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Three decades of floristic inventory, description and recovery efforts in Singapore

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Abstract. We describe the efforts in enumerating the flora of Singapore, focusing on the updating of checklists from botanical collections, comprehensive plant surveys, and investments into plant taxonomic revisions over the last three decades. These form the basis of on-going plant species recovery efforts including propagation, ex-situ conservation, seed-banking, and reintroductions of threatened native species.

Key words. Botany, vascular plants, floristic treatments, extinction, plant conservation, Species Recovery Programme

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INTRODUCTION

When the first and last authors embarked on a journey of botanical research, conservation and management as university undergraduates in the early 1990s, conservation biology had just emerged as a multi-disciplinary science that sought to address the dynamics and problems of perturbed species, communities and ecosystems, with the objective of providing the principles and tools for the conservation of biodiversity (Soule, 1985; Anderson et al., 2021). At that time, the conservation of habitat fragments and the design of reserves dominated the discourse in conservation biology. Based on the island biogeographic theory and its applications to habitat islands amidst a human-dominated landscape, the Single Large or Several Small (SLOSS) debate pitted the value of conserving species in a single large habitat patch against that of several small habitat patches (MacArthur & Wilson, 1967; Diamond, 1975; Wilson & Willis, 1975; Margules et al., 1982; Soule & Simberloff, 1986). Unfortunately, there was a general tendency towards neglecting the conservation value of small patches in places where there are no more large patches of intact habitat left (Turner & Corlett, 1996). In tandem with this, studies on the extirpation of species with habitat loss and fragmentation in the tropics gained traction, although much of these works were focused largely on birds, with little attention given to plants (Brash, 1987; Bierregaard et al., 1992; Kattan et al., 1994; Turner, 1996).

Against this backdrop, plant conservation biology started to take root in Singapore through the collective efforts of Drs. Wee Yeow Chin, Richard Corlett, Ian Turner and Hugh Tan in the then Department of Botany, National University of Singapore (NUS) between the mid-1980s and early-1990s. This was amidst the tendency to focus on molecular and genetic sciences, and other areas of research of commercial interest, such as orchidology. This tendency was of course not unique to Singapore but reflected the global issue of 'taxonomic impediment', i.e., insufficient investment into the foundational work of describing and delineating taxa necessary for downstream biological research (Funk, 2006). The combination of tropical plant ecology and systematics was brought to bear on this problem. The research findings from these initial years provided the momentum and optimism for conservation, and set off research into forest fragmentation, ecology and restoration in Singapore. These early findings and the impetuses can be summarised into three areas.

Importance of the primary and secondary rainforest successional mosaic. Corlett (1992) described the vegetation and land use transformation of Singapore from 1819 to 1990. Although primary rainforest comprised only 0.2% and native "old" secondary forest made up another 4% of the total land area by the end of the 20th century, the majority of recorded native species in all major taxonomic groups could still be found. It was also noted that while exotic species dominated the urban and open country areas, few species had invaded these forests. Turner et al. (1996a, 1996b, 1997) advanced our understanding of Singapore's remnant native-dominated forests by documenting and analysing the tree canopy and understorey plant species composition between the primary and secondary native rainforests. Together, these studies highlighted the resilience of the primary rainforest and also the ecological importance of the native-dominated secondary forest mosaic as a refuge for native plants and animals. This provided the basis for further work on secondary forest typology and succession, ecological dynamics and restoration in later years (Yee et al., 2011, 2016; Chua et al., 2013).

Value of small rainforest remnants. Turner et al. (1994) analysed the vascular plant flora of Singapore and found that 594 out of 2,277 species were extirpated. This was far less than what was predicted by the species-area relationship, in

view that more than 99% of the original rainforest would have been lost. This coupled with observations of high plant species richness at the 164-ha Bukit Timah Nature Reserve (BTNR; Corlett, 1988a, 1990; Turner, 1994) and the retention of almost half the original plant species in the 4 ha-rainforest at the Singapore Botanic Gardens (Turner et al., 1996c), illustrated the value of small rainforest remnants (Turner & Corlett, 1996). This corroborated the observations of other field workers elsewhere, e.g., Brash (1987) in Puerto Rico and Magsalay et al. (1995) in Cebu. It sparked interest and studies in the persistence of plant species in small rainforest remnants within an urban landscape matrix, e.g., the Centre for Tropical Forest Science—now known as the Forest Global Earth Observatory, or ForestGEO—plot at BTNR (LaFrankie et al., 2005). In some sense, Singapore provided a natural experiment, from which lessons on the conservation of small rainforest remnants within a highly fragmented landscape could be gleaned (Turner, 1997; Lum & Ngo, 2021).

Time-lag in extinctions. Turner et al. (1994) interpreted the significantly lower number of plant extinctions compared to that predicted by the species-area relationship as a time-lag in extinction following habitat loss, i.e., the plant communities in the rainforest remnants have not yet reached equilibrium in terms of species losses. This meant that there could still be time for conservation and management interventions. Tan et al. (1993a) also provided an account of two new ferns and 23 angiosperm taxa that were new records to the flora of Singapore. This provided optimism that some plant species may have been presumed to be locally extinct only because of the lack of botanical surveys and taxonomic studies.

Underpinning these early impetuses was the quest to enumerate and describe the native flora of Singapore. At the core of effective plant conservation are the questions of how many plant species are there, how many species have been extirpated, where can these species be found, and what are the threats to these species (Pimm, 2020). These questions require an urgent need to undertake field surveys and renaissance in plant systematics (Wilson, 2017). Much of this work was initiated by Drs. Hsuan Keng, Wee Yeow Chin, Richard Corlett, Hugh Tan, Ian Turner, Kiat Tan, Leong Chee Chiew, Chin See Chung, Ruth Kiew, Benito Tan, Wong Khoon Meng, Nigel Taylor, Tan Puay Yok and David Middleton, and others at NUS and the Singapore Botanic Gardens (SBG) and undertaken by a great number of local and overseas researchers in the 1990s, right through the 2000s and 2010s, and to date. More significantly, this spurred the development of three decadal cohorts of conservation biologists, plant ecologists and taxonomists, many of whom are today still pursuing research, conservation and management of our natural heritage. The authors of this paper span these three cohorts.

This paper traces the research efforts to enumerate and describe the plant diversity in Singapore over the last three decades, and the concomitant efforts to recover rare and endangered plant species, leading to a downward revision of plant extinction rates in Singapore.

PLANTS SPECIES INVENTORY AND DISCOVERY

Checklists. Despite being at the centre of Britain's botanical collection efforts in the Malay Archipelago in the 1800s and early 1900s, the first known comprehensive checklist of the plant species of Singapore was not produced until Ridley's Flora of Singapore in 1900 (Ridley, 1900, 1901). This was an annotated checklist of 2,218 vascular plant names, of which 1,731 are considered distinct, validly recorded native species or subspecific taxa today (including natural hybrids). Another 297 species are valid taxa but currently considered cryptogenic or not native to Singapore (e.g., naturalised species). After Ridley (1900, 1901), two other unpublished checklists of plants were produced by the SBG staff during the Japanese Occupation in 1942–1945. Titled as the 'List of Dicotyledons in Syonan' and the 'List of Monocotyledons in Syonan', a total of 2,116 native and naturalised species were listed (Turner, 1993). There was a long pause after this, before Hsuan Keng started to publish the annotated list of seed plants of Singapore in a series of papers in the Gardens' Bulletin from 1973 to 1987 (Keng, 1973, 1974a, 1974b, 1976, 1978, 1980, 1982, 1983, 1985, 1986, 1987). This formed the basis of the first volume of the Concise Flora of Singapore on gymnosperms and dicotyledons (Keng, 1990). A total of 1,930 names were listed, of which 1,252 are recognised as native species today and 622 are non-native or cryptogenic species. Another 789 names of monocotyledonous species were added subsequently in the second volume of the Concise Flora of Singapore (Keng et al., 1998), of which 557 are considered native today and another 186 are non-native or cryptogenic.

In parallel with the publications of the Concise Flora of Singapore, the plant checklist of Singapore was also updated nomenclaturally, covering both native and naturalised plant species. Corlett (1988b) produced a checklist of the naturalised flora of Singapore and recorded 136 vascular plant species believed to have been introduced into Singapore. The first nomenclaturally updated checklist of native and naturalised vascular plants for Singapore was produced by Turner et al. (1990). A total of 2,488 names were listed, of which 2,039 native and 336 non-native or cryptogenic species are recognised today. This was followed shortly by Turner (1993), who further revised the checklist of vascular plants with the key synonyms used in the 20th century. This streamlined the checklist to 2,340 native, 13 'doubtfully native', and 201 naturalised species. This, coupled with Hsuan Keng's two volumes of the Concise Flora of Singapore, were the main reference checklists of the vascular plants of Singapore until Chong et al. (2009)'s comprehensive checklist of the 'total flora' of Singapore which includes not just naturalised exotics, but also casual escapees and those found only in cultivation. In the analysis of the total flora, Chong et al. (2011) reported that native species constituted 51% (2,141

species), exotic species 44% (1,822 species) and cryptogenic species 5% (210 species). More significantly, 402 native species were presumed extinct, out of a total of 1,159 native species from the 20 largest families. The Orchidaceae was the largest family with 226 native species, and also had the largest number of extinctions (181 species, about 80%). Rubiaceae, which was the next largest family of native species, suffered far fewer extinctions (39 species, about 31%). Among the native tree flora, Meliaceae had the largest proportion of extinctions (14 species, about 35%), compared to the other major families. This is consistent with the earlier analyses by Turner (1994) and Turner et al. (1994). In particular, Turner et al. (1994) found that epiphytic species, including Orchidaceae, had the largest number of extinctions (about 62% extinction). They attributed this to the reduction of mangroves and large forest trees that are hosts for epiphytes, as well as epiphytic species perhaps being naturally sparse in the forest remnants and more susceptible to micro-climatic changes. The high number of extinctions amongst the Meliaceae tree species was proposed by Chong et al. (2011) to be associated with the decline or loss from the forests of large frugivores that help to disperse these generally large-fruited species, although this family could also be generally undercollected and overlooked, as evident from recent rediscoveries (e.g., see Chong et al., 2018; Ng et al., 2021).

In the years following the work of Chong et al. (2009), 97 native vascular plant species were newly recorded for Singapore, including species new to science and species endemic to Singapore; and a highly significant 206 native species that were presumed extinct were rediscovered. This has culminated in the publication of a new checklist of the native and naturalised flora of Singapore, with 2,388 native species, 476 naturalised and casual exotic species, and 101 cryptogenic species (Lindsay et al., 2022).

When the second edition of the Singapore Red Data Book was published, the proportion of vascular plant species presumed to be extinct from Singapore of the total number that have been recorded was reported to be 31.05% (Tan et al., 2008). With recent rediscoveries and taxonomic clarifications, this was revised downwards to 22% (Kristensen et al., 2020). Brook et al. (2003) had earlier provided an upper bound estimate of the potential extinction rate for plants as 74%, assuming unrealistically that all of the lowland flora of peninsular Malaysia could have been present on the tiny island as part of unrecorded extinctions. Using the temporal patterns of species discovery, i.e., the first and last years of record or collection of every plant species, and a new model for estimating unrecorded extinctions, Kristensen et al. (2020) provided a far more imaginable upper bound estimate of 32% [95% confidence interval: 30%–35%] using classical methods of estimation, or 35% [95% credible interval: 33%–-38%] using Baysesian methods—assuming that no more extant species remain undiscovered. However, Kristensen et al. (2020) also showed that the rate of species discovery has been fairly stable since the rapid rise during the early years of collection by Cantley and Ridley in the late 19th century. This corroborates the continual discovery of new records for Singapore and even endemic species new to science in the recent years, e.g., *Zingiber singaporensis* (Leong-Škorničková et al., 2014), *Hanguana rubinea* and *Hanguana triangulata* (Leong-Škorničková & Boyce, 2015).

These new records and rediscoveries were brought about through the various comprehensive botanical surveys of the nature reserves, nature parks and remnant forested areas, and taxonomic revisions of the floras of Singapore and the region, thereby demonstrating the importance of ongoing botanical surveys and taxonomic study of floras.

Comprehensive botanical surveys. The first comprehensive plant surveys of the nature reserves were conducted as part of a broader physical and biological Nature Reserves Survey from 1992 to 1997. At that time, there were only two nature reserves in Singapore: the BTNR and the Central Catchment Nature Reserve (CCNR). Prior to this, the BTNR was already relatively well-collected and well-studied (Wong, 1987; Corlett, 1995) in comparison to the CCNR. By the end of this survey and including a compilation from the published literature and herbarium specimens, 1,634 vascular plant species had been recorded from both reserves in total (Chew et al., 1997), constituting the lion's share of Singapore's vascular plant flora.

Complementing these comprehensive surveys of the inland forests of the nature reserves were botanical expeditions to Singapore's offshore islands, such as Pulau Ubin (Turner et al., 1992), Pulau Jong (Tan et al., 1994) as well as the mangrove and beach flora of Sungei Buloh (Tan et al., 1997) that later became the Sungei Buloh Wetland Reserve. Not all of the information from the island botanical expeditions has been published, although follow-up visits in later years made use of the records from the earlier surveys to produce checklists of Pulau Semakau (including Pulau Sakeng; Teo et al., 2011), and of the islands that make up Singapore's first Marine Park: the Sisters' Islands (Pulau Subar Darat, Pulau Subar Latu; Hung et al., 2017a), Pulau Tekukor (Hung et al., 2017b), and St. John's Island (Pulau Sakijang Bendera; Hung et al., 2017c).

Together, the floras of just these few inland and coastal forest areas include almost all of the extant native flora of Singapore. In addition, in recent years, surveys were conducted and published from patches of abandoned plantations and wastelands in Singapore, which are dominated in biomass and composition by non-native species. Some of these patches were part of existing nature parks (e.g., Bukit Batok Town Park and Bukit Batok Nature Park; Neo et al., 2013a) or were later gazetted as one of the nature parks that serve as buffers around the CCNR (e.g., Thomson Nature Park: Neo et al., 2014a; Windsor Nature Park: Neo et al., 2014b). While other patches were not protected, the publication of checklists of these patches (Neo et al., 2012, 2013b–e) assisted the work of government agencies and environmental consultants when

developmental plans for these areas were considered, and would also serve to document the status and distribution of non-native species that persisted or escaped from past cultivation.

Regularly repeating these comprehensive plant surveys is critical for monitoring the overall state of the flora of Singapore and ensure that the persistence of rare plant species is continually monitored to identify any signs of population decline or emergence of new threats such as invasive species. Another comprehensive biodiversity survey focusing specifically on the BTNR was conducted from 2014 to 2018, which contributed 10 rediscoveries of presumed extinct native species, one new native species record, and two new records of naturalised non-native species to the Singapore flora (Ho et al., 2018). Separate comprehensive surveys are ongoing that target the CCNR and the surrounding nature parks, and Singapore's southern islands.

Taxonomic revisions. Floras are important because they involve a robust investigation into the taxonomic status of the plants within their geographic boundaries and, through identification keys and detailed species descriptions, provide resources for others to put a name to new plants encountered. This is the basis for the discovery of new species and also allows for the accurate assessment of the diversity and the population sizes of biological units. In the race against time on extinction, floras may seem slow and expensive to produce, but the rigour is necessary and builds upon the first step of checklist compilations (Funk, 2006).

Following the first volume of the Concise Flora, the Angiosperm Flora of Singapore project was started (Tan et al., 1993b) which produced treatments for nine—mostly small—families: Philydraceae (Saunders, 1994), Plantaginaceae (Chua et al., 1994), Schisandraceae (Saunders, 1996a), Burmanniaceae (Saunders, 1996b), Caesalpiniaceae (now part of Fabaceae; Loo & Tan, 1997), Limnocharitaceae (Choo & Tan, 1997), Cannaceae (Tanaka, 1998), Connaraceae (Goh & Tan, 2000) and Erythroxylaceae (Chung & Tan, 2006). More work was done by students and collaborators of Hugh Tan that would have produced more accounts for other families: Aizoaceae (C.M. Boo, E.E.K. Phua), Anisophylleaceae (J.C.B. Teo), Avicenniaceae (now part of Acanthaceae; K.B.H. Er), Dipterocarpaceae (M. Newman), Eriocaulaceae (J.C.B. Teo), Fagaceae (P. Tan), Goodeniaceae (P.T. Chew), Loranthaceae (P.T. Chew), Nepenthaceae (T.K. Lowrey), Nymphaeaceae (H.H. Tan), Phormiaceae (now Asphodelaceae; S.H. Tan), Pontederiaceae (L.P.L. Toh), Rhizophoraceae (J.C.B. Teo), Sapotaceae (E.E.L. Seah), Solanaceae (J.M.Y. Foo), Sonneratiaceae (now part of Lythraceae; K.B.H. Er), Viscaceae (P.T. Chew), Vitaceae (including former Leeaceae; C.K. Yeo), etc., but the project was unfortunately discontinued.

The responsibility of coordinating and producing a national Flora fell to the National Parks Board (NParks), where the taxonomic strength of the SBG continued to be supported as part of its botanical research and conservation remit. With this, the Flora of Singapore project was initiated (Middleton, 2019) and has not only already delivered volumes on the entire, very substantial orders of the Poales and Gentianales, but also numerous nomenclatural clarifications, typifications, taxonomic revisions, new species, endemics, records, and rediscoveries, most of which are published in a 'Flora of Singapore precursors' series that is now into its 26th instalment. Despite Singapore's small land area, such botanical outputs are a critical contribution to the understanding of plant diversity in Southeast Asia, a global biodiversity hotspot.

RECOVERING THREATENED NATIVE PLANT SPECIES

Running concurrently with the taxonomic work on the local flora are the conservation efforts on the various threatened plant species of Singapore. The continually updated lists of the native species and near-comprehensive assessment of their conservation status through the editions of Red Data Books facilitates the prioritisation of which habitat patches to conserve. However, conservation of threatened plant species goes beyond just the conservation of habitats. Species recovery interventions are required, in view of the fact that some species occur in small isolated populations that may not persist (Rabinowitz et al., 1986).

Efforts to recover plant species threatened with extinction require not only an understanding of the ecology of the plants, but the know-how to successfully propagate offspring of known extant specimens in their natural habitats for ex-situ conservation and subsequent reintroductions. The SBG has had a long history of propagation and ex-situ conservation since its inception in 1859, but much of the focus in the 1990s and 2000s had been on orchids (Yam & Thame, 2005; Yam et al., 2010). The orchid conservation programme was initiated in 1995 and had successfully propagated and re-introduced 5 native species by 2009, including the world's largest orchid, *Grammatophyllum speciosum*, which was last sighted in Tuas and Pulau Ubin and presumed extinct in Singapore. This was accelerated between 2009 and 2012, where another 15 native orchid species were reintroduced (Yam et al., 2011).

In parallel with the orchid conservation programme, NParks also initiated the plant conservation project in the early 2000s, to focus on ex-situ cultivation of threatened plant species in nurseries for subsequent planting in suitable natural habitats (Lim et al., 2019). In collaboration with NParks, Dr. Hugh Tan, his research staff and students at NUS also undertook numerous collection trips to various parts of Singapore and conducted research into the propagation and ex-situ conservation of threatened native plants (Tan & Morgany, 2001; Tan & Chua, 2003; Tan, 2006). This resulted in numerous rediscoveries of extinct plant species in Singapore such as *Aeschynanthus albidus* (Lok & Tan, 2008),

Dendrobium aloifolium (Ang et al., 2010), *Freycinetia javanica* (Ang et al., 2012), and *Pinanga simplicifrons* (Ang et al., 2010). The research in propagation of native plants also yielded some early success, such as *Kopsia singapurensis, Crinium asiaticum, Brugueira sexangula, Aquilaria microcarpa, Tacca leontopetaloides, Shorea bracteolata* (Tan, 2006) and *Leea* species (Lok et al., 2011). The work had also introduced new techniques of propagation, such as air layering and micro-propagation (Tan, 2006; Yeo et al., 2011). The critically endangered *Fagraea auriculata* was propagated from off-shore islands and planted in many parts of the mainland today, largely from early efforts and innovation led by Dr. Hugh Tan's research group. In addition, a landscape garden showcasing native plant species was also set up at HortPark in 2010 to demonstrate and promote the usage of native plants and their conservation in urban landscapes (Tan et al., 2010).

This early work on plant species recovery had provided early training and exposure to young botanists, who are today leading the plant species recovery programme in NParks. This has now been expanded into a structured Species Recovery Programme in 2015, bolstered by the setting up of the Native Plant Centre at the Pasir Panjang Nursery in 2016 and the Seed Bank at SBG in 2019, where threatened plant species are identified and prioritised based on endemism, rarity and distribution (Lim et al., 2019). The Species Recovery Programme has seen progress in the propagation of many threatened native species from seeds or cuttings from the extant individuals of native stock, which are reintroduced into various parts of the nature reserves, as well as in the Singapore Botanic Gardens, and urban landscapes such as parks, roadside green verges (Lim et al., 2019). The Programme now seeks to recover 100 plant species by 2030.

FUTURE DIRECTIONS

Singapore is today probably, botanically speaking, the most densely collected country in the world, with a botanical collection density of 5,721 specimens per 100 km^2. In comparison, Peninsular Malaysia has about 200 specimens per 100 km^2 (Middleton et al., 2019). Undoubtedly, Singapore is a far smaller area to cover, but the efforts of many in NParks, SBG, the institutes of higher learning and the nature community were critical in the undertaking of plant surveys and taxonomic descriptions. This is imperative as we continue to discover new species and records, and rediscover species thought to have been extirpated. These surveys help to monitor changes in the ecosystem and allow for timely interventions, to ensure that Singapore continues to grow sustainably as a City in Nature. These carefully curated inventories of our native botanical collections, besides forming the basis of developing more complex ecological models to elucidate the mechanisms of ecological resilience within an urban landscape, also serve as an important reference for educational materials to the younger generation on our natural heritage.

In addition to the conservation of habitats, plant conservation in a highly fragmented urban landscape must focus on the conservation of plant germplasm, including living specimens to provide seed source, seeds and genetic materials. This provides the necessary insurance against any chance of stochastic extinction. This coupled with continued efforts in species recovery and restoration of natural habitats, will set the agenda for the next generation of plant ecologists and conservation biologists in Singapore.

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