CHAPTER 2

TERRESTRIAL VERTEBRATES

1. Chapter Introduction

The world is currently experiencing the sixth mass-extinction event with highly unpredictable and severe climate conditions becoming increasingly frequent (Barnosky et al., 2011; Ceballos et al., 2015). Being one of the most conspicuous taxa, vertebrates are generally well-studied, but are ironically subject to alarming levels of extinction risks (Ceballos et al., 2020; Chisholm et al., 2023). This is in part due to their wide-ranging distributions and competition with humans and domestic animals for land and food resources. In particular, Ceballos et al. (2017) found that approximately 32% of over 27,000 vertebrate species have declining populations. These are worrying numbers because vertebrates, including bats and birds, are major pollinators globally (Ratto et al., 2018). In addition, approximately 75% of major crop species globally are thought to benefit to a certain degree from animal pollination (Klein et al., 2007). Trophic interactions between vertebrates and plants are also known to play significant roles and exert notable influences on biodiversity levels within ecosystems (Zhang et al., 2018), placing further emphasis on their pivotal role in nature.

In Singapore, documented terrestrial vertebrate (amphibians, reptiles, birds and mammals) extinction rates were reported to be between 5-40% (Brook et al., 2003). This was largely attributed to the significant forest loss in the country due to rapid development. Although vertebrate diversity in Singapore is generally well-documented, there remains an imperative need to obtain a better understanding of their diversity patterns and conservation challenges. While Singapore has lost much of its natural habitat over the years, it has inadvertently become a refugia for some vertebrate species, due to the relatively lower levels of human encroachment, poaching and deforestation compared to other parts of the region. For instance, the globally critically endangered straw-headed bulbul, *Pycnonotus zeylanicus* — whose populations have plummeted due to habitat loss and poaching across most of its range (Chiok et al., 2019) — is faring intriguingly well in highly-urbanised Singapore (Yong et al., 2019; Chiok et al., 2020). Similarly, it was found that ungulate populations in Singapore have persisted through the nation's rapid urbanisation, with the lesser mouse-deer, *Tragulus kanchil* populations recovering since the 1990s (Khoo et al., 2021). These examples lend further support for the need to continue research and step up conservation efforts for terrestrial vertebrates in Singapore.

Chapter 1 touched upon the importance of ecological connectivity between Singapore's fragmented habitats, and the need to conserve them. In this chapter, we cover the current state of knowledge on the vertebrates that inhabit said habitats, their conservation status, the threats they face, and propose conservation recommendations that also complement the restoration and protection of ecological connectivity in Singapore. Each section in this chapter is dedicated to a different terrestrial vertebrate taxon.

A common thread identified across all sections is the increasing need to pre-empt, oversee and ameliorate human-wildlife conflict (HWC) as we balance urban development and habitat preservation. Some of these challenges are multifold, which include (non-exhaustive): a paucity in public knowledge pertaining to the appropriate practices in dealing with interactions with wildlife (e.g. preventing habituation), and the extensive network of roads and paths creating both fragmented habitat and increased human/road traffic that inadvertently leads to an upturn in vehicle-wildlife collisions (e.g. roadkill or road-related injuries from cars and bicycles). The authors in this chapter also recommend targeted management of alien species, either by direct removal, or through regulation of the introduction pathways that allow their establishment in the first place (e.g. wildlife trade).

Overall, the preservation of habitats and conservation of terrestrial vertebrates that inhabit these places require a multi-pronged approach that is grounded in scientific rigour and takes into account both ecological and social considerations, which will be detailed in the sections to follow.

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2. Mammals

Singapore is home to approximately 74 species of terrestrial mammals (Figs. 12 and 13 feature some examples). Bats, carnivorans, primates, rodents and ungulates make up most of the mammalian species found locally. Species that are classified in their own orders include the pangolin, Sunda colugo and shrews.

2.1. Current State of Knowledge

Mammals in Singapore are relatively well-studied, with ungulates and primates having extensive coverage, in part due to their conspicuity. Bats however, are the most diverse mammals in Singapore with 31 species recorded (National Parks Board [NParks], 2021), with local bat research gaining ground in the last decade, having at least four species recorded for the first time locally. Carnivorans in Singapore consist of eight species, which include the now-wide-ranging smooth-coated otter, *Lutrogale perspicillata*; leopard cat, *Prionailurus bengalensis*; and various civets making up the remaining species. Primates are one of the most highly researched vertebrates in Singapore, having five species recorded thus far, including two non-native species recently introduced to the country. Rodents in Singapore constitute 13 species, and is perhaps one of the most understudied groups due to the nocturnal characteristics of the majority of the species within the group, such as rats and porcupines. Five species of ungulates are recorded in Singapore, represented by the Eurasian wild pig, *Sus scrofa*; Sunda pangolin, *Manis javanica*; treeshrew, *Tupaia glis*, and two other shrew species.

2.1.1 Bats

Bats fall under the order Chiroptera and are the second most speciose mammals in the world. They are also the only mammals capable of powered flight, and play several important roles in the ecosystem - as pollinators, seed dispersers, and predators of insect pests. In Singapore, there are five species of fruit bats (family Pteropodidae) and 26 species of insectivorous bats (families Emballonuridae, Hipposideridae, Megadermatidae, Molossidae, Nycteridae, Rhinolophidae and Vespertilionidae).

Concerted research on bats in Singapore started in the 1990s (i.e. Pottie et al., 2005; Leong & Lim, 2009) which were predominantly on their presence and distribution, with only one study on the diet of the lesser dog-faced fruit bat, *Cynopterus brachyotis* (Phua & Corlett, 1989). But since the last decade, local bat knowledge has been growing. At least four species were newly recorded in Singapore, i.e. the Horsfield's myotis, *Myotis horsfieldii* (Lim & Leong, 2014); ashy roundleaf bat, *Hipposideros cineraceus* (NParks, 2017); big-eared pipistrelle, *Hypsugo macrotis* (Lee & Teo, 2018); and long-winged tomb bat, *Taphozous longimanus* (Teo, 2018). Out of the 31 species of bats, 22 are listed as threatened, with 14 critically endangered, three endangered, four vulnerable, and one (Asian wrinkle-lipped bat, *Chaerephon plicata*) presumed nationally extinct. Overall, bat richness has seen a decline in Singapore (Lane et al., 2006) Besides new records, there have also been more field studies on bats, like on the ecological role of lesser dog-faced fruit bats (Chan et al., 2021) and the effects of LED street lights on the ecology of insectivorous bats (Lee et al., 2021).

2.1.2. Carnivora

Members of the Order Carnivora have diverse morphology, diet, and behaviour. However, all carnivorans have unique carnassial teeth adapted for shearing meat. The amount of meat in their diet varies between groups. In Singapore, there are eight species of carnivorans. Table 2 provides a list of these species, and their respective conservation statuses.

Table 2: A list of carnivorans recorded in Singapore. Conservation Status is with reference to the Singapore Red Data Book (3rd edition, 2021).

Family	**Species Name**	**Common Name**	**Conservation Status**
Felidae	*Prionailurus bengalensis*	Leopard Cat	CR
Viverridae	*Arctogalidia trivirgata*	Small-toothed Palm Civet	CR
	Paguma larvata	Masked Palm Civet	CR
	Paradoxurus musangus	Sumatran Palm Civet	LC
	Viverra tangalunga	Malay Civet	CR
	Viverra zibetha	Large Indian Civet	CR
Mustelidae	*Aonyx cinereus*	Oriental Small-clawed Otter	CR
	Lutrogale perspicillata	Smooth-coated Otter	EN

Note. LC - least concern, EN - endangered and CR - critically endangered

Family Felidae. Singapore has one remaining wild cat species, the leopard cat, *Prionailurus bengalensis*. In the past, larger felid species such as the Malayan tiger, *Panthera tigris* and leopard *P. pardus* have been recorded, but have since become extirpated by the 1990s (Chuang, 1973; Yang et al., 1990). The leopard cat is a domestic cat-sized animal, with its distribution restricted to large forest fragments, namely Central Catchment Nature Reserve (CCNR), Western Catchment Forest, Sungei Buloh Wetland Reserve (SBWR), Pulau Ubin and Pulau Tekong (Chiok et al., 2022; Chua, 2015; Chua et al., 2015; 2016; Fung et al., 2017; Wan et al., 2021). The species is active from dusk to dawn (Chua et al., 2016). Its diet can consist of vertebrate prey (e.g. rodents, birds, reptiles and amphibians) and also invertebrates (Chua et al., 2016). According to the survey by Chua et al. (2016), there were an estimated 21 individuals on Pulau Tekong, but the population size is not known for the species on mainland Singapore.

Family Viverridae. There are five species of viverrids - Sumatran palm civet, *Paradoxurus musangus*; small-toothed palm civet, *Arctogalidia trivirgata*; Malay civet. *Viverra tangalunga*; masked palm civet, *Paguma larvata*; and large Indian civet, *Viverra zibetha*. Because of their nocturnal nature, sighting records for civets are few and their species distribution is restricted to nature areas/reserves with larger forest patches. The large Indian civet was last sighted in 1990, the Malay civet was observed once on camera trap in the CCNR in 2012 (Lim & Ou Yang, 2012) and the masked palm civet was observed on two occasions in the 1990s (Lim et al., 2008) and more recently a roadkill along the Pan-Island Expressway near CCNR (Kalaivanan & Yeong, 2021). The small-toothed palm civets have been sighted more regularly in CCNR & Bukit Timah Nature Reserve (BTNR) (Chua et al., 2012; D'Rozario & Yeo, 2014; Subaraj & Rajathurai, 2016) while the most common civet species, the Sumatran palm civet is found in many nature spaces and even in some urban housing areas (Xu, 2010; Chua et al., 2012). There have been several studies looking at the biology, ecology and plant-civet interactions of the Sumatran palm civet (e.g. Xu, 2010; Fung, 2011; 2016; Fung et al., 2018), however, besides these studies, little else is known about the ecology of the other civet species found in Singapore.

Figure 12: Some mammals discussed in this section. Photographs by CAHM, FTK, WXC, LIS, AA and XW. *A.* Leopard cat, *Prionailurus bengalensis*, *B.* Sumatran palm civet, *Paradoxurus musangus, C.* Small-toothed palm civet, *Arctogalidia trivirgata*, *D.* Sunda slow loris, *Nycticebus coucang*, *E.* Long-tailed macaque, *Macaca fascicularis*, *F.* Raffles' banded langur, *Presbytis femoralis femoralis*, *G.* Plantain squirrel, *Callosciurus notatus*, *H.* Slender Squirrel, *Sundasciurus tenuis*, *I.* Red-cheeked flying squirrel, *Hylopetes spadiceus*.

Family Mustelidae. In Singapore, there are two species of otters, the smooth-coated otter, *Lutrogale perspicillata* and the Oriental small-clawed otter, *Aonyx cinereus*. Otters predominantly use aquatic habitats for feeding. However, they require suitable riparian terrain and vegetation for their holts and for their survival in Singapore. The Oriental small-clawed otters are rarely encountered as they have a restricted local distribution range, with sightings on offshore islands, e.g. Pulau Ubin (Thomas et al., 2016) and Pulau Tekong (Lim et al., 2016) and typically observed with smaller local population sizes. On the other hand, the return of the smooth-coated otter is deemed to be a conservation success story. This species was once extirpated from the 1960s, but have since returned in 1998 through our northern coasts (SBWR and Pulau Ubin). By 2021, the population was estimated to be 170 individuals islandwide (numbers given by NParks in an interview by Koh, 2022 and also reported in Shivram et al., 2023). They are able to find sufficient prey and have adapted to living in many of Singapore's natural and urban waterways (Theng & Sivasothi, 2016; Khoo & Sivasothi, 2018; Khoo & Lee, 2020). Besides distribution and population sizes, there has also been research on the diet and genetics of smooth-coated otters (Theng et al., 2016; Nguyen et al., 2020) ,where evidence was uncovered of hybridisation between the smooth-coated otter and the Oriental small-clawed otters (Moretti et al., 2017; Guerrini et al., 2020).

2.2.3. Primates

Three native species of non-human primates can be found in Singapore: Sunda slow loris, *Nycticebus coucang*; long-tailed macaque, *Macaca fascicularis*; and Raffles' banded langur, *Presbytis femoralis*. Since 2019, two dusky langurs, *Trachypithecus obscurus*, likely from Johor, Malaysia, have been observed in Singapore's forests (Ang et al., 2020a). In September 2023, a silvered langur, *Trachypithecus* sp. (*cristatus* or *selangorensis*) was first observed in Clementi, and was subsequently seen in various parts of southern Singapore, including Sentosa and Chinatown.

Sunda slow loris. The Sunda slow loris is a small animal weighing between 600 g and 700 g and measuring 30 cm to 40 cm from head to tail (which is stump-like). They consume tree gum, fruits, leaves, bird eggs and small invertebrates. Slow lorises (of the genera *Nycticebus* and *Xanthonycticebus*) are the only venomous primates in the world. When under threat, they lick the glands on their forearms. The secretion from the glands mixed with saliva will produce a composite venom, which is then injected through bites. The Sunda slow loris is found in Singapore, Malaysia, Indonesia, and Thailand. In Singapore, it is found in CCNR, BTNR, some adjacent nature parks, and Pulau Tekong. While the population size of the species in Singapore is unknown, it is considered nationally endangered (NParks, 2021). It is difficult to study them as they are shy and elusive, and are active mostly during the night. Only a handful of studies and sighting records have been reported on the lorises in Singapore (e.g. Fam et al., 2014; Lim et al., 2016).

Long-tailed macaque. The long-tailed macaque has a wide distribution in Southeast Asia, from Brunei, Cambodia, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, to Vietnam. Long-tailed macaques can be found in forests, along forest edges, in coastal habitats, and in urban areas. They are omnivorous, feeding on plants and small animals such as insects and crabs. Males and females show significant differences in body size. Males weigh between 4.5 kg and 7 kg with a body length (excluding tail) of 40 cm to 47 cm, while females are 2.5 kg to 6 kg and 35 cm to 45 cm. In Singapore, they occur mainly in CCNR, BTNR, SBWR, some nature parks, Sentosa, Sisters' Islands, Pulau Ubin and Pulau Tekong. Long-tailed macaques are the most commonly seen non-human primates in Singapore as compared to the Sunda slow lorises and Raffles' banded langurs. In 2012, it was estimated that there were between 1,810 and 2,166 long-tailed macaques in Singapore (Riley et al., 2015). But culling has reduced their numbers drastically (Feng, 2013). Currently, it is unclear how many macaques are in Singapore, though it is estimated to be approximately 2,000.

Raffles' banded langur. The Raffles' banded langur was formerly considered a subspecies (Groves, 2001), until genetic data and additional morphological and geographical information provided support that it should be recognised as a species, *Presbytis femoralis* (Ang et al., 2020b).

The langurs do not exhibit sexual dimorphism. An adult weighs between 6 kg and 8 kg, reaching 60 cm to 65 cm in body length with a tail of up to 80 cm. Raffles' banded langurs have a large and multi-chambered stomach, and a gastrointestinal tract that contains a variety of bacteria to help them digest food and break down toxins. Hence, langurs have an enhanced ability to consume tough foods like leaves, but also take in significant amounts of fruits, seeds, and flowers. The Raffles' banded langur is only found in Singapore and the southern states of Peninsular Malaysia, namely Johor and Pahang. Globally, there may be fewer than 400 individuals left, with 76 in Singapore and approximately 300 in Peninsular Malaysia, making this species critically endangered and one of the top 25 most endangered primates in the world. In Singapore, they are mainly found in CCNR, with one individual spotted in Dairy Farm Nature Park in 2021 (Khoo et al., 2021a).

2.2.4. Rodents

Rodents are characterised by a pair of continuously growing incisors in each of the upper and lower jaws. Rodents play important links in the ecosystems with their feeding interactions with both plants and animals and also as a prey to other predators. Currently, there are 13 native and extant species of wild rodents in Singapore, including squirrels, rats and porcupines.

Family Sciuridae. Two groups of squirrels are found in Singapore, namely tree squirrels and flying squirrels. Tree squirrels live mostly among trees and consist of the plantain squirrel, *Callosciurus notatus*; shrew-faced ground squirrel, *Rhinosciurus laticaudatus*; and slender squirrel, *Sundasciurus tenuis*. The three-striped ground squirrel, *Lariscus insignis* and cream-coloured giant squirrel, *Ratufa affinis* are presumed nationally extinct, while the variable squirrel, *C. finlaysonii* is not native to Singapore. Flying squirrels possess skin flaps known as patagia, which allow gliding flight. They comprise the red-cheeked flying squirrel, *Hylopetes spadiceus*; Horsfield's flying squirrel *Iomys horsfieldii*; and red giant flying squirrel, *Petaurista petaurista*.

Family Muridae. Six species of native murids remain in Singapore, namely the brown spiny rat, *Maxomys rajah*; Asian house mouse, *Mus musculus*, Pacific rat, *Rattus exulans*; Asian house rat, *R. tanezumi*; Malaysian wood rat, *R. tiomanicus*; and Annandale's rat, *Sundamys annandalei*. The red spiny rat, *Maxomys surifer* is nationally extirpated, while the brown rat, *R. norvegicus* was introduced to Singapore.

Family Hystricidae. The Malayan porcupine, *Hystrix brachyura* is native to Singapore, and was once reported to be common in forested areas and plantation lands (e.g. Ridley, 1895; Chasen, 1924). However, a lack of sightings since the 1970s had prompted the assessment of its status in Singapore to be rare and near extinct (Yang et al., 1990; Lim et al., 2008). Recent records largely from camera trapping compiled by Chung et al. (2016) suggested that the species might be relatively widely distributed within mainland Singapore, Pulau Tekong and Pulau Ubin, though their numbers remain low (NParks, 2021).

2.2.5. Ungulates

Singapore's rapid agricultural land conversion in the 19th century resulted in large swaths of deforestation across the island city state (Corlett, 1992), leading to large-scale extirpations of the native fauna. Large predators such as the Malayan tiger) and leopard were extirpated due to a combination of habitat loss and hunting. Other large mammals such as the Asian elephant, *Elephas maximus* and Malayan tapir, *Tapirus indicus* had tenuous occurrences in Singapore (Chew, 2016), and were not thought to occur historically.

Apart from large carnivores and mammals, Singapore also has five species of ungulates, four of which–the sambar deer, *Rusa unicolor*; red muntjac, *Muntiacus muntjak*; wild pig, *Sus scrofa;* and greater mouse-deer, *Tragulus napu* were thought to be extirpated due to high hunting pressures as well (Chasen, 1924; Corlett, 1992). The fifth ungulate species that was not extirpated, the lesser mouse-deer, *Tragulus kanchil*, was present throughout Singapore's rapid urbanisation and forest loss (Yang et al., 1990).

Figure 13: Some mammals discussed in this section. Photographs by WXC and NB.
A. Wild pig, *Sus scrofa*, *B.* Lesser mousedeer, *Tragulus kanchil*, *C.* Sunda pangolin, *Manis javanica*, *D.* Sunda colugo, *Galeopterus variegatus*, *E.* Common treeshrew*, Tupaia glis*, *F.* House shrew, *Suncus murinus*.

Family Cervidae. Only two species of deer (Family Cervidae) are known to exist in Singapore. The sambar deer is easily distinguishable from the muntjac deer, due to its larger stature and brownish coverts. Males of the sambar also have significantly larger antlers. Muntjac deer have pale orange to reddish brown fur, along with intricate facial markings that further distinguish them from the sambar. Both species are generally nocturnal in habit, with the sambar also being crepuscular. As such, sightings of deer are rare and are usually at irregular hours. Both species are known to be herbivores and feed mostly on young grass shoots and saplings.

Sambar deer were thought to be extirpated in the 1940s, with a subsequent re-emergence in the 1970s. The current population persisting within the nature reserves is thought to be a mixture of remnant and escapee populations (Teo & Rajathurai, 1997; Khoo et al., 2021b). They are known to inhabit mainly interior and mature forests, and sometimes feed along the forest edge. The current population is only known to inhabit BTNR and CCNR, with the surrounding urban structures and roads thought to be the main dispersal barriers (Lamperty et al., 2023). The current population numbers are estimated to be between 16–29 individuals between 2019–2020 (Khoo et al., 2021b).

On the other hand, muntjac deer have not been recorded with certainty before 2014 in Singapore, notwithstanding the presence of anecdotal and unconfirmed sightings in the late 1990s (Teo & Rajathurai, 1997). This species is more adaptable than the sambar–perhaps due to the lower level of persecution it experiences–and is known to inhabit hilly and montane forests in addition to lowland forests. The first confirmed camera trap record of the species was in 2014, with a subsequent one in 2015; both were recorded within CCNR (Khoo et al., 2021b). A local expert–naturalist reported hearing the distinct call (or bark) of the species during a nocturnal survey within CCNR in 2017 (Lamperty et al., 2023).

Family Suidae. Eurasian wild pigs, *Sus scrofa* are known to be widespread globally, and sometimes regarded as invasive in their non-native ranges. The species is however, native to Singapore and despite its supposed extirpation in the 1960s, it has since recolonised several regions of the island from the 2000s (Yong et al., 2010). wild pigs are omnivorous, but their main diet consists of roots, tubers and young plantation saplings. They are also known to scavenge, and are highly adaptable to a wide variety of habitats, from mature and degraded forests, to scrublands and parks. Recent studies have shown that boar populations in Singapore are healthy (Khoo et al., 2021b) and widespread across the island (Lamperty et al., 2023). However, because of their highly-adaptable nature and anthropomorphic affinity, human-boar conflicts in recent years have resulted in culling measures as a control measure (Feng, 2014). Apart from human-boar conflicts, overpopulation of boars have sometimes been found to be overtly damaging to forests, where intense foraging pressures hinder sapling growth and regeneration. However, this remains to be seen for Singapore, and research on the impacts of boars on Singapore's forests are currently ongoing and conducted by NTU.

Family Tragulidae. Mouse-deer are the world's smallest hoofed mammals, with the lesser mouse-deer, *Tragulus kanchil* measuring less than 50 cm from head to hind body, and weighing in at less than 3 kg. Greater mouse-deer, *Tragulus napu*, are only slightly larger (<60 cm body length) and heavier (<4.5 kg) than their lesser counterparts. Lesser mouse-deer have been spotted with increasing frequencies in Singapore recently, maybe in part due to their crepuscular nature, unlike greater mouse-deer, which are mainly nocturnal in habit.

Nonetheless, the greater mouse-deer was thought to be extirpated in Singapore since the 1940s, and was only rediscovered on the offshore island of Pulau Ubin in 2014 (Chua et al., 2009). On the mainland, it has been found in the Western Catchment Forest. Whilst the lesser mouse-deer were not extirpated during Singapore's rapid development, it is only known to occur on mainland Singapore and is absent from Pulau Ubin.

2.2.6. Other mammals

Sunda pangolin. Touted as the world's most trafficked mammal, the Sunda pangolin, *Manis javanica* is critically endangered, as it is highly persecuted throughout its entire range, mainly for its keratinous scales that are erroneously thought to have medicinal healing properties. Despite being covered in hard scales, the defence mechanism of the species is to curl up in a ball when faced with a threat, inadvertently facilitating poaching. Pangolins feed mainly on ants and termites with their long tongues. Their poor sight is compensated by a strong sense of smell, which is used to locate prey. They also have broad and strong claws to aid them in digging for food.

In Singapore, the species is thought to experience a lower level of threat from poaching, perhaps in part due to the higher levels of enforcement and penalties in Singapore. However, poaching incidents of the species do occur (Low, 2020), although sporadically and likely under-reported (Quek, 2018). Due to its nocturnal nature, the species is hard to locate and study, resulting in a dearth of research and knowledge (Lee et al., 2018). Studies of local pangolin populations are lacking, and have only assessed the home range and movement ecology thus far (Lim & Ng, 2008).

Sunda colugo. Sunda colugos, *Galeopterus variegatus* are arboreal gliding mammals, and as the name suggests, they possess patagia that connect their head, paws and tail, allowing them to glide across forests. Being nocturnal creatures they have large eyes which afford them excellent night vision. Their diet consists mainly of young shoots, leaves and sometimes fruits and bark lichen.

Locally, the species is highly-adaptable to fragmented forest patches in semi-urban settings, but restricted to forests with a substantial number of mature/tall trees, as the trees have to be tall enough for them to glide and navigate. Owing to their nocturnal nature, the species is still thought to be understudied, even in Singapore. However, ecological research on the distribution, population number and habitat preference of the species in Singapore is currently ongoing.

Common treeshrew. Despite being superficially similar to squirrels, common treeshrews, *Tupaia glis,* are non-arboreal and usually forage on the forest floor or on low vegetation. They mainly feed on insects and fruits. Their highly-adaptable nature allows them to inhabit various habitats, from mature forests, to parklands and scrublands. In Singapore, the species is widely-distributed and is relatively resilient to fragmentation. They can even be found in homes and estates adjacent to degraded forests and regrowth plantation forests, exhibiting their malleable nature. However, local research on the species is scarce.

Family Soricidae. Often mistaken as rats due to their similar stature and body shapes, shrews have elongated snouts, thick tails and markedly tiny eyes unlike rats. As a result of their tiny eyes, shrews have very poor eyesight, and rely mainly on their whiskers, sense of hearing and smell to navigate and forage. They are primarily terrestrial, insectivorous and nocturnal, preferring to forage along the forest floor and grasslands. In Singapore, there are two species of shrews, namely the Asian house shrew, *Suncus murinus* and Malayan shrew, *Crocidura malayana*.

The Asian house shrew is the most common and widespread of the two, and can be found fairly easily within urbanised neighbourhoods. What is less known is the highly beneficial qualities of the species, as they are mainly insectivorous and possess highly voracious appetites. The latter qualities make them an effective biological pest control, particularly in agricultural and urban settings where pests removal is crucial. Unfortunately, not much is known about the existence of the Malayan shrew in Singapore, due to the paucity of data on the species. It is known to exist across Peninsular Malaysia, making it a possibility that the species continues to occur within Singapore's forests.

2.3. Threats

2.3.1. Habitat destruction

Mammalian species are particularly vulnerable to habitat destruction, which directly reduces living space and food resources through habitat loss and degradation, and indirectly decreases mating opportunities through habitat fragmentation. For instance, the loss of large mature trees affect the movement of colugos due to their need to glide from a certain height (Lim, 2007; Tan, 2020; Tan, 2021) and also reduces availability of roost options for forest obligate bats such as the naked bulldog bat, *Cheiromeles torquatus* (Leong & Chan, 2011). Urban development near forests brings light pollution, which can influence bat activity and disorient the animals (see Lee et al., 2021). The separation of BTNR and CCNR by the Ecolink disconnected the populations of Raffles' banded langurs, which subsequently saw the extirpation of the population in BTNR.

2.3.2. Wildlife-vehicular collisions

Urban infrastructures such as roads which go through habitats introduce challenges and risks to wildlife (Teixeira et al., 2013). One obvious scenario is when animals who traverse across these man-made networks might be inflicted with road-related injuries or mortalities, and thus face endangerment. Besides the immediate effects following road construction such as soil erosion, increased sedimentation, forest fire risks, etc. (Kleinschroth & Healey, 2017), completed road networks can continue to hamper habitat quality via vehicle pollution, reduction of food sources and traffic noise (van der Ree et al., 2011). Additionally, roads adjacent to forested areas can also reduce activities of bats (Lee, 2016) and the fragmentation of habitats by roads can isolate metapopulations (especially for road avoidant species), which then block gene flow and reduce genetic diversity (Gregory et al., 2017). As such, there is a likelihood that the above-mentioned impacts of road networks would drive local species to extinction (Linden et al., 2020). Many species of mammals have been killed in vehicular collisions in Singapore, particularly in recent years, including the Sunda pangolin (Hicks, 2021), wild pig (Zheng, 2017), long-tailed macaque (How, 2021), Raffles' banded langur (Ang, 2021a), leopard cat (Lay, 2021a), sambar deer (Today, 2018), smooth-coated otter (Tan, 2019), and Sumatran palm civet (Lay, 2021b).

2.3.3. Wildlife trade

The global wildlife trade is a multimillion dollar industry that is regarded as one of the main drivers of species extinction (Tingley et al., 2017). Nestled within one of the world's largest biodiversity hotspots (Sodhi et al., 2004), the region of Southeast Asia and its rich biota are simultaneously impacted by habitat loss and the hunting of wildlife (Sodhi et al., 2010). The island city state of Singapore is no exception, with its prominent status as a regional trade hub putting the country in a prime position for the transshipment of raw materials and goods, but it also inadvertently facilitates the trade of wildlife and their derivatives (Lin, 2005). In recent years, Singapore border authorities have seized two large shipments of ivory and pangolin scales (Ng, 2018, Liu, 2019), both of which were illicit. Apart from the ivory and pangolin seizures, the country was also involved in multiple seizures that included (non-exhaustive) wild birds (Shepherd et al., 2012) and reptiles (Goh & O'Riordan, 2007).

Singapore's domestic market for wildlife consumption has also been found to have a great deal of activity, particularly for birds (Eaton et al., 2017; Chiok & Chng, 2021; Jain et al., 2021). Additionally, prior to September 2021, the sale of ivory and related products was legal in Singapore (Choo & Menon, 2019), and was found to be actively traded (Webber et al., 2013). The ban was announced following the major seizures of ivory and pangolin scales at the country's borders. Domestic demand for wildlife is therefore not insignificant in Singapore, and has been shown to be highly active and possibly increasing (Chiok & Chng, 2021; Jain et al., 2021). Poaching activity has similarly been found to be operating at a worrisome scale (Quek, 2018), though comparatively lower to that of other Southeast Asian countries.

Aside from the consumption of wildlife via trade or poaching, the introduction of exotic species into Singapore, be it intentional or accidental, can pose potentially serious risks towards the native wildlife. Exotic species that establish populations can sometimes become invasive, outcompeting and outgrowing native populations. They can also potentially introduce novel viruses or bacteria that can negatively alter local population dynamics, and in some cases, even spread to humans. Accidental introductions, such as pet escapees or releases, do occur in Singapore, although sporadically. For instance, two leopard cats that were kept illegally as pets here were repatriated to Malaysia, after genetic tests showed that they were of Malaysian origin (Chandra, 2020). In a separate case, researchers recorded the presence of a pygmy slow loris *Nycticebus pygmaeus* within the nature reserves (Fam et al., 2014). Lorises are popular in the wildlife pet trade, and the pygmy slow loris is not found naturally in Singapore. These cases provide unequivocal evidence of smuggling and illegal wildlife trade that continues to occur in Singapore.

2.3.4. Human-wildlife conflicts

With increasing urbanisation, human-wildlife conflict (HWC) is becoming a major conservation issue for wildlife populations (Dickman, 2010). Similarly, in highly urbanised Singapore, urban-adapted mammals such as the long-tailed macaque, smooth-coated otter, Sumatran palm civet, wild pigs and bats face the brunt of negative interactions with humans (Siau, 2021; Tan, 2017).

HWC cases are complex as they occur with the interplay of people, environment and animal. For example, the clearance of forests for development could lead to animals moving into adjacent housing areas, which could end up as HWC cases or as roadkill (see Wildlife-vehicular collisions). In addition, direct or indirect food provisioning by people (Ang, 2021b; Chong, 2021) can also contribute to negative human-wildlife interactions as feeding artificially raises the carrying capacity and boosts wildlife populations. It also leads to animals becoming habituated to people, which can progress to associating humans as a food source (Sha et al., 2009).

Fear and intolerance towards wildlife, especially those that can be found residing in and around residences, can similarly lead to negative perceptions, leading to residents' complaints, calling for their removal and even trapping the animals on their own (Leong & Chan, 2011). In the past, culling was used as a wildlife management strategy for mammals such as the wild pigs and long-tailed macaques (Feng, 2014; Riley et al., 2015). However, culling is a short-term solution for HWC and is not effective in resolving the root causes of the HWC. In recent years, there has been a shift to humane wildlife management strategies coupled with the inclusion of pre-emptive measures (such as signages) to reduce chances of HWC (Tan, 2017; Jaafar, 2018). As Singapore strives to become a "City in Nature" under the Singapore Green Plan 2030, negative interactions between people and wildlife would persist if the root causes of such conflicts are not resolved. It is imperative that solutions not only target wildlife and environmental factors, but the attitudes of people as well in order to achieve coexistence between wildlife and humans.

2.4. Recommendations

2.4.1. Habitat preservation and restoration

Having only 0.2% of its primaeval forests remaining (Corlett, 1992), it is of utmost importance that any remaining unlogged forests, including regenerated and young growth forests, be retained and preserved. Most remaining forest patches in Singapore, be it protected or unprotected, have been identified and stratified according to their habitat types (Gaw et al., 2019). However, most of these patches, especially those flanking urban areas are unprotected, and are slated for development under the government's urban redevelopment plans. Approximately 47% of 2,700 ha of forested land slated for development has already been cleared, with a further ~33% of 3,700 ha of reserve land (land that has not been slated for development) already experiencing some form of clearing (LepakinSG, 2021). The deleterious impacts of deforestation and habitat fragmentation are unequivocal, threatening species extinctions globally (Harper et al., 2007). As such, every effort should be made to conserve Singapore's important remaining forest patches, and the repurposing of existing developed land areas should be explored in greater detail.

The restoration and reconnection of fragmented habitats also play a pivotal role in conservation. In recent years, Singapore has already constructed a number of wildlife crossings, specifically the Eco-Link @BKE, the partial pedestrianisation of Old Upper Thomson Road and the subsequent construction of two rope bridges along the same area. The main aim of these structures is to restore the connection between habitats fragment by urban structures, such as roads and expressways. The Eco-Link connects the BTNR and CCNR, which were segregated during the construction of the BKE, whilst the rope bridges allow for arboreal mammals, mainly the macaques, langurs and even civets, to cross from CCNR to Thomson Nature Park safely.

These laudable attempts at restoring habitat connectivity are not restricted to Singapore, and similar structures have been erected in other Southeast Asian countries as well, such as the Sungai Yu viaduct in Peninsular Malaysia. It is therefore imperative for targeted research to be done to assess the effectiveness of wildlife crossings, be it purpose-built or existing non-intended structures, as well as to conduct studies to determine ideal locations for future structures. The rewilding of corridors is an equally important factor, and it closely aligns with the "City in Nature" ethos echoed by the government. The National Parks Board, along with the Urban Redevelopment

Authority, recently initiated the Ecological Profiling Exercise (EPE), which aims to pinpoint suitable locations to implement rewilding for habitat restoration. Rewilding and connectivity restoration efforts must take an inclusive approach, leveraging on the expertise and knowledge of various academics, researchers, non-government organisations as well as the general public.

2.4.2. Enforcement

Aside from habitat conservation, there is also a need to protect important forest patches from encroachment and excessive use, via the restriction of key biodiversity sites to the public. Excessive use and trampling by park-goers and trail-users undoubtedly have detrimental impacts on Singapore's already small forest patches (Chatterjea, 2007), even more so during the COVID-19 pandemic (Miller-Rushing, 2021). Whilst certain key biodiversity areas in Singapore's nature reserves have already been designated as out-of-bounds, trespassers venturing off-trail and into restricted areas are still occurring and at increasing levels (Ang, 2021c). Land governed by Singapore's Ministry of Defence (e.g. Pulau Tekong) has also been found to harbour high biodiversity levels, likely due to its lack of development and restricted access (Chua, 2015). The importance of these forest patches and key biodiversity areas therefore make it crucial for government agencies to step up their enforcement efforts for wilful trespassers. However, it is imperative for access to restricted areas to still be granted for the purpose of research, to both government agencies and academic researchers.

Unauthorised trespassers to protected biodiversity areas should be actively mitigated and enforced upon by the relevant authorities. Apart from the detrimental impacts of unnecessary trampling by hikers or mountain bikers (Thurston & Reader, 2001; Marzano & Dandy, 2012) on unsanctioned trails, the formation of new trail and access points inadvertently creates more access points for poachers (see Wildlife Trade). Full-time park rangers should be employed to conduct regular patrols across the nature reserves and important biodiversity areas. Such practices are common throughout national parks globally, and increased monitoring (in the form of ranger patrols) has been shown to be an effective deterrence (Moore et al., 2018).

With Singapore's small nature reserve area, active and regular patrols would certainly be an effective deterrent for would-be trespassers and poachers alike. Additionally, the volunteering programme previously dubbed 'Nature Wardens' was a successful initiative that acted as a buffer for enforcement efforts, and should be revived by the National Parks Board (Fang, 2015; Tan, 2016). Volunteers from nature groups, researchers and naturalists, who spend a lot of time within parks and nature reserves, should therefore be continually engaged and recruited as new Nature Wardens, so that they can supplement the existing education and enforcement efforts conducted by the National Parks Board.

2.4.3. Biodiversity surveys

The engagement of civil society such as the nature community and subject-matter experts in biodiversity surveys can greatly increase manpower and research efficiency. In particular, biodiversity surveys are needed in areas which have not been systematically surveyed before or in recent years, such as restricted state land forests.

2.4.4. Roadkill mitigation measures

It is necessary and urgent to identify hotspots where animal roadkill happens, so that targeted mitigation measures can be explored to reduce animal mortalities and increase wildlife permeability. Depending on the location and fauna of interest, roadkill mitigation measures can be aimed at changing animal behaviour (e.g. crossing structures, fencing, noise barriers, olfactory repellents etc.) and/or driver behaviour (e.g. speed bumps, signages etc.). For example, rope bridges can help arboreal mammals traverse gaps in the canopy without descending to the ground to cross. Culverts with fences can guide ground-dwelling animals to travel under roads. Restricting night-time vehicular access on certain smaller roads allows nocturnal mammals to move safely between fragmented habitats. The recent implementation of the Roadway Animal Detection System (RADS) by the National Parks Board can help inform drivers when animals are on the road ahead so that road accidents may be avoided (Ng, 2021).

2.4.5. Mitigation of human-wildlife conflict

There needs to be a holistic understanding of underlying factors which cause human-wildlife interactions to become conflict issues. Understanding the knowledge, attitudes and beliefs of people are an important component to prevent and mitigate human-wildlife conflicts. One way to prevent human-wildlife conflicts from happening is behavioural change, people need to know how to be safe around wildlife and this can be introduced through formal and informal education. Topics on local biodiversity and issues on proper etiquette in nature areas and behaviour around urban wildlife can be introduced in the school curriculum. Besides formal education, informal education opportunities through public outreach events, such as the Festival of Biodiversity would encourage the public to learn and develop an appreciation for our natural heritage and biodiversity. In addition, in areas where human-wildlife interactions are expected to be high (e.g. new residences next to nature areas), relevant government agencies, wildlife working groups and the nature community can promote dialogue and engage with residents. Through these informal education opportunities, resources can be made known to residents to be aware of possible wildlife sightings and how to behave appropriately around them. Other behaviours that contribute to human-wildlife conflicts such as food provisioning for wildlife and trapping of wildlife need to be curbed through the strong presence of enforcement and penalties by agencies under the newly amended Wildlife Act (Elangovan, 2020; Choo, 2021; Ong, 2021).

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3. Birds

Singapore lies at the heart of Sundaland, a global biodiversity hotspot (Myers et al., 2004), and sits on the crossroads of the East Asian-Australasian and Central Asian Flyways (Li et al., 2020). Singapore stands out in Southeast Asia as having one of the region's best-documented avifauna. Records here date back to the colonial period, with the renowned naturalist Alfred Russel Wallace having spent considerable time studying the island's birdlife. There have been several major compilations on Singapore's avifauna, from as early as the 1800s (e.g. Hume, 1879a, 1879b; Kelham, 1883; Chasen & Kloss, 1921; Chasen, 1923; Bucknill & Chasen, 1927; Gibson-Hill, 1950), to more recent works published in the last two decades (e.g. Wang & Hails, 2007; Lim & Lim, 2009).

Today, we have a relatively good understanding of the natural histories of most bird species, their ecologies in various settings (Chong et al., 2012), turnovers in space and time, extirpations (Castelleta et al., 2000; Chisholm et al., 2016; 2023), and increasingly, population genetics (Cros et al., 2020; Sadanadan & Rheindt, 2015; Tan et al., 2018; Tang et al., 2016). Recent work has also helped us to better understand the population trends of several species over time (e.g. Harris et al., 2012).

3.1. Current State of Knowledge

3.1.1. Species diversity

Our comprehensive understanding of landscape changes in the nation has allowed an accurate documentation of the extinctions that followed (e.g. Corlett, 1992; Casteletta et al., 2000; Brook et al., 2003a; Chisholm et al., 2016; 2023).

Figure 14: The greater green leafbird, *Chloropsis sonnerati* is threatened by poaching in the region, but is doing well in the relatively well-protected forests of Singapore. Photograph by SYCK.

Over 25 species of birds vanished before 1950, and a further 18 around the 1950s (Wang & Hails, 2007). Extinction debt is being observed in Singapore as well—a phenomenon where extinctions are only detected after a lag time from the initial habitat loss (Tilman et al., 1994). Populations of white-bellied woodpecker, *Dryocopus javensis*; scarlet minivet, *Pericrocotus speciosus*; and Malaysian eared nightjar, *Lyncornis temmincki* have disappeared only recently—about two decades ago. This trend may continue unless measures are taken.

Yet, threatened species such as the endangered greater green leafbird, *Chloropsis sonnerati*, (Fig. 14) though under heavy poaching pressure in the region, have a comparatively safe haven in the Central Catchment Nature Reserve (CCNR). Another prominent example of a locally thriving species is the globally near-threatened grey-headed fish eagle, *Haliaeetus ichthyaetus* (Wang & Hails, 2007), which has recently been downlisted to nationally vulnerable in the Singapore Red Data Book version 3. This is an improvement on its status as nationally critically endangered in version 2. Ironically, the success of this bird-of-prey can likely be attributed to the presence of large introduced fishes in Singapore's waterways (Yong, 2011; Yong et al., 2014). Land use change across the region has led to the increase in edge and open-habitat species that historically did not occur in Singapore or had restricted range, including the red-wattled lapwing, *Vanellus indicus*; pied triller, *Lalage nigra*; and collared kingfisher, *Todiramphus chloris*; (Wang & Hails, 2007; Ward, 1968; Lok & Subaraj, 2009).

The rapid rise in observer effort, especially in the past five years following the boom of photographic interest in the community, as well as the growing popularity of citizen science platforms like eBird (Sullivan et al., 2009) and iNaturalist, provides us with up-to-date information on general species distribution and their relative abundances in Singapore. Such surveillance also extends to migratory species with regards to their baseline trends and abnormal occurrences (Sin et al., 2020).

3.1.2. Species ecology

Pest birds. Urbanisation has allowed many alien species to flourish. Various efforts to curb the spread of certain pest species have been put in place over the past decades through population control or relocation (Low, 1987; Neo, 2017; Toh, 2018). Species like the house crow, *Corvus splendens* have long been treated as pests (Brook et al., 2003b; Peh et al., 2002; Soh et al., 2002) and active control has successfully reduced their numbers (Tan et al., 2020b). Conversely, populations of other species are less managed, with the rock dove, *Columba livia* and Javan myna, *Acridotheres javanicus* (Fig. 15) being the two most abundant urban species today (Chong et al., 2012).

Figure 15: The non-native Javan mynah, *Acridotheres javanicus* has become established in Singapore, and today is one of the most common birds in the local urban landscape. Photograph by SYCK.

In addition, recent works have shown that the Javan myna is able to disperse through the country rather homogeneously, whereas the rock dove is fairly restricted to urban areas (Low et al., 2017; Tang et al., 2018). Refraining from feeding pest birds also reduces their abundance in urban areas (Soh et al., 2021).

Forest Birds. Recent genomic insights have allowed the population dynamics of local species to be understood. Surviving forest species are struggling badly, with fragmentation severely limiting gene flow between populations (Sadanandan et al., 2015; Cros et al., 2020). Dispersive species including the olive-winged bulbul, *Pycnonotus plumosus* are more resilient (Tang et al., 2016), while other edge species like the pin-striped tit-babbler, *Mixornis gularis* that were expected to experience limited impacts seem to show signs of population fragmentation instead (Tan et al., 2018).

3.1.3. Population ecology

There have been long-running initiatives that continue to monitor the local bird population and collect baseline data. The National Parks Board (NParks) established the bird banding programme in 1998 and conducts mist-netting once every two months (Teo, 2009; Teo, 2013). Citizen science initiatives like the Garden Bird Watch and Heron Watch by NParks, and the Annual Bird Census by the Nature Society Singapore (NSS), continue to provide insights into population trends (Lim, 2020; Low et al., 2020; NParks, 2021a, 2021b). Information and knowledge about these population trends are summarised in the Singapore Red Data Book (Ng & Wee, 1994; Davison et al., 2008). It provides local conservation statuses of each species that is updated periodically and will be written up into a third edition of the Red Data Book (NParks, 2021c).

3.2. Singapore's Role in Bird Conservation

3.2.1. Regional work

Conservation crosses political boundaries; the movement of animals (particularly birds) are unrestrained and the threats faced are collective. Extinctions faced in neighbouring habitat patches and islands (Sodhi et al., 2010) consequently impact metapopulations that comprise Singapore's fauna. Such fragmentation is especially pronounced for insectivorous species (Yong et al., 2011). The efficacy of conservation efforts undertaken by Singapore is viable in the long-run only through collaborations with regional partners. The wealth of collective knowledge and research expertise in Singapore has enabled the forging of effective partnerships with external organisations to conduct conservation research as well. The Panti Bird Sanctuary scientific expedition (Chow, 2020) is one such example: a collaborative effort by the Malaysian Nature Society and NSS to survey one of Johor's most important biodiversity hotspots (BirdLife International, 2021a; Lim et al., 2012).

Various non-governmental organisations with international reach have also based their regional offices in Singapore. These include Conservation International, World Wildlife Fund for Nature and BirdLife International. This has, in part, been possible through the Singapore Economic Development Board, which offers attractive work options and subsidies for selected international NGOs as well as helping them establish collaborations with Singapore-based businesses. These collaborations have matured with time. For example, Singapore Airlines funds BirdLife's work in the Hutan Harapan landscape of Sumatra, Java—a crucial habitat for threatened songbirds and hornbills like the globally critically endangered helmeted hornbill, *Rhinoplax vigil*.

BirdLife, in particular, coordinates regional conservation initiatives through partnership with local stakeholders. Feedback from regional experts are solicited for exercises such as red-listing of species. NParks also plays a critical role in coordinating regional work, such as hosting the Arctic Migratory Bird Initiative Workshop at the Sungei Buloh Wetland Reserve (SBWR) in 2017 (Arctic Council Secretariat, 2017) and serving as the local representative during the East Asian-Australasian Flyway Shorebird Science Meeting in 2020 (The East Asian-Australasian Flyway Partnership, 2020). Such engagements reaffirm Singapore as a choice venue for regional conservation workshops & conferences that can build conservation capacity in the region. Mandai Nature (formerly Wildlife Reserves Singapore) is the Southeast Asian hub for the International Union for the Conservation of Nature Species (IUCN) Survival Commission Conservation (SSC) Planning Specialist Group.

Mandai Nature also supports efforts and research in the region, especially of critically endangered species, through grants and in-situ conservation programmes (Ng, 2019; IUCN SSC Asian

Species Action Partnership, 2022). The Asian Songbird Trade Specialist Group summit was hosted by the Jurong Bird Park in 2015 (Lee et al., 2016).

3.2.2. Local work

Standardised surveys (e.g. Chan & Davison, 2019; Chong et al., 2012), along with other efforts like the Annual Bird Census conducted by the NSS (Lim & Lim, 2009), has provided a rough baseline of the avifauna in Singapore. However, population estimates of threatened species across time are lacking with the exception of focal species such as the straw-headed bulbul (Chiok et al., 2021). While a general understanding of avifaunal distributions of Singapore is available, further research will be beneficial to disentangle the dynamics and specific threats faced by focal species. Information on species abundance also plays a crucial role in prioritising spaces to protect (Snep et al., 2016), and distilling this knowledge is especially relevant for birds that have reduced detectability, such as nocturnal species. For instance, the brown wood owl, *Strix leptogrammica*—a species with no local conservation status—is currently only known from four records locally (Lim et al., 2011; Environmental Resources Management, 2016; Bird Society of Singapore [BirdSocSG], 2021a).

The environmental impacts of introduced species such as the Javan myna and house crow are not fully understood as well. In Singapore, although public feedback regarding these species as pests due to noise and human-wildlife conflicts are common (Lam, 2017; Ministry of National Development, 2019; 2021; Ng, 2018), the environmental and economic damage that these species pose are unquantified. Impacts of other non-native species to Singapore's landscape have also remained unassessed (Chong, 2013; BirdSocSG, 2021a). Subsets of introduced species are capable of causing large socio-economic harm. To maximise resource allocation, studies should be conducted locally to assess the magnitude of damage brought on by the many introduced species (Holmes et al., 2009; Shivambu et al., 2020).

3.3. Threats and Management

3.3.1. Habitats

Forests. Habitat loss is considered a strong driver for local avifauna extirpation (Brook et al., 2003a). Deforestation is thought to precede the extinction of more than half of forest avifauna (Castelletta et al., 2000). Today, species that were historically found in Singapore's core forests, such as the short-tailed Babbler, *Pellorneum malaccense* primarily inhabit the CCNR, an area dominated by mature lowland secondary forest.

Fragmentation of remaining habitats creates barriers to bird movement, resulting in isolated populations. Forest-dependent understorey insectivores are particularly vulnerable to habitat fragmentation and exhibit reduced genetic diversity (Cros et al., 2020; Sadanandan et al., 2015). Remaining forests double up as green spaces for public recreational use and are subjected to disturbance and degradation (Chatterjea, 2007). Preserving suitable habitats is important for breeding resident birds as well as for globally threatened birds such as the migratory brown-chested jungle flycatcher, *Cyornis brunneatus*.

Freshwater swamps. While Sundaic freshwater swamp specialist birds have not been formally recorded in Singapore, the white-chested babbler, *Pellorneum rostratum* has been noted for its association with the Nee Soon Swamp Forest on the mainland (Wang & Hails, 2007). This species is typically found in wet habitats such as swamps and river edges, as well as the landward sides of mangroves (Wells, 2007). Following their rapid decline since the 1970s as a consequence of habitat loss (Wang & Hails, 2007), the population on Singapore Island and Pulau Ubin went extinct over a decade ago, while individuals in Pulau Tekong reportedly still persist. However, swamp forests still serve as crucial habitat for other birds including the greater green leafbird, and remain as key biodiversity areas for taxa extending beyond birds as well (Ng & Lim, 1992; Clews et al., 2018).

Scrubland and freshwater marsh. Scrubland habitat, dominated by herbs, grasses and shrubs without a defined tree canopy layer (Yee et al., 2016), was not a core part of Singapore's terrestrial ecosystem originally, and arose as a result of recolonisation following widespread land clearance. The result of this was a wave of scrubland-adapted species that naturally colonised Singapore, such as the red-wattled lapwing, *Vanellus indicus* and savanna nightjar, *Caprimulgus affinis* (Wang & Hails, 2007). These scrubland specialists are frequently encountered on plots of cleared land pending development or inactive worksites. Resultantly, populations are frequently in locally ephemeral habitats that are eventually developed.

Freshwater marsh habitat arose owing to the intentional flooding of low-lying areas as a result of damming (e.g. Kranji Marshes). Some species (Fig. 16) inhabiting freshwater marshes like the grey-headed swamphen *Porphyrio poliocephalus*; common moorhen, *Gallinula chloropus;* and purple heron, *Ardea purpurea* have likewise only colonised Singapore within the last century, or were very rare in the past (Wang & Hails, 2007). Yet, despite the novelty of this habitat, they provide important breeding grounds for various nationally threatened species including the abovementioned purple heron and grey-headed swamphen.

Figure 16: Birds that benefit from the novel freshwater marsh habitat resulting from the damming of rivers and subsequent flooding of low-lying areas. Photographs by SYCK.
A. Common moorhen, *Gallinula chloropus*, *B.* Purple heron, *Ardea purpurea, C.* Grey-headed swamphen, *Porphyrio poliocephalus.*

Freshwater marshlands are also crucial wintering sites for numerous species of migratory birds such as reed warblers, *Acrocephalus* spp. and bitterns *Ixobrychus* spp. In addition, resident waterbirds like the little grebe, *Tachybaptus ruficollis* and lesser whistling duck, *Dendrocygna javanica* are suspected to be struggling to successfully nest owing to the presence of introduced fishes. Carnivorous fishes can upset the ecosystem by depleting food sources for local fauna, and have been documented to be a driver of extinction for the Alaotra grebe, *Tachybaptus rufolavatus* in Madagascar through predation (BirdLife International, 2022; Wilmé, 1994; Tan et al., 2020a).

3.3.2. Wildlife trade

The keeping of and trade in wild birds is well known in the region with millions of birds kept in cages for their songs on the Indonesian island of Java alone (Marshall et al., 2020). Bird keeping is also popular in Singapore, Malaysia, Thailand, and Vietnam. A significant proportion of these birds are wild-caught, causing declines and endangerment of several songbird species. To tackle this emerging crisis, conservationists came together and highlighted the plight of the songbirds through two Asian Songbird Trade Crisis summits hosted locally by the then Wildlife Reserves Singapore in 2015 and 2017. This led to the Conservation Strategy for Southeast Asian Songbirds in Trade (Lee et al., 2016) and the formalisation of the IUCN SSC Asian Songbird Trade Specialist Group in 2019/2020.

Singapore is a well known transhipment hub for the bird trade with organised import and export and breeding facilities (Aloysius et al., 2020; Poole & Shepherd, 2017). Its domestic market is generally considered small but recent studies suggest that this may not be true (Aloysius et al., 2020; Chiok & Chng, 2022; Eaton et al., 2017). Aloysius et al. (2020) compared the domestic bird market records with the import and export data for CITES-listed parrots for Singapore and found several discrepancies suggesting large numbers of parrots are regularly imported for domestic trade and kept in Singapore homes. Worryingly, the hobby of parrot-keeping seems to be on the rise in Singapore across a wide age group (young and old), with parrot owners increasingly going for larger and more exotic birds (Jain et al., 2022). This has implications on wild parrot populations globally because a third of Singapore's CITES-listed parrot imports are known to be from wild-caught sources (Aloysius et al., 2020). Songbird-keeping, however, seems to be rather stable or declining with songbird competitions being prevalent amongst the older male population (Chiok et al., 2022).

Online trade in birds is on the rise with several bird hobbyist and interest groups operating on social media, some with memberships running into thousands of people (Chiok & Chng, 2022; Jain et al., 2022). Members patronise these groups to share information regarding their pet birds and connect with like-minded pet bird owners. Some groups also allow the sale, purchase and adoption of pet birds. These groups serve as an avenue for private breeders to operate and connect with potential buyers and sellers.

Another aspect of the bird trade is the poaching of birds in Singapore. While low and not as pervasive as other countries in the region, the poaching of local birds notably in the eastern and western parts of Singapore such as Pulau Ubin and Lim Chu Kang have been witnessed. Of particular concern is the potential impact of poaching on globally threatened birds in Singapore such as the long-tailed parakeet, *Psittacula longicauda* and straw-headed bulbul, *Pycnonotus zeylanicus*.

3.3.3. Urbanisation

Singapore has a long history of record-keeping for birds and is therefore, a prime setting to study the impacts of urbanisation, fragmentation, extinctions and extinction debt in the tropics.

Bird collisions. Singapore's urban environment poses a major physical barrier to the movement of birds, including long-distance migratory species. This is exacerbated by other landscape-level threats driven by land-use change, and the complex urban-greenery interface. Man-made structures are now a ubiquitous part of nearly two thirds of Singapore (Figs. 10, 11), and present three-dimensional obstacles to the movement of wildlife. In the first-ever survey of migratory bird collisions across Singapore, more than 40 species were reported from bird-building collisions, the majority fatal (Low et al., 2017). Pittas were found to be the most commonly observed group of birds involved in window collisions (Low et al., 2017). Collisions were found to be particularly prevalent along the central and western regions of Singapore, which may correspond to the shortest open-sea crossing for birds travelling between Singapore and Sumatra. In a follow-up study, Tan et al. (2017) showed that several species of forest-edge frugivores, such as the pink-necked green pigeon, *Treron vernans,* are especially vulnerable to building collisions. Overall, bird collisions pose a clear threat to the movement and dispersal of wild birds, and policy guidance is urgently needed in the design and construction of new buildings to mitigate this problem.

Light and sound pollution. Singapore is the most light polluted country in the world, with the use of artificial lights exceeding the level of light pollution tolerable per capita (Kumar, 2019). This excessive lighting likely has some negative impacts on wildlife. Light pollution is known to impact migratory birds and disrupt sleep patterns in residents (Cabera-Cruz et al., 2018; Raap et al., 2015). The widespread use of non-targeted lights not only lights up the roads and walkways for intended users but also the sky above. Globally, there are guidelines to design built environments that use low intensity targeted lights that are lit up only when needed (International Dark-Sky Association, 2018). Some newer parks in Singapore like Jurong Lake Gardens have implemented wildlife-friendly lights. We hope these become the norm in other parks and on roads adjacent to nature areas.

A similarly neglected issue is sound pollution. Of particular concern is the low-frequency noise from vehicular traffic that circles forests like BTNR and the CCNR. It is widely known that urban sounds impact the songs of birds (Slabbekoorn & den Boer-Visser, 2006; Rheindt, 2003). Birds exhibit a variety of changes in their song in relation to urban noise, including singing louder, higher and longer (Halfwerk et al., 2018; Nemeth et al., 2013). A study on four common resident birds of Singapore showed that species varied in their response to anthropogenic noise (Li et al., 2021). Brown-throated sunbirds, *Anthreptes malacensis* with higher-pitched vocalisations exhibited a weaker response while some species, like the spotted dove, *Spilopelia chinensis*, showed a decrease in frequency in noisier environments. While more studies would need to be done to understand the relationship between noise and bird communication and the life-history implications of these changes to bird songs, anthropogenic noise is likely to increase stress levels among birds, ultimately impacting their reproductive success and fitness.

Waterways. Singapore ensures that rainwater is collected, filtered and used sensibly. PUB has expanded its Active, Beautiful, Clean Waters (ABC) programme and attempted to make our waterways biodiverse. However, from an avifauna perspective, much of these measures are limited to adding generic macrophyte vegetation along managed waterways and less about restoring native aquatic food webs and ecosystems. This has implications for aquatic birds as they depend on aquatic fauna for food and tend to have specific habitat requirements. Several birds dependent on freshwater marshes such as the grey-headed swamphen, common moorhen and white-browed crake, *Poliolimnas cinereus* have suffered a decline in populations and are nationally threatened.

3.3.4. Climate change

Climate change is well-recognised to be a pervasive and particularly formidable threat to biodiversity (Parmesan & Yohe, 2003; Ng et al., 2011). A large body of studies has examined the effects of climate change on the distribution and ecology of birds, with particular focus on changes in the state and quality of habitats, and other broader phenological changes to annual cycles of birds, including migration. There are fewer studies in the Asian tropics but the available evidence suggests far-reaching shifts and changes to tropical forest ecosystems (Corlett & LaFrankie, 1998). Changes in phenology are among the best-documented and most consistently observed impacts of climate change on animals, with advancing spring arrival dates for temperate-breeding migratory species (Knudsen et al., 2011; Lehikoinen & Sparks, 2010). Several long-distance passerines have advanced their autumn departures, while short-distance migrants have exhibited delays in departure timing (Jenni & Kéry, 2003; Péron et al., 2007; van Buskirk et al., 2009). In the only study on arrival dates of migratory species in Singapore, delays in the the first arrivals of the Japanese sparrowhawk, *Accipiter gularis* and curlew sandpiper, *Calidris ferruginea* were detected (Harris et al., 2014)—providing one of very few lines of evidence of these effects on migratory species in Southeast Asia. A recent study on breeding phenology of 53 common resident bird species in Singapore would provide a valuable baseline for monitoring and research efforts in the future (Berman et al., 2022).

3.4. Threat Management and Recommendations

3.4.1. Habitats

Forests. Improved management has been instrumental in maintaining the habitat quality of the existing forests. Policies such as limiting opening and lighting hours, coupled with enforcement, ensures that disturbance to the forests is minimal. Where necessary, authorities have also acted to close off access to forests to allow for recuperation and were successful in improving its biophysical environment (Chatterjea, 2019).

Other plans by the government to restore disturbed ecosystems include the Forest Restoration Action Plan (FRAP) under the OneMillionTrees movement. In a landmark effort to restore connectivity between the BTNR and the CCNR, the Eco-Link@BKE was completed in 2013 to reconnect the two forested areas that were separated by an expressway in 1986 (Davison & Chew, 2019). Understorey bird species that are sensitive to fragmentation such as babblers have been recorded using the Eco-Link to move between forests (Chung et al., 2018). Second of its kind here, the Mandai Wildlife Bridge was opened in 2019 to reconnect portions of the CCNR that had been fragmented by the construction of Mandai Lake Road over 60 years ago (Tan, 2019).

We look forward to greater balance between biodiversity conservation and development in Singapore. We recommend that Tagore Forest be protected as buffer Nature Parks given that it lies immediately to the northeast of the CCNR. In particular, it is in close proximity to the Nee Soon Swamp Forest and may already be serving as a buffer habitat and refuge area for wildlife, underscoring its importance. Additionally, we recommend the preservation and rehabilitation of the Bukit Brown Forest, which forms an additional buffer immediately to the south of the CCNR.

Scrubland and freshwater marsh. As scrubland in Singapore occurs spontaneously and is often unmanaged, conservation of this habitat is not often a topic of discussion. In recent years, scrubland has been incorporated into parks for recreational purposes as well as to attract scrubland species, which is a much welcomed move. In Jurong Lake Gardens for example, the barred buttonquail, *Turnix suscitator*, an uncommon resident, has been seen regularly in this habitat. In Lorong Halus, the Amur falcon, *Falco amurensis*, a very rare vagrant, has been observed feeding on insects above the scrubland.

Kranji Marshes were created in the 1970s when the construction of Kranji Dam flooded the low-lying adjacent areas (Tang, 2016). The uncommon white-browed crake and nationally near-threatened grey-headed swamphen are regularly spotted there. One of the largest freshwater marshes in Singapore, the majority of the site is recognised as ecologically sensitive habitat and has been designated as a Core Conservation Area since its opening in 2016 (Tang, 2016; NParks, 2021d). Kranji Marshes, together with the Jalan Gemala Marshland and Kranji Reservoir Marshes Nature Areas, comprise some of the key freshwater marsh habitats of the upcoming Sungei Buloh Nature Park Network (NParks, 2021e).

In restored freshwater swamp habitat in Jurong Lake Gardens, waterbirds like the rare black-winged stilt, *Himantopus himantopus* have been observed. In Lorong Halus, the very rare little grebe and rare Baillon's crake, *Zapornia pusilla* can be found.

3.4.2. Trade

The growing domestic trade in birds and shipment of birds through Singapore has prompted NParks to step up its monitoring and enforcement measures. It has an active wildlife crime unit that takes action against the illegal keep and trade of birds. Since NParks took over the role of wildlife trade management in 2019, more illegal trade seizures have occurred.

The biggest challenge with regulating bird trade in Singapore is the lack of a licensing and records system that makes it difficult to track the parentage and source of the birds. A system similar to one that exists in Australia (Department of Biodiversity Conservation and Attractions, 2022) could be implemented to track the movement of birds through local captive-breeding farms, exporting facilities and pet shops (Aloysius et al., 2020). The current disease control measures in the bird trade are mostly restricted to testing for a few pathogens that have implications for livestock and/or human health. As such, there is a need for more extensive measures such as comprehensive disease testing (e.g. *Chlamydia psittaci* in parrots can cause psittacosis in humans) and the implementation of proper biosecurity protocols in pet shops and veterinary clinics (Aloysius et al., 2020). The online bird trade also needs to be better regulated as recent reports indicate that it is growing in scale (Chiok & Chng, 2022). Finally, consumer hobbyist groups particularly for parrots and songbirds need to be engaged so appropriate behaviour change messages can be co-created to move demand from wild-caught to captive-bred birds (Jain et al., 2022).

3.4.3. Introduced species

The management of introduced birds in Singapore can be greatly improved by developing a targeted surveillance programme. While a list of introduced species is available, the population trends of these species are not being monitored. We recommend regular monitoring efforts for introduced birds, to be integrated into other planned biodiversity surveys. These surveys should record the species, counts, and localities of introduced birds, and should be carried out at sufficient frequencies to estimate population trends.

Potentially damaging species should be removed from the local ecosystem, ideally before they establish themselves. Persistent efforts have shown to be successful in provisionally reducing the numbers of perceived pests like the house crow. Similar measures should be undertaken for species like the golden-backed weaver, *Ploceus jacksoni* and monk parakeets, *Myiopsitta monachus*. The weavers could upset wetland ecosystems and are suspected to cause the observed declines in native baya weavers, *P. philippinus* (BirdSocSG, 2021b). The parakeets have been documented to cause infrastructure damage elsewhere in its introduced range (Avery, 2002). They have also caused agricultural damage, especially on grain crops, in various introduced ranges (Bruggers et al., 1998; Canavelli et al., 2014; Postigo et al., 2017), which is a cause for concern as the introduced population might spread beyond national boundaries. Nest colonies should be removed swiftly upon detection, and well-established protocols from the Indian myna, *Acridotheres tristis* control programme in Australia and the red-whiskered bulbul, *Py. jocosus* eradication programme from the Seychelles can be emulated to control other exotic species here.

Continued education is also crucial to prevent further introduction of species. We suggest efforts like 'Operation No Release', that was held for multiple years, to be resumed. Such campaigns help raise awareness among the general public who believe they are doing good by releasing animals into the wild. Campaigns could be crafted with varying messages, including but not limited to: 1) released animals typically do not survive well in nature; and 2) in the event that they do survive, the damage they cause to the region's native fauna is detrimental. The inclusion of identification tips and hotlines for reporting introduced birds would also be beneficial. Such efforts could increase sightings of underdetected populations of introduced birds, creating a positive feedback loop to help gather data to manage species before their numbers increase.

Additional enforcement to prevent the feeding of wildlife is required as well. The presence of frequent feeding in locations such as Lorong Halus has possibly contributed to the proliferation of various African finches and weavers. Cutting off such food supply could also help reduce the number of introduced birds (Soh et al., 2021).

3.4.4. Urbanisation

Urban greenery. With an increased emphasis on urban greenery, there is a real risk that natural greenery could be somewhat deprioritised especially by the building industry and district planners. A case in point is Tengah, billed as a 'forest town' where the planted urban greenery cannot make up for the lost natural greenery and its value for forest dependent birds and other wildlife but is somehow believed to be a 'consolatory measure' that is good enough by some members of the public (A. Jain, pers. comm.). Targeted education to the built environment industry is necessary to emphasise that not all green is the same and that natural greenery is superior in value to wildlife than urban greenery (Chong et al., 2014). More specifically to birds, guidelines to enhance bird populations such as bird-safe windows can be provided to the built environment industry to soften the transition from green patches to urban areas (Hwang & Jain, 2021).

Waterways. An increasing number of human-made aquatic habitats have been created in Singapore in recent years. Examples of these can be found in Jurong Lake Gardens, Punggol Waterway Park, Bishan-Ang Mo Kio Park and Gardens by the Bay. Yet, the populations of several water bird species continue to decline, which is a reminder that constructed waterways are no substitute for naturally occurring ones. Already, efforts are underway to recreate natural waterways in areas that used to boast such habitats. For instance, a swamp forest habitat at the Keppel Discovery Wetlands at the Learning Forest of the Singapore Botanic Gardens was recreated, referencing historical records. While good for flora, lost fauna may find it hard to recolonise such habitats as the Gardens are surrounded by urban development.

Comprehensive naturalisation of canals and water bodies can be carried out islandwide at locations where native mangroves and swamps once existed. Examples include Berlayer Creek where it is evident that even small patches of mangroves can be vital fauna habitat. Naturalisation of water bodies will also bring co-benefits of flood control and groundwater recharge in Singapore.

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4. Reptiles

Reptiles represent a significant proportion of vertebrate diversity in most terrestrial ecosystems. They occupy a multitude of niches, from opportunistic scavengers to apex predators (Vitt & Caldwell, 2014). In total, 102 species of native terrestrial/mangrove reptiles are recognized to be present in Singapore. These include 7 turtles, 35 lizards, 60 snakes, and 1 crocodile (Figueroa et al., 2023; NParks, 2021). In Singapore, they can be found in most habitats ranging from built-up urban spaces to primary rainforest. As such, they share several boundaries with humans, and are often the subjects of human-wildlife conflict.

With some exceptions, reptiles generally fill mesopredator (and sometimes apex predator) niches in their respective ecosystems (Vitt & Caldwell, 2014). Smaller reptiles, like geckos, may be insectivorous, and are in-turn prey for other meso-predators like birds and snakes. Meanwhile large reptiles like king cobras and crocodiles occupy the highest trophic levels in their ecosystems. Some, like monitor lizards, even perform important scavenging roles. Given their diverse range of niches, reptile conservation is critical and must be approached from several different perspectives.

4.1. Research Priorities

4.1.1. Biodiversity discovery and decrypting taxonomy

Historically, Singapore has been a hotbed of reptile description. Over a dozen species of reptiles were described from Singaporean specimens in the colonial era. Today, however, many species previously known or even described from Singapore, are seemingly extirpated. Notably, the orange-bearded flying dragon, *Draco fimbriatus* and the short-tailed blood python*, Python brongersmai*, among numerous others (Hardwicke & Gray, 1827; Stull, 1938). In most cases, the specific reasons for the extirpation of these reptiles is unclear and is generally attributed to loss of the requisite habitats to support these species (Brook et al., 2003; Brooks et al., 2002).

In recent decades, there has been a spate of reptile discoveries and rediscoveries in Singapore island. Novel species such as the Singapore bent-toed gecko, *Cyrtodactylus majulah* and the Temasek swamp skink, *Tytthoscincus temasekensis* have been delimited from cryptic taxa (Grismer et al., 2012; 2017). Simultaneously, reptiles that have gone undetected, sometimes for over a century, are being rediscovered with renewed casual survey efforts. These include the Selangor Mud Snake, *Raclitia indica*; Gimlett's Reed Snake, *Calamaria lovii gimletti;* and the Lined Blind snake, *Ramphotyphlops lineatus*; and the discovery that Bent-toed geckos in Singapore consists of multiple species superficially similar to *C. majulah*: Marbled Bent-toed Gecko, *Cyrtodactylus quadriviragatus*, Panti Bent-toed Gecko, *Cyrtodactylus pantiensis*, and Peninsular Bent-toed Gecko, *Cyrtodactylus semenanjungensis* (Baker, 2014; Figueroa & Law, 2021; Law et al., 2019; Law et al., 2020; Serin et al., 2017). Undetected species tend to be fossorial or aquatic species that elude conventional survey methods used in Singaporean surveys (Teo & Rajathurai, 1997; Teo & Thomas, 2019). The apparent challenges here are two-fold: 1) decrypting hidden diversity within diverse taxa; and 2) enhancing biodiversity discovery efforts for elusive species with improved survey methods.

To address the first challenge, we recommend intensifying the focus and support for taxonomic decrypting. Current tissue and specimen collections are tailored towards morphological identification of these species. Unfortunately, this often does not adequately provide taxonomic resolution in cryptic taxa. Many species are superficially indistinguishable from their congeners, and in the absence of niche taxonomic expertise, molecular evidence is required to accurately delimit them (Krell, 2004; Phenninger & Schwenk, 2007). Genera like *Cyrtodactylus* and *Calamaria* represent substantial diversity. Yet, they are relatively obscure, and their full richness in Southeast Asia is still being unearthed using molecular phylogeny (Brennan et al., 2017).

The second challenge is indicative of the potential of the remaining habitat in Singapore. Many of these elusive reptiles occupy niches; arboreal, aquatic and fossorial, that are difficult to survey using conventional audiovisual survey methods. Freshwater swamp forest habitat, a diminishing ecosystem (O'Dempsey & Chew, 2011), has yielded numerous discoveries and rediscoveries in recent years. These habitats, especially Nee Soon Swamp Forest and the adjacent Upper Seletar Reservoir Park should continue to be protected and enhanced. At the same time, survey efforts in these spaces, especially in aquatic and fossorial microhabitats, should be intensified. These survey efforts should be supplemented with comprehensive tissue and specimen collection, to further address the above-mentioned first challenge.

4.1.2. Potential for reintroduction

As mentioned above, Singapore has seen several reptilian extirpations. The southern green-eyed gecko, *Gekko hulk* (Fig. 17) is among the most recent likely extinctions, with the last recorded individual being heard in Bukit Timah Nature Reserve in 1997 (Teo & Rajathurai, 1997). The cause and mechanism of its loss in Singapore remains unknown. However, its disappearance coincides with a period of vertebrate losses in Singapore (e.g. cream-coloured giant squirrel). Mysteriously, *Gekko hulk* is relatively common in Peninsular Malaysia, with some individuals even thriving in urban structures like toilets adjacent to forests (Grismer, pers. comm.). Similarly, several other reptile species (like the abovementioned orange-bearded flying dragon and the short-tailed blood python) that can be found in Peninsular Malaysia, have been extirpated in Singapore (Figueroa et al., 2023). Figueroa et al. (2023) recommend that if these species are rediscovered, they should be immediate conservation priorities.

Figure 17: The southern green-eyed gecko, *Gekko hulk,* is likely extinct in Singapore. The reason for its extirpation is yet unclear. Photograph by LIT.

Given the substantial effort put into habitat restoration and rehabilitation in the last decade, it follows that the recovery of a functional ecosystem should also be a priority. Unlike birds, where adequate habitat restoration and rehabilitation will result in some level of population re-establishment, reptiles (which are far less mobile) cannot re-establish once lost. In the long term, reptile reintroductions to Singapore from closely related stock populations in the region could be explored. To this end, we recommend the establishment of ties with neighbouring countries to further this cause. This would create opportunities to study these species in their native ranges, learn their ecologies and understand why they may have become extinct in Singapore. This knowledge is valuable and can help avoid the repeat of such circumstances in other parts of the region as well. In the long term, these partnerships may facilitate the reintroduction of these reptiles into restored habitats in Singapore.

4.2. Threats and Management

4.2.1. Urban-wildlife boundaries

Forest-adjacent Drains. With rapid urbanisation in Singapore, there is an intensifying boundary between green and urban space. The establishment of the Republic's water catchment has resulted in a system of concrete drains across the country. These drains are often adjacent to forests and green spaces, posing a threat to many species of fossorial snakes. Drains with especially steep sides act as pitfall traps that allow these snakes to fall in, but do not provide a point of exit. Trapped snakes may die of desiccation or drowning. At the moment, the impact of these structures has only been observed anecdotally (I.S. Law, pers. comm.). Studies of roadside ditches in the USA suggest that such structures can capture a substantial diversity of common reptiles (Homyack et al., 2016). There are no published studies that study the rates of "drain-kills" along forest edges in Singapore.

We recommend that the impact of these forest-adjacent drains be investigated. What are the spaces where "drain-kills" are prevalent? Which species are susceptible to these effects? Pending these studies, wildlife-friendly architecture, like shallower drains that allow these snakes to exit, or bioswales that drain excess water effectively while providing refugia for riparian fauna, can be strategically adopted (Dinic-Brankovic et al., 2018).

Wildlife-vehicular Collisions. With the proliferation of roads across Singapore, the rate of wildlife-vehicular collisions (WVCs) has also increased. With over 12% of the island (Land Transport Authority [LTA], 2021a) covered in roads and servicing close to a million vehicles (LTA, 2021b), the chances of WVCs are incredibly high. Roads act as attractants, providing resources or opportunities (van der Ree et al., 2015), especially to herpetofauna. They radiate heat at night, creating favourable microclimates for wildlife looking to warm themselves up. Such basking and foraging behaviour increases an animal's time on the road, increasing mortality risk in a WVC. Furthermore, roadkill which has not been moved off the road can attract scavengers like monitor lizards. These can in-turn become secondary roadkill. Reptiles are either often too slow or small to be noticed by drivers (van der Ree et al., 2015), leading to their deaths.

While WVCs are a dire outcome for many species, roads also pose another challenge to wildlife. They can prevent or restrict the movement of urban-shy species that avoid open spaces. Moreover, the noise, light, and chemical disturbances from vehicles will worsen these effects. Road width and traffic volume further exacerbate the severity of the barrier effect (Riley et al., 2006). This can also lead to some species avoiding the road zone entirely, resulting in an impassable barrier for the individual animal or even the species as a whole.

As such, mitigation methods to make our roads wildlife-accessible have to be two-pronged; reducing risks of WVCs, while getting rid of the impassable barrier that some animals perceive roads to be. In addition to strategically constructing wildlife crossings, more considerable emphasis should be placed on educating road users on speed limits and highlighting roadkill hotspots. This could significantly reduce the chances of future WVCs. Well-placed road signs, speed cameras, and even Artificial Intelligence that detects animals on the road and warns approaching drivers of them are some of the methods that have worked well in other countries.

4.2.2. Human-wildlife conflict

Some species of reptiles are well-adapted to urban habitats. Geckos are regularly found in human residences and built-up structures. They are regularly found around electric lights in these structures that attract flying insects, which make easy prey for the geckos. Although they are not known to be harmful to humans, these urban-adapted lizards are often regarded as nuisances and pests. Four species of geckos are regularly found in these spaces - the spotted house gecko, *Gekko monarchus*; spiny-tailed gecko, *Hemidactylus frenatus*; flat-tailed gecko, *Hemidactylus platyurus;* and maritime gecko, *Lepidodactylus lugubris*. In many households, their presence is often managed by the use of glue-traps. These traps have high mortality rates, if left unattended and are not taxa-specific. They carry a substantial risk of trapping non-target species. Common urban reptiles such as the paradise tree snake, *Chrysopelea paradisi*; striped kukri snake, *Oligodon octolineatus* and even Malayan water monitors, *Varanus salvator* have been entrapped in these glue traps (Boopal, pers. comm.) It is unlikely that there is any notable impact to the viability of the populations of these relatively common reptile species that can be found in urban areas. However, these traps are non-specific, inhumane, and arguably ineffective to begin with. As such, we recommend that their use by pest management organisations be limited wherever possible.

Conflict mitigation translocation. A notable species that enters regular conflict with humans is the reticulated python, *Malayopython reticulatus*. Regularly exceeding 6m in the wild, these are the longest snakes in the world (Shine et al., 1998). They are widespread throughout Singapore, and are common in urban spaces (Devan-Song et al., 2017). They are considered by the general public to be interlopers, and are often relocated by pest control operators and wildlife management. Urban pythons appear to feed mainly on rodents, and may represent a biological pest-control. Pythons as apex predators exert substantial pressure on their prey populations (Dorcas et al., 2012). Their removal can initiate trophic cascades in the form of prey population expansion (Morris & Letnic, 2017). Their prey are largely introduced, commensal rats (Devan-Song et al., 2017; Sankar, 2019; Shine et al., 1998). The potential expansion of these prey populations poses a substantial public health concern, as they can be vectors of zoonotic diseases like rat lungworm and hantavirus (Bahaman & Ibrahim, 1988; Lim et al., 2017; Wong et al., 1989).

The existing management strategies for such large urban-adapted reptiles include long-distance translocation to forested areas. Although it is a short-term solution, it comes with its own set of conservation challenges. Studies conducted in other countries have found that long-distance translocation of “problem individuals” often results in increased mortality and greater movement (Butler et al., 2005; Devan-Song et al., 2016; Germano & Bishop, 2009; Sullivan et al., 2004; Wolfe et al., 2018). In some species, translocated individuals often quickly move back into adjacent human spaces, sometimes even moving back to their point of capture. This appears to be the case with reticulated pythons as well. In one study in Singapore, 28 pythons were radio tracked after translocation. 60% of them moved into forest edges and urban areas. 14% of the pythons died after translocation (Mandai Wildlife Reserve, 2021). Given the mounting evidence against the effectiveness of long-distance mitigation translocations, we recommend against continuing to use this management technique wherever possible. Instead, a combination of short-distance translocations and intensified public education would strike a balance between minimising ecological impact, and managing public expectations.

4.2.3. Alien species

There are numerous introduced reptiles found across Singapore. Their origins can be traced to various points in Singapore’s history. Some, such as the changeable lizard, *Calotes versicolor* were introduced several decades ago, while others like the brown anole, *Anolis sagrei*, only established in the 21st century. (Savage, 2012; Tan & Lim, 2012). The majority of introduced reptiles are chelonians (turtles) and lizards, as discussed below.

Chelonians. Reservoirs are especially vulnerable to alien species establishment. Alien chelonians find their ways into these aquatic spaces mainly through intentional pet abandonment, and the practice of “mercy release” (*fang sheng*) of food and pet species for perceived spiritual merit. To date, at least 15 species of chelonians have been introduced to varying degrees (Ng & Lim, 2010). The non-native red-eared slider, *Trachemys scripta elegans* (Fig. 18) has become the most common turtle in Singapore. Although its population is the result of consistent introduction, there is also alarming evidence of some breeding (Leong & Lim, 2014). Although there has been no evidence of direct negative impact to the ecosystem, their ubiquity is concerning due to their competitive nature and constant import (Ng, 2009; Pearson et al., 2015). There is also a substantial population of

Chinese softshell turtles, *Pelodiscus sinensis* in reservoirs. These turtles are sold as food species in some markets and are often bought for release (Ng & Lim, 2010) .

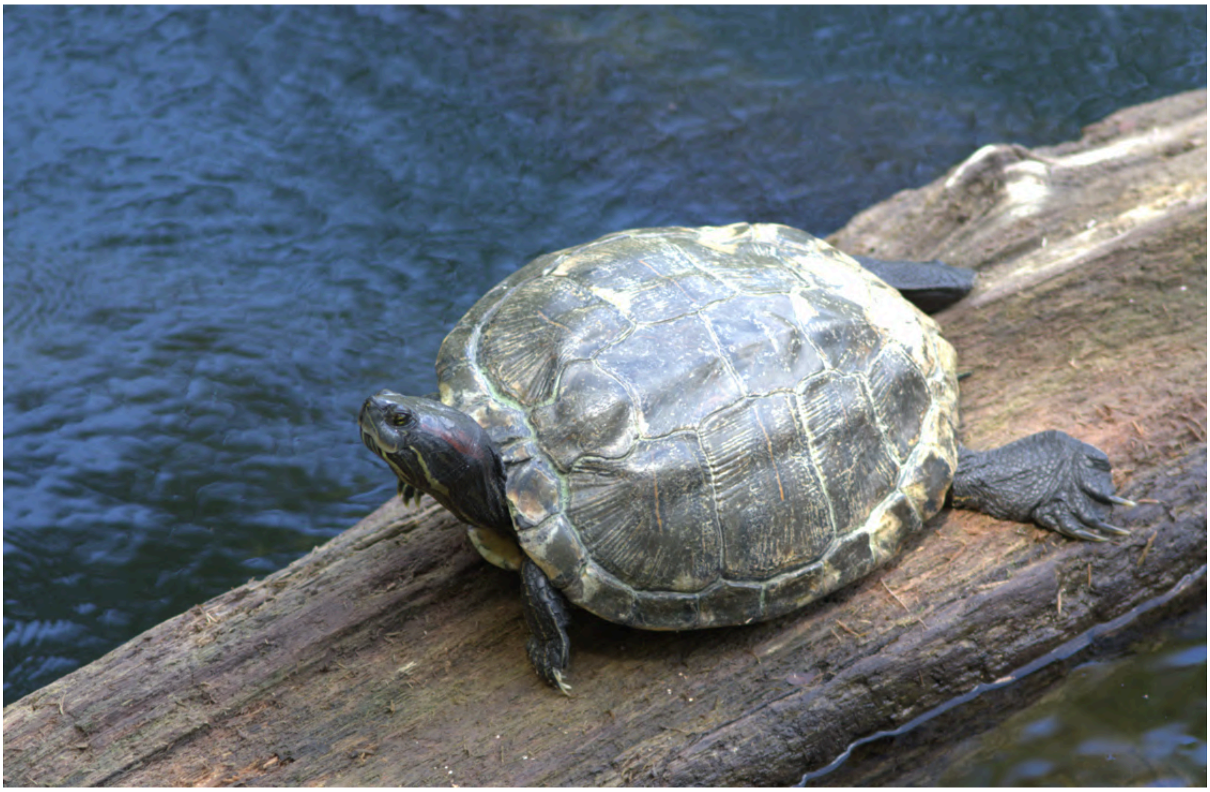

Figure 18: The red-eared slider, *Trachemys scripta elegans*, is the most commonly seen turtle in Singapore. Its success is largely due to the high propagule pressure as a result of consistent pet abandonment. Photograph by LIS.

As noted by Ng and Lim (2010), although education is important, it will likely have little effect on liberation practices, which have deep roots in culture. Strict policing and proper prosecution of offenders can curb such behaviour in the short term. Exercises like Operation No Release are carried out every year by the Public Utilities Board during periods where higher release volume is anticipated. These efforts are laudable, but should be more consistent, and are an opportunity to galvanise the public to be involved. Long-term, engaging with religious groups to discourage unethical *fang sheng* can go a long way in changing the cultural mindset in Singapore. As the established population has shown the capacity to breed, we recommend humane culling of red-eared sliders. This can be done selectively, as suggested by Ng (2009).

A number of native turtle species (e.g. black marsh terrapin, *Siebenrockellia crassicollis* and Malayan box turtle, *Cuora amboinensis*) are also released into freshwater habitats. Due to the poorly-regulated trade of these chelonian species, it is no longer feasible to ascertain the proportion of released versus native individuals in the wild. There is likely to be introgression between them (Ng & Lim, 2010). Notably, the globally critically endangered Malaysian giant terrapin, *Orlitia borneensis*, has been introduced into several water bodies around Singapore. These individuals may be good candidates for captive breeding and repatriation, given the species' conservation status in its home range.

Lizards. The most ubiquitous introduced lizard in Singapore is the changeable lizard. It was first detected in the 1980s. Its pathway of introduction is unclear, but may have been accidentally imported from its native range in Northern Malaysia and Thailand via the railway network that existed at the time (Savage, 2012). Its introduction is often linked to the decline of the native green crested lizard, *Bronchocela cristatella* in rural and suburban areas (Savage, 2012).

The brown anole was first detected in 2012 in Gardens by the Bay, likely having been brought over to Singapore along with neotropical ornamental plants (Tan & Lim, 2012). Since then, it has spread to other nurseries and gardens, including Jurong Lake Gardens and Singapore Botanic Gardens (Kwak et al., 2020). Green iguanas, *Iguana iguana*, which are mostly escapees from the Jurong Bird Park and the poorly-regulated pet trade, have become ubiquitous in many rural parts of Singapore as well. Both lizards are established as invasive species in many parts of the world. Thus, their proliferation in Singapore is alarming.

Changeable lizards are widespread in Singapore's landscape (Chou, 1994). Their spread is largely restricted to disturbed spaces, and they rarely occur inside forested spaces. It is likely that any attempt at eradicating them will not be successful. It is also unknown if there will be any beneficial effects to removing them. On the other hand, brown anoles and green iguanas are generally found in localised clusters. We recommend pre-empting potential invasions into sensitive nature spaces, and humanely culling existing populations of these two species.

Brook's house gecko, *Hemidactylus* cf. *brookii* represents a species complex that was historically (Sworder, 1925) and recently recorded in Admiralty Park (Groenewoud & Law, 2016) but has since spread to most parts of urban Singapore (Law, pers obs.). More research is needed to confirm the specific identity of the current population and determine if it originated from native stock.

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5. Amphibians

Although there have been significant historical collection efforts aimed at documenting the vertebrate taxa of Singapore during the colonial era, its amphibian fauna was largely undocumented. As such, historical records of Singapore's original amphibian assemblage between the 19th and 20th century can be expected to be inaccurate and impoverished (Brook et al., 2003). Currently, there are 27 native species known to occur in Singapore, of which 25 are anurans and two are caecilians (Baker & Lim, 2012; Figueroa et al., 2023; NParks, 2021). These can be found in a variety of habitats, ranging from common urban commensals that live in highly disturbed environments, to locally critically endangered species that are restricted to isolated pockets within the central forests of the island.

Amphibians typically fill the niche of prey, as they serve as an important food source for many mesopredators in their respective ecosystems, such as snakes, varanids, birds and small mammals. Tadpoles are an important food source for many aquatic invertebrates and fish. Frogs in turn prey on insects, which may also include pest species like mosquitoes and midges (Raghavendra et al., 2008). The wide range of microhabitat requirements and threats makes amphibian conservation complex, and as such it must be treated from a variety of perspectives as well.

5.1. Research Priorities

5.1.1. Biodiversity discovery and decrypting taxonomy

Challenges. Nearly all of the new amphibian descriptions occurring from Singapore took place after the 1960s, for species such as the Singapore black caecilian, *Ichthyophis singaporensis*, the black-eyed litter frog, *Leptobrachium nigrops* and the Malesian frog, *Limnonectes malesianus*. This is indicative of a previous lack of interest in the amphibian taxonomy of Singapore. This highlights the pertinence of present day research on the taxonomy of the island's amphibian fauna.

Even relatively common amphibians like the copper-cheeked frog, *Chalcorana labialis* sensu lato represent potentially undescribed taxa (Inger et al., 2009). Anuran genera such as *Limnonectes* and *Micryletta* harbour great cryptic diversity across their geographic range (Gorin et al., 2020; Mcleod, 2010; Sankar et al., 2022), and their outward morphological similarities beg for genetic data to supplement any new species descriptions originating from them.

The challenges faced here are similar to those faced for reptile conservation: 1) decrypting hidden diversity within cryptic species complexes, and 2) enhancing biodiversity discovery efforts for elusive species, using improved survey methods.

Recommendations. As mentioned, there is a dearth of genetic data for the amphibian fauna of Singapore. In order to address the first challenge adequately, we recommend intensifying the focus and support for taxonomic decrypting. This can be achieved by prioritising the collection of genetic samples for local amphibians, so future taxonomic research may benefit from the availability of both morphological and genetic information. This will greatly aid efforts to resolve cryptic diversity. Thus, it should be a national priority to establish a Singaporean genetic library to further support the taxonomic work that underpins so much of conservation science.

Amphibian species discovery in Singapore is less prolific than that of reptiles. Yet, previously unknown native species have been uncovered. The most recent example of this is Subaraj's paddy frog, *Micryletta subaraji* (Sankar et al., 2022) (Fig. 19). There have been new locality discoveries for previously known species (Figueroa & Selveindran, 2011), as well as new species records for Singapore entirely (Law et al., 2019; Leong et al., 1996; Leong & Chou, 1997; Lim, 1989). These discoveries were largely made in and around swamp forest habitats (similar to reptiles). As such, the conservation and enhancement of swamp forest habitat would be beneficial for both taxa. The second challenge may thus be addressed by enhanced survey efforts in such important microhabitats, bolstered by adequate tissue and specimen collection in order to further address the first challenge stated above.

Figure 19: Subaraj's paddy frog, *Micryletta subaraji* is the most recently described amphibian species in Singapore. Photograph by LIT.

Amphibian survey methods stand to benefit from the inclusion of bioacoustic monitoring, as most anurans are vocally active and rely extensively on a wide variety of calls to communicate with conspecifics. Many species may also be identified based on unique calls. Whilst technology and survey methods for bioacoustics have improved globally (Köhler, 2017), our local knowledge of anuran bioacoustics has remained relatively impoverished due to its exclusion as a standard method for comprehensive surveys (Teo & Rajathurai, 1997; Teo & Thomas, 2019). A centralised database with the various calls of local species can thus greatly aid in species discovery and acoustic monitoring efforts.

5.1.2. Indicators of ecosystem health

Furthermore, since amphibians serve as good indicators of ecosystem and microhabitat health**,** amphibian-conservation related research could also inform and benefit larger scale ecosystem and habitat management decisions across taxon groups (Collins & Storfer, 2003). As local and international genetic libraries become more comprehensive and as technologies become more affordable, passive ecological monitoring using eDNA becomes relevant in the local context (McKee et al., 2015).

5.2. Threats and Management

5.2.1 Alien species

There have been multiple introductions of non-native amphibian species in the past (Groenewoud & Law, 2016; Law, 2015; Ng & Yeo, 2012; Leong & Lim, 2011). Much like the reptiles, some amphibians such as the banded bullfrog, *Kaloula pulchra* were introduced during the country's colonial era (Flower, 1896), while others such as the East Asian ornate chorus frog, *Microhyla* cf. *fissipes* and greenhouse frog, *Eleutherodactylus planirostris* are very recent introductions (Fig. 20).

Figure 20: The non-native greenhouse frog, *Eleutherodactylus planirostris* is ubiquitous in Singapore. Their success can partly be attributed to their ability to reproduce without water bodies, through direct development. Photograph by LIS.

Ng and Yeo (2012) provide an early insight into the possible implications of the arrival of potentially invasive amphibian species to Singapore. Although the pertinence of monitoring these alien populations was highlighted back then, the number of studies looking into these issues remains depauperate. The effects of alien amphibian species on local amphibians is still poorly understood. Some of these species occur sympatrically with local species outside Singapore, while others are completely alien in the geographic sense. Therefore, any upcoming research and monitoring effort should focus on studying the interactions between these species with local amphibians, as well as determining the introduction pathways of such species so that they are not beyond a measure of control, should the need arise.

In the event that these alien species are determined to be harmful to native amphibian populations, immediate measures should be taken to curb the spread of these taxa across the island, where applicable. For species that are already widespread such as Gunther's frog, there could perhaps be recurring removal measures such as those already in place for the invasive apple snail in our reservoirs.

5.2.2 Chytridiomycosis

Chytridiomycosis is a highly infectious disease in amphibians that is caused by zoosporic chytrid fungi, namely *Batrachochytrium dendrobatidis*; the disease has already been widely linked with drastic population declines and extinctions of many amphibian species across the world (Voyles et al., 2009). The chytrid fungus has been detected in multiple localities and species of amphibians in Singapore (Gilbert et al., 2012). However, it seems that the frogs in Singapore are resilient to the strain of chytrid fungus present. Chong et al. (2018) found no individuals with overt signs of chytrid infection or frogs that had died due to the infection. The chytrid fungus should still be treated as a potential threat to our amphibian populations and should be monitored with consistent sampling in both urban and forested areas.

5.2.3 Habitat degradation and conversion

Amphibians are susceptible to widespread land clearance and habitat modification (Cushman, 2006), and in Singapore 68% of amphibian species are wholly dependent on mature forests in Bukit Timah and the Central nature reserves. Continued protection and habitat enhancement for suitable areas outside of the nature reserves can help conserve amphibian populations in Singapore.

5.2.4 Ex-situ conservation

Currently there has only been one species of amphibian that has had an ex-situ conservation programme. The cinnamon bush frog, *Nyctixalus pictus* was chosen by the National Parks Board as a suitable candidate for a Species Recovery Programme and was reintroduced into the Singapore Botanic Gardens (SBG) (Ng & Izzah, 2019). As a pilot study, it was deemed successful as individuals released into the forest managed to survive and breed. Ideally, amphibians classified vulnerable and above in the Singapore Red Data Book, should be supported by Species Recovery Programmes (NParks, 2021). However, critically endangered frog species such as the Malayan horned frog, *Megophrys nasuta*; Subaraj's paddy frog, *Micryletta subaraji*; Inger's cross toadlet, *Pelophryne ingeri*; blue-legged bush frog, *Leptomantis cyanopunctatus;* and thorny bush frog, *Theloderma horridum* should be prioritised as their populations are restricted to small patches of forest or occur in low populations (Baker, 2013; Figueroa et al., 2023; Figueroa & Selveindran, 2011; Leong et al., 1996; Leong & Teo, 2009)

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