older and younger hunter in the knowledge transfer relationship, by far the most common mode of knowledge transfer was active participation in a pig hunt. Respondents in our study frequently described accompanying older hunters, observing and assisting them, before gradually taking on more hunting responsibilities (Wexler 2014). These themes highlight the importance of geographic proximity, cultural connectedness, and active hunting lifestyles for continued pig hunting knowledge transfer within KDM communities.

Widespread loss of hunting knowledge

We record an unfolding process of widespread loss of hunting knowledge transfer within our KDM respondent pool that reflects global trends of loss in Indigenous knowledge. Of the 23 hunters who answered whether they have (or will) teach their children to hunt, 15 (65%) said that they had not or plan not to transfer their knowledge. Additionally, 16 hunters said that they perceived that hunting was not important to the younger generation, sometimes citing this as the reason they would not teach their children to hunt. These findings accord with case studies from around the world, in both Indigenous and post-industrial societal contexts, showing a widespread diminishing of traditional hunting knowledge and desire to practice hunting among youth (Condon et al. 1995, Manfredo & Zinn 1996, Rambaldi et al. 2007, Blenkinsop 2017). Respondents also raised the possibility that increased hunting restrictions and technological distractions contributed to the decline in hunting among KDM youth. In other case studies, education has been negatively tied to hunting practices among youth (Ohmagari & Berkes 1997, Wexler 2014, Luz et al. 2015); however, this was not cited as a major factor by respondents in our study.

Implications of African Swine Fever

Exacerbating the unfolding loss of pig hunting knowledge among KDM communities, bearded pig population collapse due to ASF threatens to further reduce hunting knowledge. ASF has now decimated bearded pig populations across most of Sabah east of the Crocker Range (S.

Nathan, pers. comm.). African Swine Fever is a rapidly spreading emerging infectious disease in the pig family (Suidae), with close to 100% case fatalities reported among free-living Eurasian wild boars *(Sus scrofa*) and domestic pigs (*S. scrofa*) (Luskin et al. 2020). In early 2021, the disease spread to Sabah, resulting in confirmed deaths of bearded pigs in the Lower Kinabatangan Wildlife Sanctuary, Danum Valley Conservation Area, Imbak Canyon Conservation Area, and other forests in the state.

As a result, there are fewer opportunities for the active, relational hunting contexts in which most pig hunting knowledge transfer occurs. The timescale of a potential recovery of bearded pigs in this region is unknown. Bearded pigs have the capacity to reproduce quickly, with average litter sizes of 7-9 piglets (Luskin & Ke 2018). Therefore, recovery of the species in favorable, protected habitat could occur relatively quickly if the habitats are ASF-free or if some individuals are resistant to the viral disease. However, low pig populations for several years, as well as potential ASF transmission concerns or hunting restrictions for an additional period of time, could severely reduce opportunities for KDM communities to participate in bearded pig hunts. While hunting has of course led to many conservation problems (Harrison et al. 2016, Peres et al. 2016), including local species extinctions (Brashares et al. 2001), it is also increasingly being recognized as an important conduit for environmental value formation and conservation (Heffelfinger et al. 2013, Delibes-Mateos et al. 2014). Proximity to wildlife, and even techniques used in hunting (e.g. falconry), lead to tangible conservation benefits, such as conservation volunteering and payment of fees for habitat conservation (Kenward 2009, Schummer et al. 2020). Robust conservation ethics have been reported among KDM bearded pig hunters in Sabah; some hunters recognize the importance of sustainable levels of offtake and discourage hunting pig meat for sale (Kurz et al. in review). A drop in bearded pig hunting knowledge and activity in Sabah raises concerns for how future generations of Sabahans will value bearded pigs and conserve critical habitat that protects pigs and a wide range of other species (Bernard et al. 2013). For integrated biocultural conservation goals (Rozzi 2013), cultural sensitivity as well as ecological integrity is critical for long-term sustainability.

CONCLUSION

The complex, ancient socio-ecological relationships between bearded pigs and KDM communities are more imperiled than ever. In addition to the declines in hunting knowledge transfer within KDM communities that we report, the effects of ASF on pig populations, hunting restrictions, and public perceptions of hunting will likely reduce pig hunting in Sabah in at least the near-term. This could therefore be a critical inflection point for the ways that bearded pigs are valued within KDM communities and managed by state authorities. Long-term research attention, balanced management, public outreach, and empowerment of local stakeholders in Sabah are needed to protect the integrated goals of sustainable food provision and cultural heritage of KDM communities as well as robust bearded pig populations.

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Chapter 5. Concluding Remarks

LESSONS FROM TELECOUPLING

Global forces of telecoupling are shifting the scale and speed of human-environment interactions globally (Hull & Liu 2018), including a number of telecoupling effects connected to Sabah. In Chapter 3, I discussed the ways that global demand for oil palm has led to land-use change in Sandakan District, Sabah, reshaping Indigenous hunting practices. I also considered the tragic and profound example of telecoupling through disease, with the outbreak of African Swine Fever (ASF) leading to local population crashes of bearded pigs throughout central and eastern Sabah. In a world in which globalized markets, trade, and transit are nearly impossible to avoid, these developments in my study system are a stark reminder of the new degrees to which human society and the environment are deeply interconnected, even from opposite ends of the globe.

LAND USE CHANGE, SOCIAL CHANGE, AND WILDLIFE DISTRIBUTIONS

The telecoupling of global markets with local land-use change is also tied to social change in Sabah. As industrial oil palm plantations and forest concessions—for logging and conservation—have taken primacy on Sabah's lands, many local people have decided, or been forced to, move to cities. Chapter 3 explored pathways through which this urbanization has shifted dietary habits, including lowered consumption of bearded pig meat in urban settings, and has made it more difficult for people to hunt. Moreover, as Chapter 4 showed, most Kadazandusun-Murut (KDM) hunters we interviewed are deciding not to pass on their hunting knowledge to their children. At the same time, land-use change has also increased logging road coverage and reduced the distance to forest edges in many parts of Sabah (Gaveau et al. 2014), thereby making hunting more accessible, as I explored in Chapter 2. This paradox, of declining connections to nature in the midst of increased accessibility to nature, in tandem with ethnically-distinctive hunting preferences, seems to have context-specific influences on bearded pig distributions, as shown in Chapter 2. The intricate interweaving of environmental change, social change, and wildlife responses reminds us of the importance of quantifying and centering socio-cultural factors as we seek to understand and manage complex coupled human and natural systems (Liu et al. 2007).

LOOKING TO THE FUTURE OF HUMAN-ENVIRONMENT INTERACTIONS

In a more fragmented world that is less connected to nature, many questions must be asked about the conservation of the natural world and our place in it. What does it mean for hunting to be in decline in many parts of the world, including in many Indigenous societies? What are the bases for, and conduits through which, we most robustly feel connected to nature? What are the implications for conservation values in a more tech-engaged, and less nature-engaged, young generation? How do we make funding mechanisms work, or create new mechanisms, to fund conservation that has been supported in many places through recreational hunting?

There are no easy answers to these questions, but my dissertation strives to make a few inroads into these rich, complex areas. In Chapter 4, I discussed how intergenerational hunting

knowledge transfer is declining, in part due to low interest in hunting and in the forest among the young generation. These trends point to a future in which hunting among KDM peoples in Sabah is diminished, with important implications for values associated with conservation — for bearded pigs and generally. Similarly, these dynamics are echoing across the world, as many Indigenous communities try to reconcile their deeply place- and nature-based historical values and practices with a rapidly modernizing world in which these connections are diminished (e.g., Ohmagari & Berkes 1997, Blenkinsop 2017). In Sabah and globally, these trends also raise important questions about food security and the safety net of wild meat for communities who lack other protein or livelihood options (Brashares et al. 2011). These complex narratives challenge us all, as a conservation community, to refrain from assumptions about the place of hunting and other cultural practices, and to welcome introspection, investigation, and inclusion of diverse voices at the table. Long-standing socio-ecological links—from hunting to creation stories—are often tied to intangible, but profound, value systems and opportunities for sustainability. I am grateful to join many others in asking questions, and pursuing insights, about the reciprocal relationships that tie us to wildlife, ecosystems, and to one another.

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