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The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia.

Holly Elizabeth Marshall[1*], Matthew Grainger[2], Niti Sukumal[1], Tommaso Savini[1]

[1] Conservation Ecology Program, King Mongkut's University of Technology Thonburi, 49 Thakham, Bangkhuntien, Bangkok, 10150, Thailand; Email: hollymarshall@live.co.uk (*corresponding author)
[2] Norwegian Institute for Nature Research, P.O. Box 5685 Torgard, NO-7485 Trondheim, Norway.

Abstract. The global population of domestic dogs is estimated at 900 million, making them the world's most abundant carnivore. Southeast Asia is considered extremely vulnerable to wildlife declines linked to free-ranging dogs yet few studies report specific cases of dog-wildlife interactions in this region. To overcome this lack of data, the perceived risk to bird and mammal species from free-ranging domestic dogs was modelled using Bayesian networks considering the life history traits of each individual species. The spatial distribution of perceived risk across Southeast Asia was then modelled using a Bayesian network incorporating landscape and demographic characteristics. The number of species considered as high perceived risk in the region was over five times that previously reported. Overall, 11% of bird species and 10% of mammal species were classified as at high perceived risk from free-ranging domestic dogs and eight of these species were listed as Critically Endangered or Endangered by the IUCN Redlist. Furthermore, 50% of mainland Southeast Asia was predicted to be of high perceived risk from free-ranging domestic dogs with only 9% of the region considered as low perceived risk. When empirical data is lacking on IUCN Redlist assessments, incorporation of single threat models can provide missing information critical for accurate evaluation. It is recommended that species are re-evaluated considering domestic dogs as a threat and that this study be used as a template to assist in the development of species action plans and to define key areas where dog management needs to be considered. Management practices should be culturally appropriate and overall promote responsible pet ownership.

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Key words. *Canis familiaris*; Dog-Wildlife Conflict; Predation; Bayesian network; Threat map

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INTRODUCTION

Less than 12% of Southeast Asia's forests are protected (Estoque et al., 2019) despite the region being one of the most biologically diverse in the world (Sodhi et al., 2010). Yet, even with a protected area status, often anthropogenic pressure is not eliminated (Jones et al., 2018). A growing number of human settlements surround and often encroach on forests, increasing pressure on wildlife species (Wittemyer et al., 2008). One threat associated with human settlements is the increasing number of domestic species that can encounter native wildlife (Plaza et al., 2019). The disruption of ecosystems by domestic species is well documented in livestock (Gordon, 2018; Zhang et al., 2017) and domestic cats (*Felis catus*) (Loss et al., 2013; Gillies and Clout, 2003; Woods et al., 2003) but less so in domestic dogs (*Canis familiaris*) despite being the world's most abundant predator (Villatoro et al., 2019).

The global population of domestic dogs is estimated at 900 million (Gompper, 2014). In many parts of the world, dogs live a free-ranging lifestyle where they are unrestricted in their movements, these semi-independent dogs make up the majority of dogs in developing countries (Ortega-Pacheco and Jiménez-Coello, 2011). Their lack of confinement enables them to freely enter natural habitats surrounding their settlement putting them into close proximity with wildlife (Torres and Prado, 2010). Their presence within natural habitats negatively affects wildlife as natural food chains are altered with their introduction through direct predation (Newsome et al., 2014). The provision of anthropogenic foods allows dogs to exist in higher densities than natural predators as their populations are unaffected by prey density fluctuations (Young et al., 2011). Additionally, a consistently high density of dogs can prevent the recovery of declining or fragmented prey populations (Banks and Bryant, 2007). Predation events are the most commonly reported impact from domestic dogs; however, other impacts include disturbance, competition, hybridisation and the transmission of diseases (Doherty et al., 2017).

There is a large regional bias on published studies of domestic dog impacts to wildlife. Doherty et al (2017) reported that Southeast Asia had the highest number of species negatively impacted by dogs in the world using the IUCN Red List. On the contrary, literature reviews of domestic dog-wildlife interactions conducted by Young et al (2011) and Hughes and Macdonald (2013) included no studies based in Southeast Asia. Of the studies available on domestic dog-wildlife conflict within Southeast Asia (search carried out 20/05/21 in Web of Science databases and Google Scholar) most refer to the predation of primate species (Najmuddin et al., 2019; Riley et al., 2015) or this conflict was not the primary focus of the study (Azhar et al., 2012; Gumert et al., 2013; Ramli and Norazlimi, 2017; Yasué et al., 2008). Not

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only is there a regional bias on published studies, Doherty et al (2017) found a large taxonomic bias towards mammals; Hughes and Macdonald (2013) also found that most studies reviewed focused only on domestic dog interactions with a singular wildlife species. Furthermore, the majority of studies published tend to be opportunistic predation events or collected incidentally from studies targeting different aims (Young et al., 2011). Consequently, the number of species known to be impacted by dogs could be underestimated.

When considering conservation management, it is vital to understand how free-ranging domestic dogs may also be impacting wildlife. This is crucial within Southeast Asia considering the wide-ranging impacts free-ranging domestic dogs can have and as many species in this region are understudied. An absence of comprehensive empirical data prohibits quantification of the magnitude of free-ranging domestic dog impacts. However, the use of expert opinions can facilitate focus for decision-makers and primary research in these fields. Therefore, the aims of this study are: 1) to investigate the impact of free-ranging domestic dogs on wildlife species within mainland Southeast Asia using species life history traits and expert knowledge on how these characteristics can influence the vulnerability of each species, and 2) to uncover the spatial distribution of perceived risk to wildlife from free-ranging domestic dogs, landscape characteristics and expert knowledge on their existence in different parts of Southeast Asia.

MATERIALS & METHODS

Study Site. The study was conducted across the six countries that make up mainland Southeast Asia: Cambodia, Lao People's Democratic Republic, Myanmar, Peninsular Malaysia, Thailand and Vietnam. The region is characterised by its tropical and monsoonal climate (Resurreccion and Sajor, 2008) and contains the majority of the Indo-Burma biodiversity hotspot and part of the Sundaland biodiversity hotspot.

Model Development. Bayesian networks (BN) were used to define the perceived risk levels from free-ranging domestic dogs to wildlife and to uncover the spatial distribution of perceived risk from free-ranging domestic dogs. To better enable management decisions, BNs are a useful approach as they allow for the integration of both empirical data and professional opinions when data is incomplete (Jellinek et al., 2014; McBride and Burgman, 2012). BNs are directed acyclic graphical models in which variables are represented as nodes and “parent nodes” impact the state of “child” nodes. The linkages between “parent” and child” nodes are known as arcs or edges and they represent the

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relationship between the two nodes (Tantipisanuh et al., 2014). The influence of the arcs to each node's state in the models are quantified using conditional probability tables (CPTs) and the outcome state of a "child" node depends solely on its "parent" nodes and no other nodes within the model (Bennett et al., 2021). The initial input nodes' (or parentless nodes) states were defined using empirical data (for definition of input nodes and state in Mammalia and Avian BN see Supplementary Material 1). BNs explicitly incorporate uncertainty into models and can be updated with new data to keep models relevant in a changing system (Glendining and Pollino, 2012). They can identify areas where more research needs to be conducted as well as distinguish issues that should be prioritised.

Using Netica software (Norys Software, 1995-2015) four BNs were created: perceived risk to Carnivora Mammalia species from free-ranging dogs (Fig. 1a), perceived risk to non-Carnivora Mammalia species from free-ranging dogs (Fig. 1b), perceived risk to Avian species from free-ranging dogs (Fig. 1c) and the spatial distribution of areas of perceived risk from free-ranging dogs in mainland Southeast Asia (Fig. 1d). The structure and linkages of the models were determined through multiple meetings between the authors, the models were then reviewed by a researcher with Bayesian network experience. This was to ensure that no errors existed within the structural designs and that each model could produce viable results. CPT values were then derived from expert opinions (Supplementary Material 2); experts (n = 28) had experience of 5 – 20+ years in the field of conservation and were affiliated with a wildlife conservation NGO, specialist wildlife group or university lab focused on ecological sciences. Additionally, free-ranging domestic dog experts were selected who had recently published (< 5years) a paper or had published a paper on free-ranging domestic dogs that had been cited more than 100 times. Depending on their qualifications, discussions with experts were either concerning the vulnerability of mammal or bird species from domestic dogs, factors influencing dog presence within an area or dog control within Southeast Asia. Each expert was informed of the aim of the study and the scope of the BN model in question prior to discussions. Each BN was broken down into child nodes and the corresponding parent nodes and experts were asked via a questionnaire (Supplementary Material 3) to weigh the importance of parent nodes on their child nodes using a scale of 1 – 5. This was repeated for every child node in the BN. Additionally, experts working within protected areas in Southeast Asia were asked how likely it was that dog control took place within and outside protected areas of the corresponding country they had experience in and if the presence of a charismatic species influenced the likelihood of dog control taking place. Experts only provided responses for topics they were well-informed in, and responses were weighted equally and pooled together to obtain the mean response/score (Martin et al., 2012). This score was then assigned to the corresponding parent nodes of each child node. To create the conditional probability table of a child node, the score of each relevant parent node was multiplied with its

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state (e.g., low = 0.33, high = 1). This value was then summed with the values generated for all parent nodes linked to the child node and divided with the maximum possible score available for that child node (i.e., where all parent node states are equal to 1). This score was then transformed into a percentage and this percentage was used to determine the values in the conditional probability tables (Supplementary Material 2). This process was then repeated for every combination of the corresponding parent nodes' states.

Finally, each BN model was evaluated by calculating the sensitivity of each outcome node against all other nodes within the model. This was calculated within the Netica software and the outcome allows influential nodes to be identified. The entropy reduction value (mutual information) is the degree of influence a node has for altering the state of another node and its use is appropriate for categorical nodes (Dlamini, 2010). The variance reduction of real describes the expected reduction in variance of a node and is a more appropriate measure for continuous nodes (Pascoe et al., 2020).

Species Risk Models

Species sensitivity to the threats associated with free-ranging domestic dogs is likely to depend on their life history traits and habitat use (e.g., Bromham et al., 2012). Therefore, to overcome the lack of data available, life history traits were used to predict the perceived risk from free-ranging domestic dogs on individual native species. Mammalia and Avian species from mainland Southeast Asia were extracted from the IUCN's Red List of Threatened Species (IUCN, 2020) in July 2020. All Red List categories excluding Extinct and Extinct in the Wild were included. Land regions were filtered to include only peninsular Malaysia, Cambodia, Vietnam, Lao People's Democratic Republic, Thailand and Myanmar. Marine species, locally extinct species or species with rare occurrences in the region were manually removed from the list. Empirical traits were selected for each of the classes that were likely to influence vulnerability to domestic dogs and could be assigned reliably from the literature and through discussions with taxa experts. This included morphological, behavioural and ecological traits. Information for each trait for each species was then compiled using the IUCN Red List, field guides and expert opinion when information was scarce, and all species traits were cross-checked by a taxa expert.

Threats that were recognised as strongly affecting animal populations were selected as outcomes of the model, and included competition, disturbance, predations, hybridisation and disease as specified and defined by Doherty et al. (2017). These threats were collated to give the overall perceived risk outcome with a probability assigned to each of the

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three outcome states: low, medium and high. Each species' perceived risk score was equal to 100; however transformation was required as the probability was split between the three outcomes and not given as one overall score. To transform the result into one continuous scale from 0 – 100, the following equation and weights were adapted from Petersen et al. (2020), which determined the final estimated perceived risk score:

$$r = (x*0) + (y*50) + (z*100)$$

r= perceived risk, x= low risk value, y= medium risk value, z=high risk value

Species that received a perceived risk score of 33.33 or less, including 0, were categorised as low risk, those that received a score of 66.66 or less were categorised as medium risk and those with a score above 66.66 were categorised as high risk. A "no risk" category was not provided as it would be impossible to determine if a species was at no risk from domestic dogs; therefore, even if a species received a 100% probability of low risk and subsequently an overall perceived risk value of 0, it would not equate to no risk. If a species received a 70% probability of low risk and a 30% probability of medium risk, it would receive a perceived risk value of 15; consequently, both species would be assigned into the low risk category.

Perceived Risk Spatial Distribution. A BN approach was used once more to estimate the perceived risk by free-ranging dogs within mainland Southeast Asia. By investigating the accessibility of habitats to free-ranging domestic dogs in reference to their roaming behaviours, the perceived risk to those areas can be estimated whilst accounting for any deterrents that may be present such as control methods deployed by protected areas. From previous studies (Doykin et al., 2016; Farris et al., 2017; Sepúlveda et al., 2015; Silva-Rodríguez and Sieving, 2012; Zanin et al., 2019) and discussions with experts, 10 potentially important drivers of domestic dog distribution and their perceived risk were identified: forest type, protected area status, country, large predator presence, charismatic species presence, landuse type, human density, distance from farmland, distance from settlements and elevation (Table 1). The model was split into forested habitats and non-forested habitats as dog prevention level was only considered in forested habitats. The model calculated dog presence within both habitats, with overall potential risk from dogs as the final outcome. Urban areas and water bodies were excluded from the analysis however, due to the number of species that utilise agricultural land and degraded habitats these areas were included (Fig. 1d).

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Euclidian distance was used to calculate the “Distance to Farmland” and the “Distance from Settlements” nodes from their respective data sources (Table 1). Multiple data sources were combined for the “Distance from Settlements” node to account for smaller settlements that could be missed. To create the “Charismatic Species” node, species identified from Smith et al. (2012) which reside in Southeast Asia and used as a flagship species by two or more NGOs were selected and their range extracted from the IUCN Red List. The habitat range of three large predators found within the region, tiger (*Panthera tigris*), leopard (*Panthera pardus*) and clouded leopard (*Neofelis nebulosa*), comprised the “Large Predator Presence” node. Lastly, the “Country” node was weighted through expert opinion. Experts with work based in each country were asked to rate how likely dog control was within and outside of protected areas and if the presence of a charismatic species influenced the chances of control occurring due to the additional conservation funding charismatic species often provide (Smith et al., 2012). They were also asked to rate how likely local people were to be accompanied by dogs when entering the forest. Responses were averaged across each country and weighted appropriately.

All geospatial datasets (Table 1) were converted to 300 m resolution raster files using ArcGIS Pro 2.6 (Environmental Systems Research Institute, 2020). Following the methods of Petersen et al. (2020), raster files were stacked and converted into a matrix using the ‘raster’ package (Hijmans et al., 2020) in the program R (R Core Team, 2020). The XY coordinates for the matrix were removed and saved in R to later be merged with the output data from the BN. Due to the large size of the remaining matrix, it was split into three case files and the resulting matrixes were then processed through Netica individually using the BN created (Fig. 1d). The model consisted of 18 nodes and the output produced a perceived risk level with 4 states: high, medium, low and NA. NA contained the excluded habitat types of urban areas and water bodies. Urban areas were excluded as these are not considered areas where conservation could be a priority. As domestic dogs are terrestrial mammals, water bodies were also excluded from the analysis. However, the habitats surrounding water bodies, such as beaches, were included. This final node was influenced by three nodes: dog presence, land use concern (to eliminate urban areas and water bodies from the analysis) and distance from human modified landscape. The output case files from Netica were then inputted into the program R, merged back into one table and the perceived risk value for each cell was calculated using the same equation as that for the species perceived risk models (Petersen et al., 2020). The output was then merged with its corresponding XY coordinates and converted into raster files using the function rasterFromXYZ from the ‘raster’ package (Hijmans et al., 2020).

RESULTS

Species Perceived Risk. In total 11% (125) of bird species and 10% (47) of mammal species from 35 families and 14 orders in Southeast Asia are classified as at high perceived risk from free-ranging dogs (Supplementary Material 4 and 5). Of all these species, four are classified as Critically Endangered, four as Endangered, 15 as Vulnerable and five as Data Deficient (Fig. 2). Within the 125 species of bird, 36 species were in the order Galliformes, 20 in Charadriiformes, 11 in Gruiformes, 55 in Passeriformes and one in Strigiformes, Otidiformes and Anseriformes (Fig. 3). Mammal orders consisted of 10 Carnivora, six Cetartiodactyla, three Lagomorpha, five Primates, 18 Rodentia, four Scandentia and one Eulipotyphla (Fig. 3). The sensitivity analysis conducted on output nodes of the two mammalian models revealed that "Predation Risk" was the most influential child node for "Overall Risk Carnivora" and "Overall Risk Non-Carnivora" (Table 2). For the Avian model, "Disturbance Risk" was the most influential child node on "Overall Risk" (Table 3).

Perceived Risk Spatial Distribution. It was predicted that across mainland Southeast Asia only 185,331km^2 of low perceived risk habitat remains (Fig. 4). This makes up only 9% (Table 4) of the region. The remaining area is categorised as high perceived risk (1,023,840 km^2) and moderate perceived risk (727,668 km^2) at 50% and 36%, respectively. Thailand contained the largest area of high perceived risk habitats consisting of 69.9% in comparison to Lao People's Democratic Republic which had the smallest percentage of high perceived risk areas at 30.6%. NA corresponds to the percentage of areas excluded from the analysis, this includes water bodies and urban areas. The sensitivity analysis performed on the output node "Potential Dog Risk" highlighted that "Landuse Type" was the most influential child node within the model (Table 5).

DISCUSSION

The results of this study were alarming; both the mammalian and avian assessment revealed that the number of species predicted to be at high perceived risk from domestic dog is over five times higher than the previously reported 30 species at risk in the region (Doherty et al., 2017). This emphasises the need for domestic dogs to be considered when looking at individual wildlife species threats. In the region, 10% of mammals and 11% of bird species are considered as at high perceived risk from domestic dogs. Additionally, free-ranging domestic dogs pose a high perceived risk to 50% of the region. This is of particular concern within Thailand, Peninsular Malaysia and Vietnam which all had more than 50% of their land area considered as high perceived risk. Furthermore, all countries possessed a significant perceived risk from dogs with no country retaining low perceived risk area as their majority.

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Species Perceived Risk. Forty-seven mammal species were considered as at high perceived risk from free-ranging domestic dogs. This includes both predators and prey species indicating that domestic dogs could disrupt entire ecosystems. Amongst the Carnivora order, 10 species were flagged as high perceived risk including all three Canidae species (golden jackal (*Canis aureus*), racoon dog (*Nyctereutes procyonoides*) and dhole (*Cuon alpinus*)), although only golden jackal is at risk from hybridisation. Hybridisation can cause loss of genetic diversity and reduce fitness, and increase the risk of disease transmission across species (Galov et al., 2015). Carnivore species as a whole are particularly vulnerable to diseases such as rabies, canine distemper and canine parvovirus along with various parasites from domestic dogs (Berentsen et al., 2013). Out with the Carnivora order, all mammal species are at risk of rabies (Rocha et al., 2017). Large populations of unvaccinated free-ranging dogs can provide opportunities for transmission of multi-host pathogens to wildlife species (Belsare and Gompper, 2015); additionally, Southeast Asia is still a hotspot for rabies affecting approximately 23,995 people per year in the region (Gongal and Wright, 2011).

Domestic dogs were previously thought of as insignificant predators of primates; however, they are important predators of macaque species (Riley et al., 2015). Five primate species were identified as being at high perceived risk from the analysis and all belonged to the *Macaca* genus. Macaques are commonly found around human settlements and are known to spend more time on the ground within these modified habitats which can put them into contact with domestic dogs (Riley, 2008). Macaque species with overlapping ranges with domestic dogs have disruptions to their group composition, habitat use and group activity patterns (Riley et al., 2015). Yet, it is not just macaques that can be impacted by dogs; predation events on largely arboreal species including Schlegel's banded langur (*Presbytis neglectus*) in Malaysia (Najmuddin et al., 2019) and black capuchin monkey (*Cebus nigritus*) in Brazil have been recorded (Oliveira et al., 2008).

Twenty-five small mammal species were classified as high perceived risk in the orders Rodentia, Scandentia and Eulipotyphla. There have been limited studies on the influence of domestic dogs on small mammals but it has been indicated that their presence can reduce abundance (Murphy et al., 2017; Tobajas et al., 2020). Zamora-Nasca et al. (2021) also found that Lagomorpha and Rodentia were the most commonly reported mammals to be chased or predated by domestic dogs in Argentina. Small mammals are an important food source for mesocarnivores and a reduced abundance could disrupt the natural food chain (Newsome et al., 2014). In contrast, domestic dogs are unaffected by decreasing prey numbers as they are usually subsidised with food from humans so can maintain a high population (Young et al., 2011). If high densities of free-ranging domestic dogs are maintained they could outcompete native

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mesocarnivores, particularly as they have a greater tolerance to human disturbance (Butler et al., 2004). In addition to the dangers free-ranging dogs pose to wildlife, trained dogs are commonly used to improve efficiency when tracking and hunting wildlife (Constantino, 2019). They are frequently used for hunting mammalian species however, they can be indiscriminate in their foraging behaviour, killing non-target species (Koster, 2008).

Within the Aves class, 125 species were identified as high perceived risk. This is unsurprising as although most bird species are able to escape a ground predator through flight, dogs are a known disturbance agent. Banks and Bryant (2007) found that dog presence reduced bird diversity by 35% and abundance by 41%. All species classified as high perceived risk were ground nesters excluding Jerdon's babbler (*Chrysomma altirostre*) and yellow-eyed babbler (*Chrysomma sinense*). Dogs can severely impact ground-dwelling bird populations (Hunt et al., 1996; Taborsky, 1988) and are known nest predators (Henry, 1969). Ground-foraging birds also have greater flight initiation distances than those in the canopy so disturbance involves a greater energy deficit for them (Blumstein et al., 2005). Species that breed in coastal areas, such as the 10 species from the Laridae family categorised as high perceived risk, are exceptionally vulnerable to nest predation from domestic dogs due to the increased urbanisation of beaches (Baudains and Lloyd, 2007).

There were 58 species that were classified as data deficient by the IUCN Red List. Nearly one-third of these species were Chiroptera, a vastly understudied order (Francis et al., 2010). However, due to their volant nature, dogs are not considered a high risk to them. All species in the Data Deficient category were small mammals with the exception of six muntjac species and the only avian species, the white-faced plover *(Charadrius dealbatus*). Those that were perceived as high risk included the white-faced plover, Gongshan muntjac (*Muntiacus gongshanensis*), silver-backed chevrotain (*Tragulus versicolor*), Williamson's chevrotain (*Tragulus williamsoni*) and the leaf muntjac (*Muntiacus putaoensis*). These Cetartiodactyla species are herbivorous ground foragers and are all recent discoveries to science being described from only a small number of specimens (Amato et al., 1999; Kloss, 1916; Ma et al., 1990) and a recent rediscovery in 2018 of the silver-backed chevrotain (Nguyen et al., 2019). Although the primary threats to these Cetartiodacyla species is habitat degradation and poaching (Meijaard et al., 2017; Nguyen et al., 2019; Rabinowitz et al., 1999) any additional pressures from domestic dogs could halt their recovery.

Doherty et al. (2017) found that only 30 species across Southeast Asia had domestic dogs listed as a threat by the IUCN Redlist. Additionally, only three species highlighted by Doherty et al. (2017) were considered as high perceived risk in

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this study. Despite this, species such as red panda (*Ailurus fulgens*) which were considered low perceived risk by this study, were deemed as threatened by domestic dogs according to the IUCN Red List. In fact, in recent years there has been mounting evidence of predation and disease transfer from domestic dogs to red panda (Bagardi et al., 2021; Home et al., 2017). However, these studies have not been cited during the IUCN Red List assessment, which should be revised. Therefore, despite species having a low-perceived risk from free-ranging domestic dogs, it does not rule out the threat entirely. This is concerning due to the small number of species that have been assessed against threats from domestic dogs. It suggests that many species could be missing important threat information which has the potential to influence their Red List status and should be updated. Where empirical data is lacking, using a model as demonstrated to assess a single threat will allow more accurate assessments of species. Although the models used in this study focus solely on domestic dogs, BNs can be used to give more information on threats such as those from invasive species (Wyman-Grothem et al., 2018), hunting (Grainger et al., 2018) and illegal wildlife trade (Bennett et al., 2021) to update species assessments where this data is absent.

Perceived Risk Spatial Distribution. Only 9% of the region was predicted to be at low perceived risk from domestic dogs, with the majority of this habitat in the northern regions. This is most likely due to the higher elevation and lower human populations in the area. Another notable low patch was Thailand's Western Forest Complex which extends across the Myanmar border. This forest complex consists of 11 national parks and six wildlife sanctuaries covering approximately 18,000 km^2. However, this area is not free of human settlements as there are some small towns located between reserves providing a supply of dogs to the forests around them. The presence of domestic dogs within a forest can be considered as an edge effect reducing available habitat for wildlife species (Lacerda et al., 2009). This is particularly important in mainland Southeast Asia where large forest patches no longer exist and high deforestation rates result in the majority of countries losing more forest than they are gaining (Estoque et al., 2019). Although protected areas can reduce human settlements encroaching into on forested areas, there was little faith in dog management across the whole region when consulting with experts. All countries were rated as having little to no dog control implemented within and outside protected areas.

Thailand was found to have the highest area of perceived risk from free-ranging domestic dogs in mainland Southeast Asia, which could be due to the limited forest within the country. Thailand has the lowest percentage of forest cover in the region per country size followed by Vietnam and Cambodia. Additionally, Vietnam and Thailand both have the highest populations in the region, suggesting that human settlements may encroach onto forested areas and free-ranging

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domestic dogs create an edge effect on these habitats. Furthermore, both counties also have large coastlines at approximately 3,260 km and 2,815 km, respectively, that are largely developed. This is also seen in peninsular Malaysia, which despite its smaller area, has a competitive coastline of approximately 2,068 km. Urbanised beaches are key sites for domestic dogs as beach management is rarely for conservation purposes and tends to be improvements for recreational and economic purposes. Consequently, dogs can freely exist in these areas (Schlacher et al., 2015). Identifying areas and habitats of potential risk from free-ranging domestic dogs is an excellent starting point, allowing stakeholders to concentrate efforts where they are needed the most. Combining this threat map with additional threat maps such as hunting and habitat loss for vulnerable wildlife species allows for more insight into the threats these species are facing (Grainger et al., 2018). This will enable us to highlight threatened populations at a local level and recommend realistic management strategies.

Limitations. Whilst expert opinions have filled a knowledge gap on free-ranging domestic dogs within Southeast Asia it is acknowledged that this is not a replacement for empirical data. This study should be considered as a first step to focus future research and the addition of empirical data would improve the accuracy of these models. Furthermore, the addition of empirical data on documented impacts from free-ranging domestic dogs on individual species would allow this model to be validated and adjusted with this new information. By incorporating new predictions, the model can be continuously improved. It should also be considered that this species assessment did not take into account species population sizes, ranges or habitat preferences, all factors that could increase or decrease a species vulnerability to threats. Additionally, reptiles and amphibians were not included in this study due to the lack of data available on them within Southeast Asia. Lastly, free-ranging domestic dogs can exist both solitary, in pairs or packs. Whilst this study only considered the impacts from solitary free-ranging dogs the risks from pack dogs can be much greater. In a study by Homes et al. (2017) approximately 57% of all chases and attacks on wildlife by domestic dogs were from pack dogs and 14% of all chases and attacks on wildlife by domestic dogs were from pairs of dogs. It is also worth noting that when hunting in packs domestic dogs can predate much larger prey than when hunting alone, thus the impacts on medium-large mammals could be underestimated (Paschoal et al., 2012).

Management Implications. Given the close relationship between dogs and humans, when considering population management strategies social, cultural and economic aspects must also be considered (Hughes and Macdonald, 2013). Strategies that involve culling dogs may not be effective in this region as many dogs are owned by families yet able to roam freely. Additionally, slaughtering of animals is condemned within Buddhist teachings (Finnigan, 2017), a

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prominent religion in the region. Trap-neuter-vaccine-release (TNVR) programs have been proven to be more effective than culling strategies in the long run although culling can quickly decrease a population size it is possible for populations to recover with the sudden vacant niche (Yoak et al., 2016). However, TNVR programs can be expensive and in low-income areas may not be feasible. Furthermore, TNVR does not reduce the population in the short-term and may need to be combined with additional efforts, such as adoption, in order for it to reduce the population in a shorter timeframe (Coe et al., 2021). Although TNVR is seen as more ethical than culling, there can still be welfare issues associated with it during the capture and post-operative stage (Bacon et al., 2019). Focusing on responsible dog ownership may be an option in these areas, encouraging individuals to restrict dog movement and transporting feral dogs to shelters (Doherty et al., 2017). Most likely a combination of these management options should be implemented, considering the size of the population, the vulnerability of native wildlife, the willingness of local people to assist and the economic situation in the area. Management of dog populations will not only benefit wildlife species, it can also reduce risks to human health, due to diseases and unconfined dogs that provide a collision risk to vehicles and thus endangering drivers (Canal et al., 2018). Carcasses are often seen at the side of highways; Silva et al. (2020) found that in Thailand dogs were the most common mammal to be involved in a road collision. Therefore, dog management is in the best interest of both conservationists and the public.

This study qualifies the regional perceived risk from domestic dogs and evaluates the vulnerability of mammal and bird species within the region to this threat for the first time. It is hoped that this study will provide a framework for future studies on free-ranging dog impacts in the region and will assist in species threat assessments when compiling data for the IUCN Red List. Overall, appropriate dog population control measures are encouraged when considering wildlife species management.

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LITERATURE CITED

Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Amato G, Egan MG, Rabinowitz A (1999) A new species of muntjac, *Muntiacus putaoensis* (Artiodactyla: Cervidae) from northern Myanmar. Animal Conservation 2: 1–7.

Azhar B, Lindenmayer D, Wood J, Fischer J, Manning A, McElhinny C, Zakaria M (2012) Contribution of illegal hunting, culling of pest species, road accidents and feral dogs to biodiversity loss in established oil-palm landscapes. Wildlife Research 40: 1–9.

Bacon H, Walters H, Vancia V, Connelly L, Waran N (2019) Development of a robust canine welfare assessment protocol for use in dog (*Canis familiaris*) catch-neuter-return (CNR) programmes. Animals 9: 564.

Bagardi M, Rabbogliatti V, Bassi J, Gioeni D, Oltolina M, Villa L (2021) *Angiostrongylus vasorum* in a red panda (*Ailurus fulgens*): clinical diagnostic trial and treatment protocol. Acta Parasitologica 66: 282–286.

Banks PB, Bryant JV (2007) Four-legged friend or foe? Dog walking displaces native birds from natural areas. Biology Letters 3: 611–613.

Baudains TP, Lloyd P (2007) Habituation and habitat changes can moderate the impacts of human disturbance on shorebird breeding performance. Animal Conservation 10: 400–407.

Belsare AV, Gompper ME (2015) A model-based approach for investigation and mitigation of disease spillover risks to wildlife: Dogs, foxes and canine distemper in central India. Ecological Modelling 296: 102–112.

Bennett EL, Underwood FM, Milner-Gulland EJ (2021) To trade or not to trade? Using Bayesian belief networks to assess how to manage commercial wildlife trade in a complex world. Frontiers in Ecology and Evolution 9 : 1–16.

Berentsen AR, Dunbar MR, Becker MS, M'soka J, Droge E, Sakuya NM, Matandiko W, McRobb R, Hanlon CA (2013) Rabies, canine distemper, and canine parvovirus exposure in large carnivore communities from two Zambian ecosystems. Vector-Borne and Zoonotic Diseases 13: 643–649.

Blumstein DT, Fernández-Juricic E, Zollner PA, Garity SC (2005) Inter-specific variation in avian responses to human disturbance. Journal of Applied Ecology 42: 943–953.

Bromham L, Lanfear R, Cassey P, Gibb G, Cardillo M (2012) Reconstructing past species assemblages reveals the changing patterns and drivers of extinction through time. Proceedings of the Royal Society B: Biological Sciences 279(1744): 4024-4032.

Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Butler JRA, du Toit JT, Bingham J (2004) Free-ranging domestic dogs (*Canis familiaris*) as predators and prey in rural Zimbabwe: threats of competition and disease to large wild carnivores. Biological Conservation 115: 369–378.

Canal D, Martín B, Lucas M de, Ferrer M (2018) Dogs are the main species involved in animal-vehicle collisions in southern Spain: Daily, seasonal and spatial analyses of collisions. PLoS One 13: e0203693.

Coe ST, Elmore JA, Elizondo EC, Loss SR (2021) Free-ranging domestic cat abundance and sterilization percentage following five years of a trap–neuter–return program. Wildlife Biology 2021: 1–8.

Constantino P de AL (2019) Subsistence hunting with mixed-breed dogs reduces hunting pressure on sensitive Amazonian game species in protected areas. Environmental Conservation 46: 92–98.

Dlamini WM (2010) A Bayesian belief network analysis of factors influencing wildfire occurrence in Swaziland. Environmental Modelling & Software 25: 199–208.

Doherty T, Dickman C, Glen A, Newsome T, Nimmo D, Ritchie E, Vanak A, Wirsing A (2017) The global impacts of domestic dogs on threatened vertebrates. Biological Conservation 210: 56–59.

Doykin N, Popova E, Zlatanov V, Petrov P, Zlatanova D (2016) Preliminary data on the distribution of free-ranging dogs (*Canis familiaris L.*) in Np Vitosha, Bulgaria. Annuaire de l'Université de Sofia "St. Kliment Ohridski" Faculte de Biologie 101: 11–22.

Environmental Systems Research Institute (2020) ArcGIS PRO Release 2.6.0. Redlands, California, USA.

Estoque RC, Ooba M, Avitabile V, Hijioka Y, DasGupta R, Togawa T, Murayama Y (2019) The future of Southeast Asia's forests. Nature Communications 10: 1829.

Farris ZJ, Gerber BD, Valenta K, Rafaliarison R, Razafimahaimodison JC, Larney E, Rajaonarivelo T, Randriana Z, Wright PC, Chapman CA (2017) Threats to a rainforest carnivore community: A multi-year assessment of occupancy and co-occurrence in Madagascar. Biological Conservation 210: 116–124.

Finnigan B (2017) Buddhism and animal ethics. Philosophy Compass 12: 1–12.

Francis CM, Borisenko AV, Ivanova NV, Eger JL, Lim BK, Guillén-Servent A, Kruskop SV, Mackie I, Hebert PDN (2010) The role of DNA barcodes in understanding and conservation of mammal diversity in Southeast Asia. PLoS One 6: e12575.

Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Galov A, Fabbri E, Caniglia R, Arbanasić H, Lapalombella S, Florijančić T, Bošković I, Galaverni M, Randi E (2015) First evidence of hybridization between golden jackal (*Canis aureus*) and domestic dog (*Canis familiaris*) as revealed by genetic markers. Royal Society Open Science 2: 150450.

Gillies C, Clout M (2003) The prey of domestic cats (*Felis catus*) in two suburbs of Auckland City, New Zealand. Journal of Zoology 259: 309–315.

Glendining NS, Pollino CA (2012) Development of Bayesian network decision support tools to support river rehabilitation works in the lower snowy river. Human and Ecological Risk Assessment: An International Journal 18: 92–114.

Gompper ME (2014) Free-ranging dogs and wildlife conservation. Oxford University Press, Oxford, United Kingdom, 311 pp.

Gongal G, Wright AE (2011) Human rabies in the WHO Southeast Asia region: forward steps for elimination. Advances in Preventive Medicine 2011: 1–5.

Gordon IJ (2018) Review: Livestock production increasingly influences wildlife across the globe. Animal 12: 372–382.

Grainger MJ, Garson PJ, Browne SJ, McGowan PJK, Savini T (2018) Conservation status of Phasianidae in Southeast Asia. Biological Conservation 220: 60–66.

Gumert MD, Hamada Y, Malaivijitnond S (2013) Human activity negatively affects stone tool-using Burmese long-tailed macaques *Macaca fascicularis aurea* in Laem Son National Park, Thailand. Oryx 47: 535–543.

Henry VG (1969) Predation on dummy nests of ground-nesting birds in the Southern Appalachians. The Journal of Wildlife Management 33: 169–172.

Hijmans RJ, Etten J van, Sumner M, Cheng J, Baston D, Bevan A, Bivand R, Busetto L, Canty M, Fasoli B, Forrest D, Ghosh A, Golicher D, Gray J, Greenberg JA, Hiemstra P, Hingee K, Institute for Mathematics Applied Geosciences, Karney C, Mattiuzzi M, Mosher S, Nowosad J, Pebesma E, Lamigueiro OP, Racine EB, Rowlingson B, Shortridge A, Venables B, Wueest R (2020) Raster: Geographic Data Analysis and Modeling. https://cran.r-project.org/web/packages/raster/index.html (Accessed 05 March 2021)

Home C, Vanak A, Bhatnagar Y (2017) Canine conundrum: domestic dogs as an invasive species and their impacts on wildlife in India. Animal Conservation 21: 275–282.

Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Hughes J, Macdonald DW (2013) A review of the interactions between free-roaming domestic dogs and wildlife. Biological Conservation 157: 341–351.

Hunt GR, Hay R, Veltman CJ (1996) Multiple kagu *Rhynochetos jubatus* deaths caused by dog attacks at a high-altitude study site on Pic Ningua, New Caledonia. Bird Conservation International 6: 295–306.

IUCN (2020) The IUCN Red List of Threatened Species. Version 2020.2. www.iucnredlist.org (Accessed 30 July 2020).

Jellinek S, Rumpff L, Driscoll DA, Parris KM, Wintle BA (2014) Modelling the benefits of habitat restoration in socio-ecological systems. Biological Conservation 169: 60–67.

Jones KR, Venter O, Fuller RA, Allan JR, Maxwell SL, Negret PJ, Watson JEM (2018) One-third of global protected land is under intense human pressure. Science 360: 788–791.

Kloss CB (1916) On a new mouse deer from upper Siam. Journal of the Natural History Society of Siam 2: 88-89.

Koster J (2008) The impact of hunting with dogs on wildlife harvests in the Bosawas Reserve, Nicaragua. Environmental Conservation 35: 211–220.

Lacerda ACR, Tomas WM, Marinho-Filho J (2009) Domestic dogs as an edge effect in the Brasília National Park, Brazil: interactions with native mammals. Animal Conservation 12: 477–487.

Loss SR, Will T, Marra PP (2013) The impact of free-ranging domestic cats on wildlife of the United States. Nature Communications 4: 1–8.

Ma SL, Wang YX, Shi LM (1990) A new species of the genus *Muntiacus* from Yunnan. China. Zoological Research 11: 47–52.

Martin TG, Burgman MA, Fidler F, Kuhnert PM, Low-Choy S, Mcbride M, Mengersen K (2012) Eliciting expert knowledge in conservation science: elicitation of expert knowledge. Conservation Biology 26: 29–38.

McBride MF, Burgman MA (2012) What is expert knowledge, how is such knowledge gathered, and how do we use it to address questions in landscape ecology? Expert Knowledge and Its Application in Landscape Ecology 1: 11-38.

Meijaard E, Chua MAH, Duckworth J (2017) Is the Northern chevrotain, *Tragulus williamsoni* Kloss, 1916, a synonym or one of the least-documented mammal species in Asia? The Raffles Bulletin of Zoology 65: 506–514.

Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Murphy AJ, Goodman SM, Farris ZJ, Karpanty SM, Andrianjakarivelo V, Kelly MJ (2017) Landscape trends in small mammal occupancy in the Makira–Masoala protected areas, Northeastern Madagascar. Journal of Mammalogy 98: 272–282.

Najmuddin MF, Haris H, Norazlimi N, Md-Zain M, Mohd-Ridwan AR, Shahrool-Anuar R, Husna HA, Abdul-Latiff MAB (2019) Predation of domestic dogs (*Canis lupus familiaris*) on Schelgel's banded langur (*Presbytis neglectus*) and crested hawk-eagle (*Nisaetus cirrhatus*) on dusky leaf monkey (*Trachypithecus obscurus*) in Malaysia. Journal of Sustainability Science and Management 14: 39–50.

Newsome TM, Ballard GA, Crowther MS, Fleming PJS, Dickman CR (2014) Dietary niche overlap of free-roaming dingoes and domestic dogs: the role of human-provided food. Journal of Mammalogy 95: 392–403.

Nguyen A, Tran VB, Hoang DM, Nguyen TAM, Nguyen DT, Tran VT, Long B, Meijaard E, Holland J, Wilting A, Tilker A (2019) Camera-trap evidence that the silver-backed chevrotain *Tragulus versicolor* remains in the wild in Vietnam. Nature Ecology & Evolution 3: 1650–1654.

Oliveira VB de, Linares AM, Corrêa GLC, Chiarello AG (2008) Predation on the black capuchin monkey *Cebus nigritus* (Primates: Cebidae) by domestic dogs *Canis lupus familiaris* (Carnivora: Canidae), in the Parque Estadual Serra do Brigadeiro, Minas Gerais, Brazil. Revista Brasileira de Zoologia 25: 376–378.

Ortega-Pacheco A, Jiménez-Coello M (2011) Debate for and against euthanasia in the control of dog populations. euthanasia - the "good death" controversy in humans and animals. InTech, Rijeka, 233–246 pp.

Paschoal AMO, Massara RL, Santos JL, Chiarello AG (2012) Is the domestic dog becoming an abundant species in the Atlantic forest? A study case in Southeastern Brazil. Mammalia 76: 67–76.

Pascoe S, Van Putten I, Hoshino E, Vieira S (2020) Determining key drivers of perceptions of performance of rights-based fisheries in Australia using a Bayesian belief network. ICES Journal of Marine Science 77: 803–814.

Petersen WJ, Savini T, Ngoprasert D (2020) Strongholds under siege: Range-wide deforestation and poaching threaten mainland clouded leopards (*Neofelis nebulosa*). Global Ecology and Conservation 24: e01354.

Plaza PI, Speziale KL, Zamora-Nasca LB, Lambertucci SA (2019) Dogs and cats put wildlife at risk. The Journal of Wildlife Management 83: 767–768.

Rabinowitz A, Myint T, Khaing ST, Rabinowitz S (1999) Description of the leaf deer (*Muntiacus putaoensis*), a new species of muntjac from northern Myanmar. Journal of Zoology 249: 427–435.

Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Ramli R, Norazlimi N (2017) The effects of disturbance on the abundance and foraging behaviour of shorebirds and waterbirds in the tropical mudflat areas. Sains Malaysiana 46: 365–372.

R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/ (Accessed 10 May 2021)

Resurreccion BP, Sajor EE, Fajber E (2008) Climate adaptation in Asia: knowledge gaps and research issues in South East Asia. A full report of the South East Asia Team. Climate Change Adaptation Southeast Asia, ISET-International and ISET-Nepal, 76pp.

Riley CM, Koenig BL, Gumert MD (2015) Observation of a fatal dog attack on a juvenile long-tailed macaque in a human-modified environment in Singapore. Nature in Singapore 8: 57–67.

Riley EP (2008) Ranging patterns and habitat use of Sulawesi Tonkean macaques (*Macaca tonkeana*) in a human-modified habitat. American Journal of Primatology 70: 670–679.

Rocha SM, Oliveira SV de, Heinemann MB, Gonçalves VSP (2017) Epidemiological profile of wild rabies in Brazil (2002–2012). Transboundary and Emerging Diseases 64: 624–633.

Schlacher TA, Weston MA, Lynn D, Schoeman DS, Huijbers CM, Olds AD, Masters S, Connolly RM (2015) Conservation gone to the dogs: when canids rule the beach in small coastal reserves. Biodiversity and Conservation 24: 493–509.

Sepúlveda M, Pelican K, Cross P, Eguren A, Singer R (2015) Fine-scale movements of rural free-ranging dogs in conservation areas in the temperate rainforest of the coastal range of southern Chile. Mammalian Biology 80: 290–297.

Silva I, Crane M, Savini T (2020) High roadkill rates in the Dong Phayayen-Khao Yai World Heritage Site: conservation implications of a rising threat to wildlife. Animal Conservation 23: 466–478.

Silva-Rodríguez EA, Sieving KE (2012) Domestic dogs shape the landscape-scale distribution of a threatened forest ungulate. Biological Conservation 150: 103–110.

Sodhi NS, Posa MRC, Lee TM, Bickford D, Koh LP, Brook BW (2010) The state and conservation of Southeast Asian biodiversity. Biodiversity and Conservation 19: 317–328.

Smith RJ, Veríssimo D, Isaac NJB, Jones KE (2012) Identifying Cinderella species: uncovering mammals with conservation flagship appeal. Conservation Letters 5: 205–212.

Taborsky (1988) Kiwis and dog predation: observations in Waitangi State Forest. Notornis 35: 197–202.

Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Tantipisanuh N, Gale GA, Pollino C (2014) Bayesian networks for habitat suitability modeling: a potential tool for conservation planning with scarce resources. Ecological Applications 24 (7): 1705–1718.

Tobajas J, Jiménez J, Sánchez-Rojas G, Tobajas J, Jiménez J, Sánchez-Rojas G (2020) Factors affecting the abundance of Peters's squirrel, *Sciurus oculatus*, in a population of Central Mexico. Revista mexicana de biodiversidad 91: 1–8.

Torres PC, Prado PI (2010) Domestic dogs in a fragmented landscape in the Brazilian Atlantic Forest: abundance, habitat use and caring by owners. Brazilian Journal of Biology 70: 987–994.

Villatoro FJ, Naughton-Treves L, Sepúlveda MA, Stowhas P, Mardones FO, Silva-Rodríguez EA (2019) When free-ranging dogs threaten wildlife: Public attitudes toward management strategies in southern Chile. Journal of Environmental Management, 229: 67–75.

Wittemyer G, Elsen P, Bean WT, Burton ACO, Brashares JS (2008) accelerated human population growth at protected area edges. Science 321: 123–126.

Woods M, Mcdonald RA, Harris S (2003) Predation of wildlife by domestic cats *Felis catus* in Great Britain. Mammal Review 33: 174–188.

Wyman-Grothem KE, Popoff N, Hoff M, Herbst S (2018) Evaluating risk of African longfin eel (*Anguilla mossambica*) aquaculture in Michigan, USA, using a Bayesian belief network of freshwater fish invasion. Management of Biological Invasions 9: 395–403.

Yasué M, Dearden P, Moore A (2008) An approach to assess the potential impacts of human disturbance on wintering tropical shorebirds. Oryx 42: 415–423.

Yoak AJ, Reece JF, Gehrt SD, Hamilton IM (2016) Optimizing free-roaming dog control programs using agent-based models. Ecological Modelling 341: 53–61.

Young JK, Olson KA, Reading RP, Amgalanbaatar S, Berger J (2011) Is wildlife going to the dogs? impacts of feral and free-roaming dogs on wildlife populations. BioScience 61: 125–132.

Zamora-Nasca LB, di Virgilio A, Lambertucci SA (2021) Online survey suggests that dog attacks on wildlife affect many species and every ecoregion of Argentina. Biological Conservation 256.

Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Zanin M, Bergamaschi CL, Ferreira JR, Mendes SL, Oliveira Moreira D (2019) Dog days are just starting: the ecology invasion of free-ranging dogs (*Canis familiaris*) in a protected area of the Atlantic Forest. European Journal of Wildlife Research 65.

Zhang J, Hull V, Ouyang Z, Li R, Connor T, Yang H, Zhang Z, Silet B, Zhang H, Liu J (2017) Divergent responses of sympatric species to livestock encroachment at fine spatiotemporal scales. Biological Conservation 209: 119–129.

Figure legends

Figure 1 Bayesian networks modelling (**a**) perceived risk to carnivore mammalian species (**b**) perceived risk to non-carnivore mammalian species (**c**) perceived risk to Avian species and (**d**) the spatial distribution of perceived risk from domestic dogs in mainland Southeast Asia.

Figure 2: Percentage perceived risk in redlist categories. Height of peaks represent number of species scaled to 2, see Supplementary Materials 4 and 5.

Figure 3: Percentage perceived risk in Avian and Mammalian orders. Height of peaks represent number of species scaled to 2, see Supplementary Materials 4 and 5.

Orders with two or less species were removed for visualisation including Otidiformes, Dermoptera, Perissodactyla, Pholidota, Proboscidea.

Figure 4: The spatial distribution of perceived risk from domestic dog (*Canis familiaris*) across mainland Southeast Asia. Excluded human settlements and water bodies have been marked in white.

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Table legends

Table 1: Spatial data layers used as variables in the perceived risk spatial distribution.

Table 2: Results of a sensitivity analysis on the mammalian perceived risk BN (Fig. 1a,1b) with calculations of entropy reduction.

Table 3: Results of a sensitivity analysis of the "Overall Risk" node in the Avian perceived risk BN (Fig 1c) with calculations of entropy reduction.

Table 4: Percentage of perceived risk area per country.

Table 5: Results of a sensitivity analysis of the "Potential Dog Risk" node in the spatial distribution of perceived risk BN (Fig. 1d) with calculations of entropy reduction.

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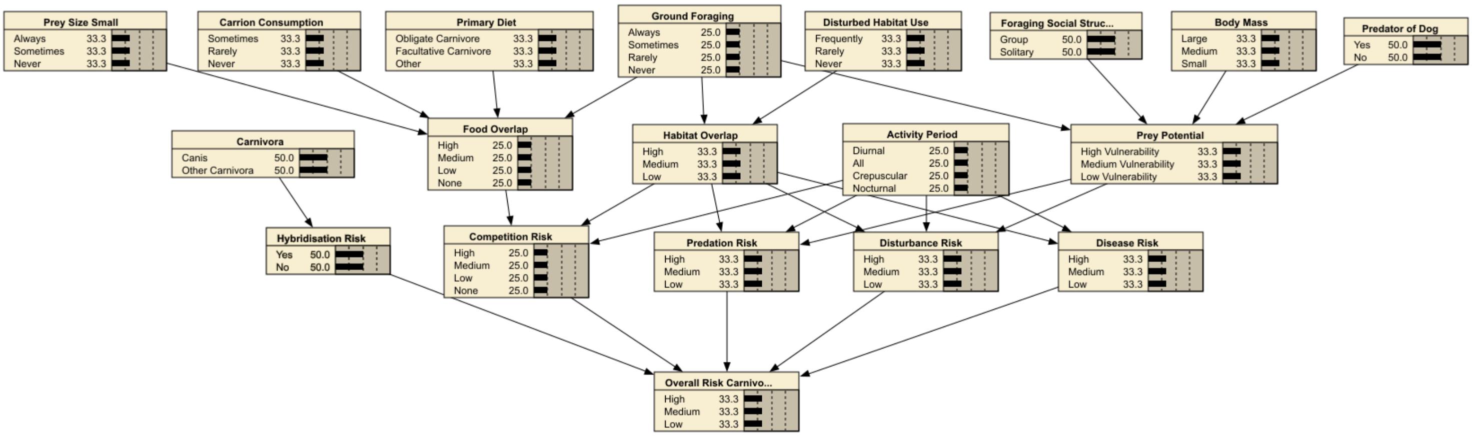
Figure 1a



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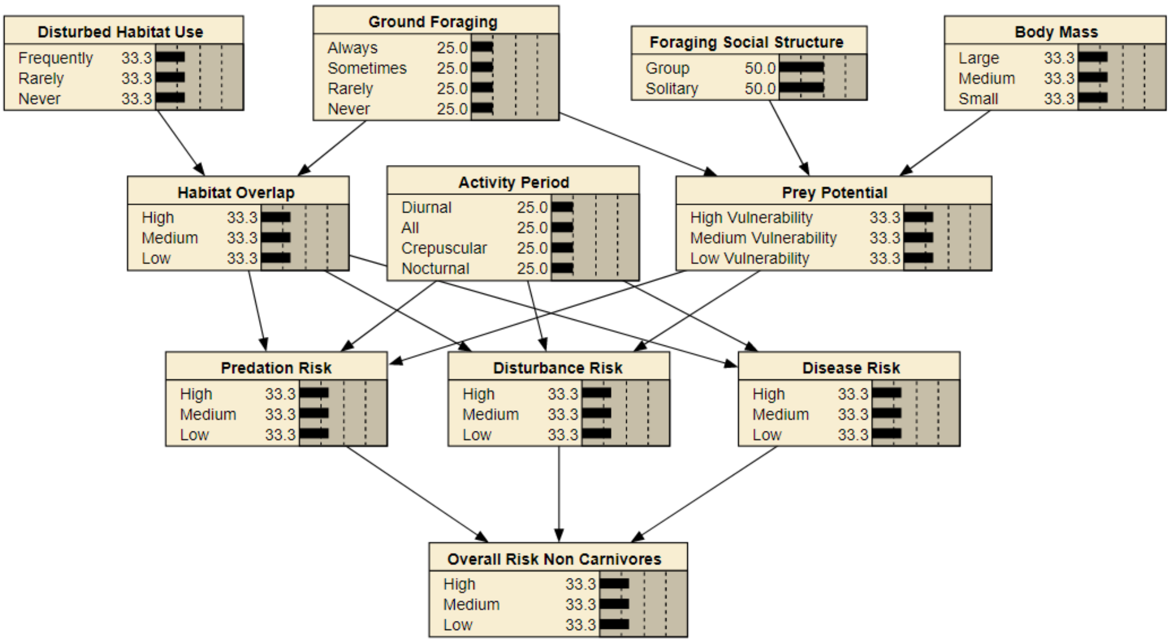
DOI: 10.26107/RBZ-2022-0012

Figure 1b



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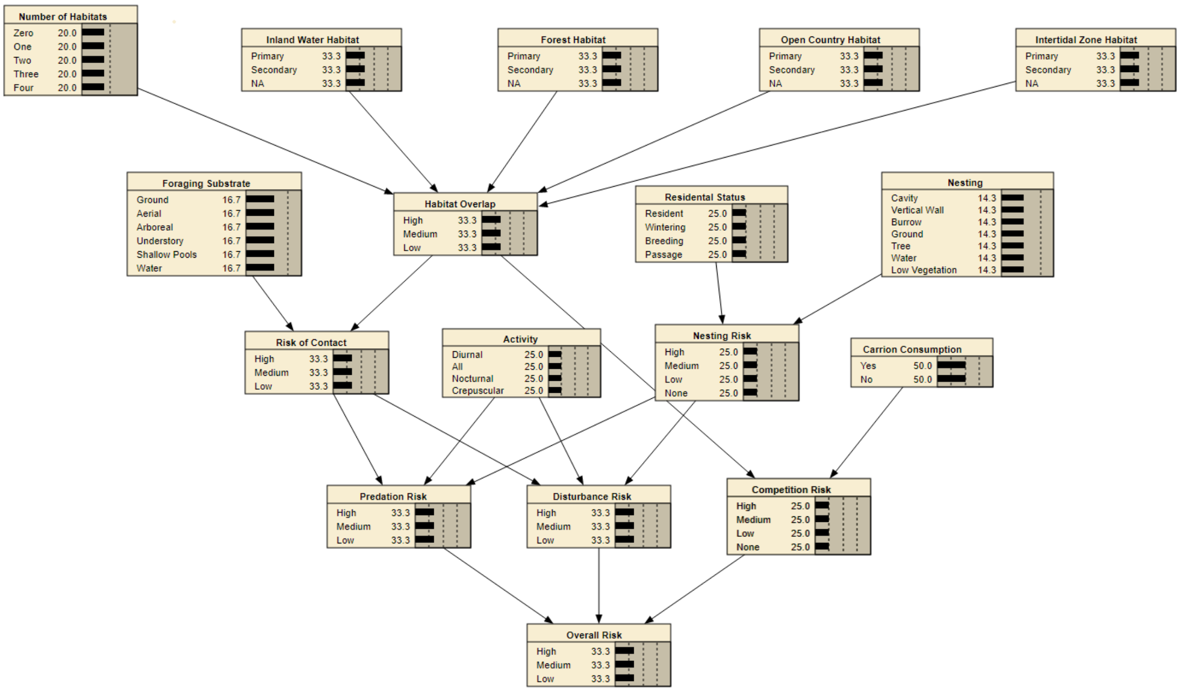
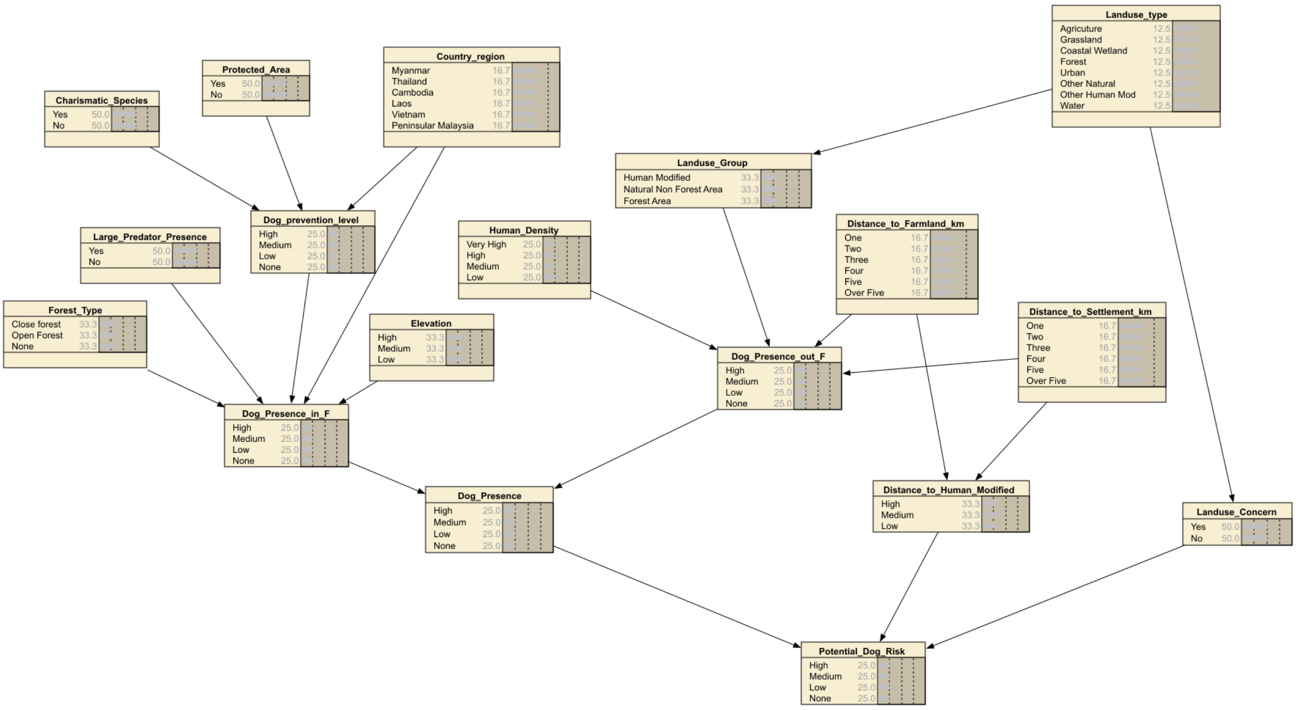
DOI: 10.26107/RBZ-2022-0012

Figure 1c



Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Figure 1d



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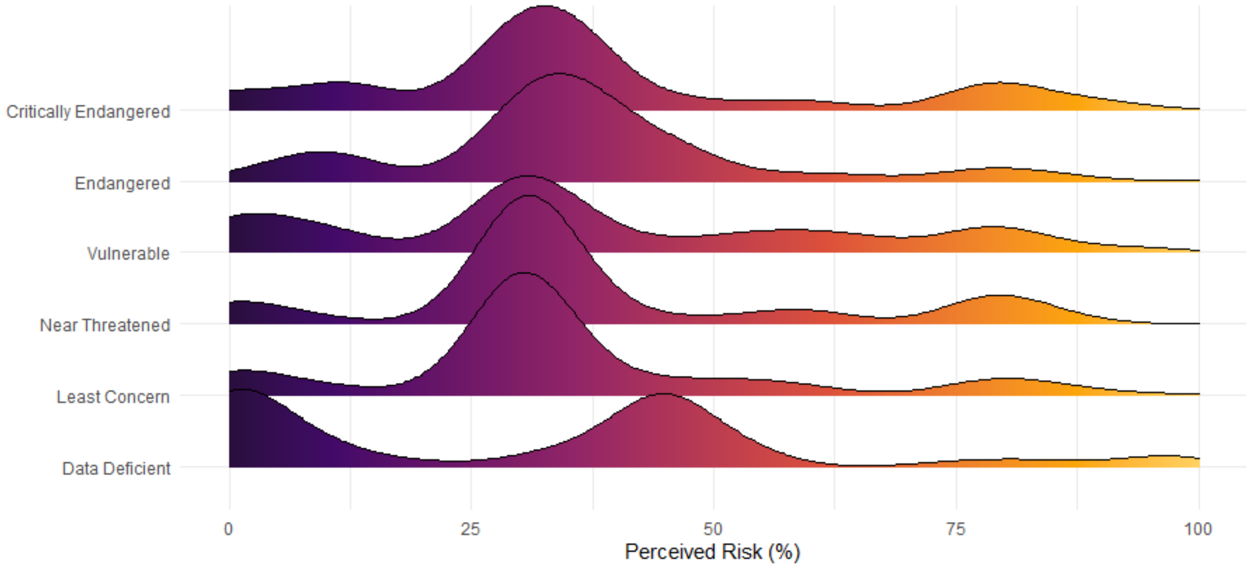
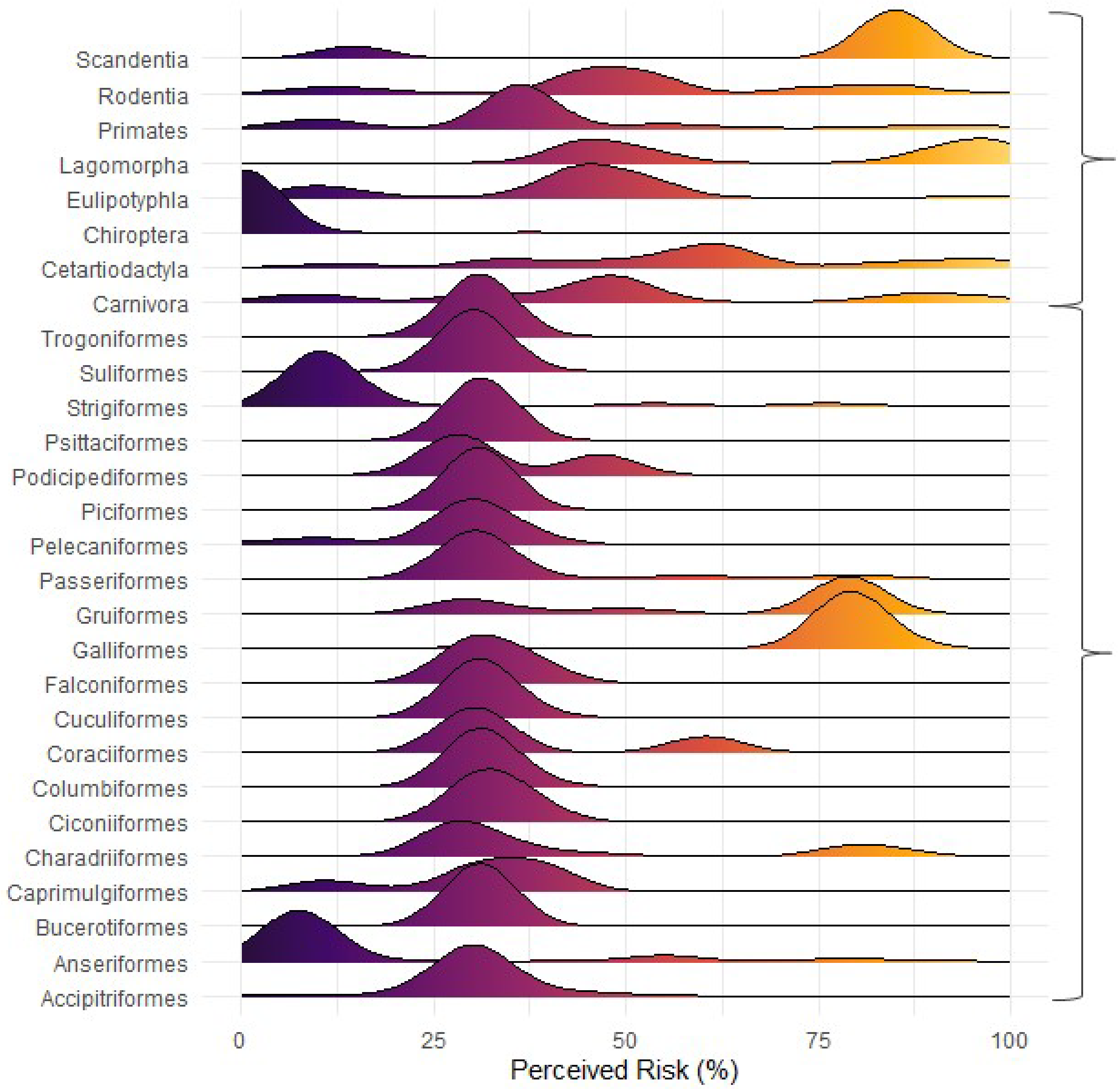
DOI: 10.26107/RBZ-2022-0012

Figure 2



Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
DOI: 10.26107/RBZ-2022-0012

Figure 3



Marshall, H.E. et al 2022 The threat of free-ranging domestic dog to native wildlife: implication for conservation in Southeast Asia. Raffles bulletin of zoology 70:275-288
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Figure 4

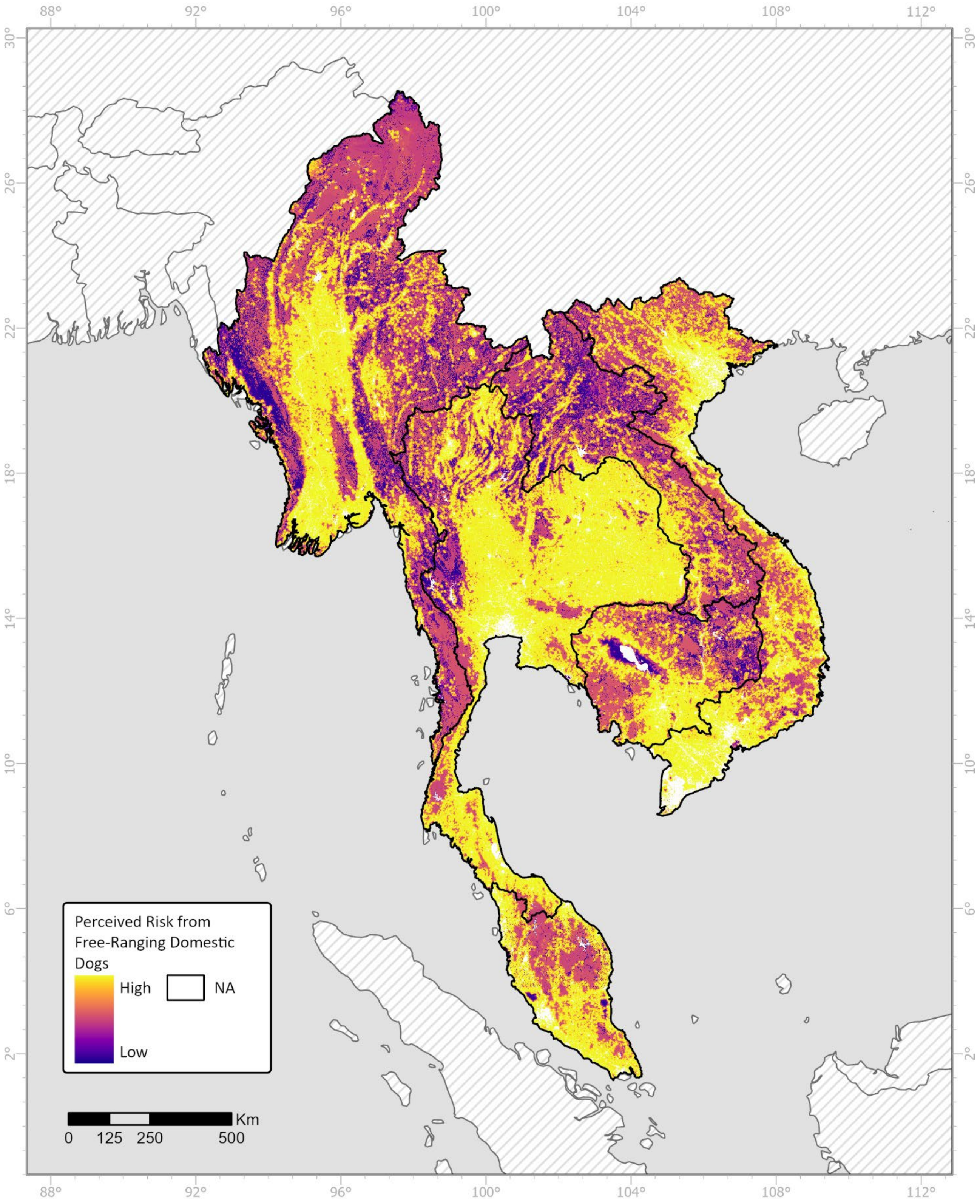

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Table 1

Variable (node)	Source	States
Elevation	Shuttle Radar Topography Mission (SRTM) Digital Elevation Map. Earth Explorers	Low (<250m) Medium (<1000m) High (>1000m)
Land Use Type	Clark Labs – Clark University. 2018. Tropical Pond Aquaculture and Coastal Wetlands. ESA CCI Land Cover project (2019)	Agriculture, Grassland, Coastal Wetland, Forest, Urban, Other Natural, Other Human, Water
Human Density	Center for International Earth Science Information Network—CIESIN—Columbia University, 2016. Gridded Population of the World Version 4 (GPWv4): Population Density.	Low (<25/km^2) Medium (<100/km^2) High (<200/km^2) Very High(>200/km^2)
Forest Type	ESA CCI Land Cover project (2019)	Non-Forest (<15%) Open Forest (<40%) Closed forest (>40%)
Charismatic Species Presence	IUCN Redlist	Present: Yes/No
Protected Area	World Database on Protected Areas (2019)	Present: Yes/No
Large Predator Presence	IUCN Redlist	Present: Yes/No
Distance from Settlement	ESA CCI Land Cover project (2019) Myanmar Information Management Unit Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS DNB) WorldPop (2020) Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University. 2016.	<1km, <2km, <3km, <4km, <5km, >5km
Distance from Farmland	ESA CCI Land Cover project (2019)	<1km, <2km, <3km, <4km, <5km, >5km

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Table 2

Node	Entropy Reduction Value	%
Carnivora Model		
Predation Risk	0.53	38.57
Disturbance Risk	0.53	38.23
Disease Risk	0.48	34.58
Habitat Overlap	0.31	22.29
Competition Risk	0.31	22.28
Ground Foraging	0.16	11.68
Activity Period	0.14	10.05
Prey Potential	0.11	8.25
Disturbed Habitat Use	0.08	6.03
Food Overlap	0.08	5.69
Primary Diet	0.04	3.06
Body Mass	0.01	0.81
Predator of Dog	0.01	0.65
Hybridisation Risk	0.00	0.19
Carnivora	0.00	0.19
Foraging Social Structure	0.00	0.12
Prey Size Small	0.00	0.02
Carrion Consumption	0.00	0.02
Non-Carnivora Model		
Predation Risk	0.72	51.59
Disturbance Risk	0.72	51.51
Disease Risk	0.58	41.33
Habitat Overlap	0.39	28.27
Ground Foraging	0.31	22.46
Prey Potential	0.21	15.04
Activity Period	0.13	9.24
Body Mass	0.02	1.52
Foraging Social Structure	0.02	1.32
Disturbed Habitat Use	0.00	0.18

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Table 3

Node	Entropy Reduction Value	%
Disturbance Risk	0.58	56.44
Predation Risk	0.53	52.31
Nesting Risk	0.23	22.84
Residential Status	0.10	9.58
Risk of Contact	0.09	8.93
Activity	0.09	8.41
Nesting	0.07	7.15
Habitat Overlap	0.04	3.51
Foraging Substrate	0.03	3.12
Competition Risk	0.03	2.64
Number of Habitats	0.01	0.88
Open Country Habitat	0.00	0.06
Intertidal Zone Habitat	0.00	0.03
Inland Water Habitat	0.00	0.03
Forest Habitat	0.00	0.02
Carrion Consumption	0.00	0.01

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Table 4

Country	NA (%)	Low (%)	Medium (%)	High (%)
Cambodia	3.7	10.7	39.6	46
Lao People's Democratic Republic	1.3	19.7	48.4	30.6
Malaysia (Peninsular)	8.4	2.6	30.1	58.9
Myanmar	2.4	13.5	46.6	37.5
Thailand	6.3	4.4	19.4	69.9
Viet Nam	10.5	1.8	30.2	57.5
Overall Region	5	9	36	50

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Table 5

Node	Entropy Reduction Value	%
Landuse Type	0.84	45.40
Landuse Concern	0.81	43.95
Dog Presence	0.44	23.86
Dog Presence out Forest	0.41	22.03
Distance to Human Modified	0.31	16.88
Distance to Settlement	0.18	9.49
Landuse Group	0.09	4.77
Distance to Farmland	0.07	3.90
Dog Presence in Forest	0.02	0.96
Forest Type	0.02	0.85
Human Density	0.01	0.55
Large Predator Presence	0.00	0.01
Country Region	0.00	0.01
Elevation	0.00	0.01
Dog Prevention Level	0.00	0.00
Protected Area	0.00	0.00
Charismatic Species	0.00	0.00

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