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Bearded pig (Sus barbatus) utilisation of a fragmented forest-oil palm landscape in Sabah, Malaysian Borneo

Running head: Bearded pigs in fragmented tropical landscapes


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**Context:** Oil palm plantations have become a dominant landscape in Southeast Asia, yet we still understand relatively little about the ways wildlife are adapting to fragmentated mosaics of forest and oil palm. The bearded pig is of great ecological, social, and conservation importance in Borneo and is declining rapidly due to habitat loss and overhunting.

**Aims:** We sought to assess how the bearded pig is adapting to oil palm expansion by investigating habitat utilisation, activity patterns, body condition, and minimum group size in a mosaic composed of forest fragments and surrounding oil palm.

**Methods:** We conducted our study in Sabah, Malaysian Borneo, in and around the Lower Kinabatangan Wildlife Sanctuary, an area consisting of secondary forest fragments (ranging 1200-7400 ha) situated within an extensive oil palm matrix. We modelled bearded pig habitat use in forest fragments and oil palm plantations using survey data from line transects. Camera traps placed throughout the forest fragments were used to assess pig activity patterns, body condition, and minimum group size.

**Key results:** All forest transects and 80% of plantation transects showed pig presence, but mean pig signs per transect were much more prevalent in forest (70.00 ± 13.00 SE) than in plantations (0.91 ± 0.42 SE). Pig tracks had a positive relationship with leaf cover and a negative relationship with grass cover; pig rooting sites had a positive relationship with wet and moderate soils as compared to drier soils. Pigs displayed very good body condition in forests across the study area, aggregated in small groups (mean = 2.7 ± 0.1 SE individuals), and showed diurnal activity patterns that were accentuated for groups with piglets and juveniles.
Conclusions: Our findings suggest that bearded pigs in our study area regularly utilise oil palm as habitat, given their signs in most oil palm sites surveyed. However, secondary forest fragments adjacent to oil palm remain the most important habitat for the bearded pig, as well as many other species, and therefore must be conserved.

Implications: Consistent bearded pig presence in oil palm is a potential indication of successful adaptation to agricultural expansion in the study area. The good physical health displayed by most pigs may result in part from year-round cross-border fruit subsidies from oil palm plantations, whilst the predominance of diurnal activity (especially by groups containing piglets and juveniles) may indicate a behavioural response to predation or human hunting. However, the net effect of oil palm expansion in the region on bearded pig populations remains unknown.

Additional keywords: activity pattern; body condition; habitat use; Lower Kinabatangan; matrix; mosaic; Suidae
Introduction

One of the most pressing areas of conservation research in recent years has been understanding the extent to which forest species can (or cannot) adapt to habitat loss and fragmentation caused by land use change (e.g. Fitzherbert et al. 2008; Gilroy et al. 2015; Newbold et al. 2015). This is particularly true for large parts of Southeast Asia, where oil palm (*Elaeis guineensis*) expansion is the primary driver of deforestation and subsequent wildlife loss (Koh and Wilcove 2008). Many taxa – including ants (Fayle et al. 2010), bats (Fukuda et al. 2009), beetles (Chung et al. 2000), birds (Aratrakorn et al. 2006), frogs (Konopik et al. 2015), lizards (Glor et al. 2001), moths (Chey 2006), primates (Danielsen & Heegard 1995), and small mammals (Yue et al. 2015) – exhibit declines in species richness when tropical forests are replaced by oil palm monocultures. Moreover, even when species are not lost, deforestation caused by oil palm expansion can lead to declines in wildlife abundance, loss of functional diversity, and changes in animal behaviour (Foster et al. 2011; Alfred et al. 2012; Edwards et al. 2014). However, species do not respond uniformly to oil palm expansion and forest fragmentation; species richness and abundance sometimes stay the same or even increase in oil palm as compared to forest (e.g. Liow et al. 2001; Davis & Philips 2005; Luke et al. 2014). Frequently, specialist species are the ecological ‘losers’ that are declining in this transition due to habitat loss or modification, whilst generalist species that thrive in human-altered environments tend to be among the ‘winners’ (McKinney & Lockwood 1999, Fitzherbert et al. 2008).

Southeast Asia is known for its widespread and highly diverse Suidae, the majority of which are listed as vulnerable or endangered (IUCN 2016), yet the...
response of wild pigs to oil palm expansion is understudied. The Eurasian wild boar
(Sus scrofa), perhaps the best-studied wild pig species, has been known to reach
high abundances in forest remnants adjacent to oil palm, likely benefitting from fruit
subsidies provided by plentiful, year-round fruit production in plantations (Ickes
2001). However, whether this pattern is consistent in other areas and with other wild
pig species has yet to be investigated. Given the important role played by wild pigs in
structuring plant communities (Ickes et al. 2001; Ickes et al. 2003; Cole et al. 2012),
understanding how pigs (native or introduced) are responding to tropical land use
change could hold major ecological implications for forest-oil palm landscapes.

The bearded pig (Sus barbatus) has great ecological, social, and conservation
importance in its native Sundaland (Caldecott et al. 1993). As a forest-dwelling suid
(Bernard et al. 2013), it is adapted to a migratory lifestyle in response to mast fruiting
cycles, although it can also be found in oil palm plantations (Yue et al. 2015). It is
also an ecosystem engineer, removing saplings to build its nests, turning over soil
through its rooting behaviour, and acting as a seed predator of many rainforest tree
species (Boogaarts 1938; Curran and Leighton 2000; Curran and Webb 2000; Linkie
and Sadikin 2003). Bearded pigs are known to be an important prey species for large
predators including the Sunda clouded leopard (Neofelis diardi), estuarine crocodile
(Croodylus porosus), and reticulated python (Python reticulatus) (Pfeffer and
Caldecott 1986; Caldecott 1988; Auliya 2003; Ross et al. 2013). Additionally, the
bearded pig has been an important protein source for humans in Borneo for over
35,000 years (Medway 1958), of which it has been the primary mammalian target for
at least 15,000 years (Harrison 1998). The bearded pig continues to provide the
majority of wild meat consumed in Borneo, accounting for between 54 and 97% of
wild meat consumption by weight (Bennett et al. 2000; Chin 2001; Puri 2005). As a
result of its popularity as a game species, overhunting (exacerbated by habitat fragmentation), along with habitat loss, has led to an estimated 30% decline in bearded pig populations over a recent 21-year period, leading to its designation as a Vulnerable species on the IUCN Red List (Kawanishi et al. 2008). Given its vital ecological functions and abundant provision of protein, sustainable bearded pig management should be a high conservation priority in Borneo.

Basic ecological research on bearded pig adaptation to forest-oil palm mosaics is therefore a clear first step. We studied several aspects of bearded pig natural history in a fragmented alluvial forest that serves as both an important wildlife corridor and a case study for tropical landscapes characterised by interspersed patches of forest and oil palm. We sought to assess how the bearded pig is adapting to oil palm expansion by comparing pig habitat use between secondary forest fragments and oil palm plantations, as well as collecting data in forest fragments on daily and seasonal activity patterns, minimum group size, and body condition. We present management implications from these findings and outline directions for future research.

Materials and methods

Study area

The study was conducted in the landscape surrounding Danau Girang Field Centre (5.413711, 118.037646), located in the Lower Kinabatangan floodplain in eastern Sabah, Malaysia. The Lower Kinabatangan Wildlife Sanctuary (LKWS) consists of ten protected forest lots. The lots display a range of sizes (1200 - 7400 ha) and structural connectivity, including narrow riparian corridors and small areas of
privately-owned forest (Abram et al. 2014). In addition to designating protections of wildlife sanctuaries, the Sabah Wildlife Enactment of 1997 declared the bearded pig a protected species, although hunting is allowed outside of protected areas with a license. Mean annual precipitation is approximately 3460 mm, with mean monthly temperatures ranging from 23-40°C (B. Goossens, unpubl. data). In drier areas, the landscape is dominated by secondary lowland dipterocarp forest, with some areas of riparian forest (Ancrenaz et al. 2004). Frequent inundation by flooding causes zones of low-stature forest and grassland, with wetter regions encompassing areas of mangrove and swamp forest (Ancrenaz et al. 2004; Estes et al. 2012). Between 1960 and 1995, large parts of the region were logged for hardwoods and cleared for agriculture (Gillespie et al. 2012; Gaveau et al. 2014). Oil palm plantations now occupy at least 48% of the floodplain (Abram et al. 2014).

Data collection

Bearded pig presence was assessed using line transects, and data on body condition, activity patterns, and minimum group size were collected using camera traps. Ten line transects (100 m long x 10 m wide) were randomly placed (minimum 2 km apart) in both oil palm and secondary forest sites (Fig. 1). Each transect was surveyed five times by a team of 2-5 surveyors between February and April 2014. One observer (K. Love) was present for all data collection, allowing for standardization of protocol. Intervals between surveys ranged from 12-16 days to allow sufficient time for sign accumulation. Surveyors indirectly recorded pig habitat utilisation along each transect by noting the number of tracks, rooting sites, mud grazes, wallowing holes, scat, and nests (Payne et al. 1985). Pig signs were cleared
or marked between transect surveys to prevent duplicate counts. The quantity of individual signs was recorded for each sign type on each transect, and all equivalent signs within 1 m$^2$ were used as a single sign count to standardize tallies. A Topofil thread measuring device (Fremaco Devices Inc., Owen Sound, Canada) and compass were used for straight surveying that ensured comparable transect pathways during repeat surveys. Transects were examined with surveyors spread equally across the 10 m wide transect.

Soil texture from each survey was categorised using a 1-5 score based on moisture level (1: very wet, 5: dry and dusty). Understory density was recorded every 25 m of each transect using a Robel pole, which contained 47 equally partitioned 2 cm stripes. Density estimations were made at a height of 0.5 m above ground level, and a distance of 10 m between observers. Substratum composition for each transect was estimated from a 2 m$^2$ plot placed every 25 m along transects, in which the percentage of the following substrata were recorded: leaves, soil, grass, shrub and stone (Fig. S1). Using ImageJ (version 1.45S) software, we calculated average canopy cover by taking canopy photos at a height of 1.65 m in the middle of each substrate plot. We used Google Earth (version 7.1.2.2041) to calculate the distance from transect mid-sections to water sources and forest-plantation boundaries. For the purpose of the study, we assumed that pigs did not cross the main river during the short sampling period, as crossings are mainly reported during migratory behaviour rather than during typical daily movements (Meijaard 2000).

To assess bearded pig body condition and minimum group size, we used an extensive network of 110 camera trapping stations spread across the same forest fragments as the line transects, although covering a much larger area than the
transect locations (Figs. 1, 2). Camera traps were not placed in oil palm plantations due to the high risk of theft. Camera trap images of bearded pigs were collected from November 2011 to December 2013 using Reconyx HC500, Hyperfire, and PC800 infrared digital camera traps. Each camera station was positioned 30-50 cm off the ground along ridges and existing wildlife trails. Physical condition of pigs was assessed following the categories of Wong et al. (2005) (Table S2). Pigs were given a fat index of 1-5, with 5 being the best possible body condition. Pig age classes (i.e. infant, juvenile, sub-adult and adult) and time of activity (date and time of day) were documented. For photographs of pig groups taken within 1 hr of one another, we considered the independent sample to be the photograph with the highest number of individuals (Bernard et al. 2013, Brodie and Giordano 2013). We removed images that were blurred, too dark, blocked from view, or otherwise unsuitable for assessing body condition.

**Data Analysis**

We used generalized linear mixed effects models in the *lme4* package (Bates et al., 2014) to model the number of bearded pig tracks and rooting sites as a function of nine habitat variables: the percentage ground covered by leaves, soil, shrub, grass, and stone, the distance to the nearest permanent water source (river, oxbows, and/or tributaries) and to the nearest forest-oil palm boundary, ground fruit presence, and soil texture (with textures 1 and 2 considered “wet”, texture 3 considered “moderate”, and textures 4 and 5 considered “dry”). We used a correlation matrix to ensure that all variables were relatively independent ($| r | < 0.6$). We did not model wallow holes, mud grazes, scat, or nests because there were insufficient frequencies
of these signs to produce statistically rigorous results. These signs are known to appear relatively infrequently (wallow holes, mud grazes, nests), or are difficult to detect due to high decomposition rates in rainforest conditions (scat, e.g. Heise-Pavlov & Meade 2012). We modelled the number of rooting sites only in forest because there were also insufficient frequencies of rooting sites in oil palm. We included site as a random effect to account for dependence between the transects at each site, and in our models of pig tracks we included habitat type (forest or oil palm) as a variable in every model to account for the strong effects of habitat type on the other environmental variables. We scaled and centered all continuous variables prior to analysis. We created generalized linear mixed effects models for the negative binomial family, which is useful for modelling overdispersed ecological count data (Lindén and Mäntyniemi, 2011). To focus modelling on the most influential variables, we first compared generalized linear mixed effects models of each of the habitat variables independently to a global model and a null model only containing the intercept. We selected the best models to determine the strongest predictors of pig tracks and rooting sites using the Akaike information criterion corrected for small samples sizes (AICc) (Burnham and Anderson, 2004). We considered models with ΔAICc values of at least two less than the null model as plausible models, and considered the model with the lowest AICc value as our best model. Model parameters were determined to be significant if the 95% confidence interval around the estimate did not overlap zero. After we determined which variables had a significant effect on the bearded pig signs independently, we modelled all combinations of significant parameters to determine if any models containing a combination of variables performed better than the single-variable models. All models were run in R statistical software Version 3.2.4. (R Core Team, 2000).
All other analyses were conducted using Minitab (version 17) and R (version 3.0.1) statistical software. Anderson darling and Shapiro-Wilk tests were used to test for normally distributed pig sign and activity data. We used a two-sample t-test to test for differences in the mean number of detected pig signs between forest and oil palm, based on the total number of signs per transect.

To characterise pig activity patterns, we pooled photographs in two different ways: (i) using four intervals (0300 – 0859 h, 0900 – 1459 h, 1500 – 2059 h and 2100 – 0259 h) representing dawn, daytime, dusk and night (Payne et al. 1985; Ross et al. 2013); and (ii) using two intervals, diurnal (0600-1759 h) and nocturnal (1800-0559 h). The same values could be used throughout the year due to the small variation in day length in our study area. Chi-squared tests were used to compare differences in activity between time classifications. We used body condition scores (Table S3) to determine average body condition for each month. As there were likely pigs that were not captured in our camera trap photographs, group size estimates are considered minimum group sizes and may be underestimates. However, we report group sizes in line with other camera trap studies of wild pigs (Linkie and Sadikin 2003, Bengsen et al. 2011).

Results

Habitat use

A total of 93 transect surveys (forest = 44, plantation = 49) across 20 transects (forest = 10, plantation = 10) confirmed bearded pig presence in all transects in forest and 8 of 10 transects in oil palm plantations. Pig sign was 1-2 orders of
magnitude more prevalent \( (t = 13.07, \text{df} = 18, \ p < 0.01) \) in forest than in plantation transects (Table 1). When comparing the models of pig tracks and rooting sites containing each habitat variable independently and a global model to a null model, every model performed better than the null model; this pattern emerged because the habitat variable (i.e. ‘forest’ or ‘oil palm’) had a strong, significant effect in every model, with forest having significantly more pig tracks and rooting sites than oil palm.

In the single-variable models of pig tracks, all models had \( \Delta \text{AICc} \) values of at least two less than the null model because the habitat type variable was highly significant in every model. The other significant variables were percentage of ground covered by leaves and grass. When modelling pig tracks using the combination of the two variables (with habitat type remaining as a controlling variable), the model of percentage of ground covered by leaves still had the lowest AICc value (Table S5). Leaf cover had a significant positive relationship with number of pig tracks (Table 2). Grass cover had a significant negative effect on number of pig tracks when it was the only variable in the model (Table 2).

In the single-variable models of pig rooting sites in forest, the only significant variable was soil texture. Moderate and wet soils both had significantly more pig rooting sites than dry soils (Table 2).

\[ \text{Approximate location of Table 2} \]

\textit{Minimum group size and encounter rate}

Camera traps documented a total of 1995 independent encounters of bearded pigs, with a mean minimum group size of 2.68 individuals (\( \pm 0.1 \ \text{SE}, \min = 1, \max = 32 \)).
Pigs were recorded at all camera sites, with a total camera trap encounter rate of 0.63 independent photographs/100 hours.

**Body condition and minimum group size**

From the 1995 independent encounters, 4161 individual pigs were scored to body condition. The majority of pigs possessed ‘Very Good’ (59.4%) and ‘Good’ body condition scores (35.6%), with relatively few pigs defined as ‘Fair’ (4.6%) and ‘Poor’ (0.4%). No pigs classified as ‘Very Poor’ were identified. During each month of the sampling period, >90% of individual pigs detected had a body condition of ‘Very Good’ or ‘Good’.

[Approximate location of Figure 3]

**Activity patterns**

Activity patterns varied significantly over the course of 24 hours (Chi-Sq. = 168.25, df = 3, p < 0.01), with far fewer pig occurrences at night (Chi-Sq. = 129.87, df = 1, p < 0.01). Activity was mostly diurnal, peaking early in the morning from 0600 – 0700 h, and again from 1700 – 1900 h (Fig. 3). Groups containing infants and juveniles (n = 218) were almost exclusively active during daytime hours (Fig. 3).

**Discussion**

We show that bearded pigs are widespread in a fragmented forest-oil palm mosaic landscape increasingly typical of Southeast Asia. Bearded pigs in our study region appear to preferentially utilise secondary forest habitat as compared to oil palm plantations. Pig habitat utilisation is positively associated with leaf cover and
negatively associated with grass cover. Additionally, pigs preferentially used wet and moderate soil types (as compared to drier soils) for rooting behaviour. Bearded pigs tended to aggregate in small groups (mean = 2.7 individuals ± 0.1 SE) and the vast majority appeared to be in ‘Good’ or ‘Very Good’ physical condition (Table S3), suggesting that the population of bearded pigs detected at camera traps was generally healthy throughout the study period. Pigs were largely diurnal, with activity peaks at dawn and dusk, and groups containing infant and juvenile pigs were even more active during the day than groups without piglets and juveniles. These findings provide a basic ecological foundation for future work on the adaptation of a threatened large mammal species to extensive anthropogenic influences, especially deforestation, habitat fragmentation, and over-hunting.

Implications of bearded pig habitat use

Bearded pig signs were recorded on all forest and most oil palm transects in our study area, although far more signs were documented in forest than oil palm. This pattern could either reflect a difference in habitat utilisation by the pigs or a difference in sign detectability. Given the strong influence of habitat and substrate features in our models, it is likely that the much more abundant pig sign in forest does in fact reflect a higher degree of utilisation of forest by pigs. The positive relationship between leaf cover and pig tracks suggests that certain habitat features within forest (e.g. trees, leaf litter) are preferred by pigs. Additionally, the negative
relationship between grass cover and pig tracks may help explain the lower presence of pig tracks in oil palm, which contained a higher proportion of grass cover than forest did (mean grass cover – oil palm: 33.9%, forest: 8.1%). Lower detectability of tracks in grass could also play a role in this relationship. There is also a strong possibility that bearded pigs are using forest and oil palm habitats differently; for example, we did not record wallowing, mud grazing, or nest building behaviours in plantations (Table 1). Furthermore, oil palm habitats may have less favourable conditions for rooting behaviour, given the hotter and drier conditions as compared to forest (Luskin and Potts 2011). Our models show that rooting behaviour was positively associated with wet and moderate soils, which were more frequently found in forest (mean soil texture – forest: 3.4, oil palm: 4.6; lower values are wetter). These patterns align with other studies on wild pig habitat use showing lower levels of pig sign in grassy habitats (e.g. Welander 2000) and a positive relationship between rooting activity and moist soils (e.g. Mitchell et al. 2008).

Whilst our results suggest that bearded pigs are using forest more than oil palm to meet many of their ecological needs, they also suggest that bearded pigs may be adapting somewhat successfully to fragmented forest-oil palm landscapes, an encouraging sign for conservation. The healthy body condition of pigs as well as the utilisation of 80% of the oil palm sites surveyed point to the presence of some resources of value to pigs in oil palm. Feral pigs take advantage of agricultural areas near forest habitat in many parts of the world, often increasing in density (Caley 1993, Ickes 2001) and/or body size (Dexter 2003) as a result of the extra food subsidies. However, there also appear to be thresholds of agricultural area relative to natural habitat area at which pigs are unable to persist due to their need to access forest and woodlands (Choquenot & Ruscoe 2003, Kawanishi et al. 2008). Finally, it
is possible that oil palm plantations may be having adverse effects on bearded pigs by functioning as an “ecological trap” that decouples typical cues from true habitat quality (Weldon & Haddad 2005), attracting pigs to favourable habitat features or food resources and thereby making them more vulnerable to hunting for subsistence, commercial sale, pest control, and/or sport, as is the case with *S. scrofa* in Sumatra (Luskin et al. 2014). However, our study notes only general patterns of bearded pig habitat use; further research in a variety of landscapes is needed to ascertain the net effect of oil palm expansion on bearded pig habitat utilisation, behaviour, and resource selection.

**Body condition and fruit availability**

Bearded pig body size and condition is known to fluctuate dramatically in sync with the abundance of resources available and the competition for those resources (Wong et al. 2005, Luskin & Ke, in press). Therefore, the year-round good body condition we observed could speak to significant hunting-limited pig densities (as observed elsewhere, e.g. Chin 2001), abundant food availability within our study landscape, or both. Bearded pig meat is easily the most preferred species of wild meat in Borneo, accounting for 54-97% of the wild meat consumed in non-Muslim rural areas on the island (Bennett et al. 2000, Chin 2001, Puri 2005). However, there have been no studies quantifying the effects of hunting on bearded pig populations in
the Kinabatangan; while hunting is known to occur, it is not clear how important it is in limiting bearded pig densities and thereby influencing body condition.

While bearded pigs feed on leaves, roots, fungi, invertebrates, small vertebrate, and carrion, their cycles of body condition, growth, and breeding have been mainly linked to fruit availability (Caldecott et al. 1993, Curran & Webb 2000, Wong et al. 2005, Luskin & Ke in press). Oil palm fruit subsidies from plantations are widespread in our study area, and Ficus sp. are abundant in the LKWS (Azmi 1998) and are likely to be a key food source. Ficus sp. fruit has been described as a ‘keystone resource’ that helps sustain bearded pig populations during the extended, inter-mast intervals of low productivity that characterise Southeast Asian rainforests (Appanah 1985; Wong et al. 2005). However, in a human-modified, fragmented landscape like our study area, it is unclear how bearded pig body condition responds to periods of extended drought. The constant supply of year-round fruit from oil palm plantations could mitigate the population-suppressing effects of this natural cycle for bearded pigs in the Lower Kinabatangan, but the complex interactions between oil palm fruit subsidies, rainforest phenological cycles, habitat fragmentation, and bearded pig population dynamics have yet to be untangled.

**Behavioural implications of minimum group size and activity patterns**

Minimum group sizes in the LKWS averaged 2.7 (± 0.1 SE) individuals, as compared to 1.9 (± 0.3 SE) reported in Kerinci Seblat National Park in Sumatra (Linkie and Sadikin 2003). Given the distribution of pigs throughout most of our study area, the lack of large-scale herding behaviour, and the continuous abundance of oil palm fruit subsidies, pig populations of the LKWS may be largely sedentary (Caldecott et al.
Caldecott et al. (1993) reference a bearded pig population state similar to this in the *Koompassia-Burseraceae* forest in Peninsular Malaysia, characterised by populations with local movements that exploit concentrated, predictable food resources that allow for high breeding and growth rates. This would appear to be the closest known population state corresponding to the bearded pigs in our study, although further research is necessary to corroborate this hypothesis.

Bearded pigs without young were mostly diurnal, with the highest peaks of activity at dawn (0600-0700 h) and dusk (1700-1900 h) and low levels of activity at night (Fig. 3). These results accord with previous research showing that pigs tend to be diurnal (Pfeffer and Caldecott 1986; Linkie and Sadikin 2003; Ross et al. 2013) and avoid the hottest hours of the day (Caley 1997, Saunders and Kay 1991).

Additionally, bearded pigs are known to alter their activity patterns in response to nocturnal clouded leopard hunting patterns (Ross et al. 2013), suggesting that their diurnal tendencies may be in part a response to the clouded leopards present in the LKWS. Groups of pigs including juveniles and infants were more strictly diurnal than those containing only adults, with almost no activity recorded at night (Fig. 3). This accentuated diurnal pattern could be due to the particular vulnerability of young pigs to predation by clouded leopards; past research has shown that female bearded pigs (which raise the young) respond more strongly to clouded leopard activity patterns than male bearded pigs (Ross et al. 2013).

In addition to clouded leopard activity patterns, human hunting poses a major threat to bearded pig populations in Borneo (Kawanishi et al. 2008). Bearded pig hunting is extremely common in Borneo (Bennett et al. 2000; Puri 2005), and illegal poaching occurs in our study area (K. Love, pers. obs.). More data on bearded pig
movement ecology, e.g. GPS collaring studies collecting location and accelerometer data, are needed to determine to what extent this human hunting activity influences bearded pig activity patterns. Tracking fine-scale pig movements in mixed landscapes would build upon our results on relative habitat utilisation by illuminating the role of forest fragments in bearded pig foraging and behavioural ecology. These data would help determine the minimum threshold, quality, and configuration of forest cover needed to ensure stable and genetically diverse bearded pig populations in the Lower Kinabatangan region and other fragmented tropical landscapes.

Conclusions

In a fragmented tropical forest-oil palm landscape, bearded pig signs were found in all secondary forest sites and most oil palm plantation sites. This prevalence throughout the mosaic, coupled with consistently high body condition scores, indicates some adaptability of bearded pigs to fragmented landscapes. Oil palm plantations may have some conservation value for the species by providing valuable supplemental resources to primarily forest-dwelling pigs, whilst likely unable to provide the habitat structure (e.g. wallowing and nest sites) needed to sustain bearded pig populations in the absence of forest. Bearded pig groups, especially those containing piglets and juveniles, are diurnal in the Lower Kinabatangan region, possibly in response to predation or human hunting.

Our findings provide foundational data on bearded pig habitat use, activity patterns, minimum group size, and body condition in a forest-oil palm mosaic, providing a starting point for future research on how the threatened pig is adapting to
these important and expanding landscapes in Southeast Asia. Future work should extend this study by investigating bearded pig movements through mixed landscapes, migration patterns (or lack thereof) in different parts of Borneo, and genetic diversity and gene flow in relation to fragmentation, as well as the effects of human hunting on bearded pigs in both oil palm plantations and forest fragments. Understanding at finer scales how individual resources and microhabitats within forest and oil palm are utilized for different purposes (e.g. thermoregulation, predator avoidance, food acquisition) by bearded pigs will provide a more detailed picture of their ecological requirements and conservation needs. In the meantime, given that our results suggest that pigs preferentially utilise forest habitat much more than oil palm, protection of secondary forest fragments adjacent to oil palm plantations should be a major conservation priority in order to ensure healthy bearded pig populations in the Lower Kinabatangan.

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**Conflict of Interest Statement**

Funding for the research included funds from the Sime Darby Foundation, the main philanthropic arm of Sime Darby Berhad, a multinational conglomerate that owns oil palm plantations. However, no representatives of any of the funding sources were involved in the study design, execution, analysis, or interpretation of results.

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and temporal avoidance by prey in response to Sunda clouded leopard


**Figure Legends**

**Figure 1.** Transect positions for forest transects (red flags) and oil palm plantation transects (blue flags) sites within the Lower Kinabatangan Wildlife Sanctuary and surrounding region. The blue boundaries represent permanent water sources. The green lines correspond to the forest regions.

**Figure 2.** The camera trap stations within the Lower Kinabatangan Wildlife Sanctuary (LKWS) and surrounding areas. Illustrated are twenty corridor sites (yellow icons) and 75 forest patch sites (purple icons). The blue outlines display the Kinabatangan River and neighbouring oxbow lakes. The green markings show forest areas of LKWS. The grey lines show privately owned forest areas and yellow lines display degraded forest within plantation fragments.

**Figure 3.** The activity patterns of bearded pigs throughout an average day, based on the percentage of independent camera trap detections (min. 1 hr apart) occurring at various times of day. The solid line displays the diurnal activity pattern of the entire
population (n = 1995), whereas the checked line illustrates the more strictly diurnal activity patterns of groups containing juveniles and piglets (n = 221).

Figure 1.
Figure 2.

![Map Image]
Figure 3.
Table 1. Summary table displaying the mean number of signs detected (± SE) during transect surveys in forest and plantation habitats.

<table>
<thead>
<tr>
<th>Habitat</th>
<th>Mean tracks (± SE)</th>
<th>Mean rooting sites (± SE)</th>
<th>Mean mud grazes (± SE)</th>
<th>Mean wallowing holes (± SE)</th>
<th>Mean scat (± SE)</th>
<th>Mean nest (± SE)</th>
<th>Mean total sign (± SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>58.57 (±9.41)</td>
<td>9.02 (±3.97)</td>
<td>2.39 (±2.00)</td>
<td>0.02 (±0.03)</td>
<td>0.00 (±0.00)</td>
<td>0.02 (±0.02)</td>
<td>70.00 (±13.00)</td>
</tr>
<tr>
<td>Plantation</td>
<td>0.65 (±0.18)</td>
<td>0.27 (±0.30)</td>
<td>0.00 (±0.00)</td>
<td>0.00 (±0.00)</td>
<td>0.00 (±0.00)</td>
<td>0.00 (±0.00)</td>
<td>0.91 (±0.42)</td>
</tr>
</tbody>
</table>
Table 2: Parameter estimates, Standard errors, z-values, p-values, and AICc values of generalized linear mixed effects models using all combinations of predetermined influential variables to predict number of pig tracks and rooting sites. All models of pig tracks contain habitat type as a controlling variable, which had a highly significant effect in every model. Moderate and wet soil textures are compared to the dry soil texture.

| Model          | Parameters  | Estimate | Std. Error | z value | Pr(>|z|) | AICc  |
|----------------|-------------|----------|------------|---------|---------|-------|
| Pig Tracks     | Leaves      | 0.43     | 0.15       | 2.86    | 0.004   | 548.29|
|                | Leaves + Grass |         |            |         |         |       |
|                | Leaves      | 0.32     | 0.18       | 1.83    | 0.067   | 549.31|
|                | Grass       | -0.17    | 0.15       | -1.14   | 0.254   |       |
|                | Grass       | -0.32    | 0.13       | -2.43   | 0.015   | 550.27|
| Rooting Sites  | Soil Texture |         |            |         |         |       |
|                | Moderate - Dry | 1.39     | 0.36       | 3.81    | 0.0001  | 238.07|
|                | Wet - Dry   | 1.90     | 0.55       | 3.48    | 0.0005  |       |
Supplementary Material

Figure S1. A 10 x 100m line transect displaying the habitat analysis layout. The black dashed rectangular box displays the transect area whilst the solid black bar represents the transect midline. The five smaller checked boxes represent the 2m² plots where the substrate composition was estimated. Crossed circles signify five points where canopy cover photos were taken. The grey arrows symbolise five sections where person 1 stood and measured the understory density, whilst the white arrows indicate where person 2 stood and held the Robel pole.
Table S1. Example photographs of pig sign used for detecting pig habitat use on transects.

<table>
<thead>
<tr>
<th>Sign</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track</td>
<td><img src="image_url" alt="Example Image" /></td>
</tr>
<tr>
<td><strong>Scat</strong></td>
<td>![Scat Image]</td>
</tr>
<tr>
<td><strong>Nest</strong></td>
<td>![Nest Image]</td>
</tr>
<tr>
<td><strong>Rooting site</strong></td>
<td>![Rooting site Image]</td>
</tr>
<tr>
<td><strong>Wallowing hole</strong></td>
<td>![Wallowing hole Image]</td>
</tr>
<tr>
<td><strong>Mud graze</strong></td>
<td>![Mud graze Image]</td>
</tr>
</tbody>
</table>
Table S2. Visual factors used to determine bearded pig body condition from camera trap images (used with permission from Wong et al. 2005).

<table>
<thead>
<tr>
<th>Index</th>
<th>Category</th>
<th>Fur condition</th>
<th>Neck size</th>
<th>Body fat and muscle</th>
<th>Bones</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Very good</td>
<td>Sleek, dense</td>
<td>Thick</td>
<td>Fat, muscular</td>
<td>Not visible</td>
</tr>
<tr>
<td>4</td>
<td>Good</td>
<td>Sleek, dense</td>
<td>Thick</td>
<td>Little fat, Muscular</td>
<td>Not visible</td>
</tr>
</tbody>
</table>
Bones include the scapulae, vertebral columns, ribs and hipbones

Table S3. Example photographs used for categorising body condition of pigs from camera photos.

<table>
<thead>
<tr>
<th>Category</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very good</td>
<td><img src="image" alt="Very good" /></td>
</tr>
<tr>
<td>Poor</td>
<td><img src="image" alt="Poor" /></td>
</tr>
<tr>
<td>Very poor</td>
<td><img src="image" alt="Very poor" /></td>
</tr>
<tr>
<td>Rating</td>
<td>Image</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
</tr>
<tr>
<td>Good</td>
<td><img src="image1" alt="Good Image" /></td>
</tr>
<tr>
<td>Fair</td>
<td><img src="image2" alt="Fair Image" /></td>
</tr>
<tr>
<td>Poor</td>
<td><img src="image3" alt="Poor Image" /></td>
</tr>
</tbody>
</table>
Table S4. Example photographs used for categorising age of pigs from camera trap photos.

<table>
<thead>
<tr>
<th>Age</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very poor</td>
<td>(Wong et al. 2005)</td>
</tr>
<tr>
<td>Infant</td>
<td>![Infant Image]</td>
</tr>
<tr>
<td>--------</td>
<td>----------------</td>
</tr>
<tr>
<td>Juvenile</td>
<td>![Juvenile Image]</td>
</tr>
<tr>
<td>Sub-adult</td>
<td>![Sub-adult Image]</td>
</tr>
<tr>
<td>Adult</td>
<td>![Adult Image]</td>
</tr>
</tbody>
</table>
Table S5. The null and competing generalized linear mixed effects models investigating the effects of the identified influential parameters on pig tracks and rooting sites. All models of pig tracks include habitat type as a controlling variable. The models are ranked based on the differences in the cumulative corrected Akaike’s Information Criteria (AICc). Table includes the number of estimated parameters (K), the AICc, the difference in AICc with the top model (Delta_AICc), the weight of each model (AICcWt), and the -2log-likelihood output (LL).
<table>
<thead>
<tr>
<th></th>
<th>K</th>
<th>AICc</th>
<th>Delta_AICc</th>
<th>AICcWt</th>
<th>LL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pig Tracks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaves</td>
<td>5</td>
<td>548.29</td>
<td>0</td>
<td>0.51</td>
<td>-268.80</td>
</tr>
<tr>
<td>Leaves + Grass</td>
<td>6</td>
<td>549.31</td>
<td>1.02</td>
<td>0.30</td>
<td>-268.17</td>
</tr>
<tr>
<td>Grass</td>
<td>5</td>
<td>550.27</td>
<td>1.97</td>
<td>0.19</td>
<td>-269.79</td>
</tr>
<tr>
<td>Null</td>
<td>3</td>
<td>603.76</td>
<td>55.47</td>
<td>0.00</td>
<td>-298.75</td>
</tr>
<tr>
<td><strong>Rooting Sites</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Texture</td>
<td>5</td>
<td>238.07</td>
<td>0</td>
<td>1.00</td>
<td>-113.24</td>
</tr>
<tr>
<td>Null</td>
<td>3</td>
<td>250.45</td>
<td>12.38</td>
<td>0</td>
<td>-121.92</td>
</tr>
</tbody>
</table>