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Establishing a network of long-term forest monitoring plots in Singapore

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ABSTRACT. We review the history of plot-based studies of forests in Singapore and their contribution to our understanding of tropical forest ecology, especially of the regenerative capabilities of forest remnants after fragmentation, land-use change, and other disturbances. With this, we describe the establishment of the Long-Term Forest Ecological Monitoring plot network that includes the continued utilisation of sets of recently established, standardised plots along with the re-establishment of a historical set of plots surveyed by a team led by Wong Yew Kwan in 1992, ensuring the plot design is harmonised across the network.

Keywords. Long-term study, permanent plot, vegetation

Introduction

The forests of Southeast Asia make up about 15% of the world's tropical forest (Stibig et al., 2014). However, the region is also undergoing rapid economic development with expansions in agriculture, forestry and urbanisation. This has brought about a high rate of deforestation and habitat fragmentation, resulting in the loss of biodiversity (Sodhi et al., 2010; Jamaluddin et al., 2022). The forests of Southeast Asia could potentially decrease by a further 5.2 million ha by 2050 under a worst-case scenario of weak global institutions and a lack of cooperation in addressing global environmental concerns (Estoque et al., 2019). This, coupled with the impact of climate change, highlights the need for a renewed focus on the conservation and restoration of the tropical forests of Southeast Asia (Strassburg et al., 2020).

An understanding of forest responses to landscape and habitat changes is critical for successful conservation and restoration. Throughout the tropics, permanent forest inventory plots—also often known as permanent sample plots—where trees above a minimum diameter are tagged, identified and re-measured periodically within the demarcated boundary of the plot, can provide long-term tree growth and biomass data. This has traditionally been used by foresters to project the yield of timber that could be extracted from the forest (Dawkins & Philip, 1998). Over time, forest ecologists have also used such plots to answer ecological questions such as on the diversity of tree species in forests and to gain insights into the forest dynamics, especially of forest structure, composition, and succession in terms of tree recruitment and mortality (Hubbell & Foster, 1992; Condit, 1995; Bakker et al., 1996). In the last few decades, global networks of permanent forest plots have also been established as observatories of the resilience of the forest ecosystem to habitat disturbance, landscape changes and the effects of climate change, e.g., the Forest Global Earth Observatory, or ForestGEO, network (Davies et al., 2021); the ForestPlots network (ForestPlots.net et al., 2021); and the Global Ecosystem Monitoring network (Malhi et al., 2021). Information gleaned from permanent forest plots have therefore been critical for the formulation of forest management strategies and policies for sustainable timber harvesting, forest conservation and restoration, and carbon stock accounting (Baker et al., 2020). Despite the advent of remote sensing technologies, these are still dependent on model training or validation by ground-based, plot-based surveys. Moreover, some forms of forest changes and degradation may not be readily discerned from space, especially when they occur in the forest understorey and not the canopy (Pennington & Baker, 2021). Permanent plot studies also offer far more precise information about forest succession and responses to environmental changes than one-off short-term studies or space-for-time substitution studies (e.g., inferring temporal trends from a one-off study of different-aged forest sites) (Bakker et al., 1996; Chytrý et al., 2019).

The establishment of permanent forest plots in Southeast Asia has a long history that has also evolved in their application as mentioned above. The early permanent forest plots in Southeast Asia were also set up for the purpose of estimating forest growth yields and, hence, the projected volume of timber that could be extracted. The first known permanent forest plot was set up in Myanmar in 1857 by the German forester Dietrich Brandis, who was working for the British colonial administration in what was then Burma (Dawkins & Philip, 1998). Other permanent forest plots that were set up for the same purpose included plots that were installed in Sabah in the 1950s by the Australian forester Don Nicolson who was working for the Food & Agriculture Organisation (FAO) (Nicolson, 1965). Almost in parallel with this, other permanent forest plots were set up to better understand the ecological dynamics of the forest. Perhaps, the longest-standing ecological permanent forest plots in Peninsular Malaysia are the 2-ha plots that were established in the primary lowland and hill dipterocarp forest in the Bukit Lagong and Sungei Menyala Forest by John Wyatt-Smith in 1947. These plots were monitored regularly by Wyatt-Smith until the early 1960s when he departed Malaysia (Wyatt-Smith, 1966). Monitoring of the plots was then continued by N. Manokaran, K.M. Kochummen and others in the Forest Research Institute Malaysia (FRIM) (Manokaran & Kochummen, 1987; Manokaran & Swaine, 1994). In 1970, ten 0.4-ha plots were also set up by Wong Yew Kwan at Pasoh Forest Reserve for the purpose of studying how tree distribution varied with soil type (Wong & Whitmore, 1970). Five of these plots were subsequently enlarged to 2-ha plots by Peter Ashton to better understand the effects of environmental variation on tree distributions (Ashton, 1976). In 1986, Pasoh Forest Reserve was designated as a study site to compare against the forest dynamics observed from the Barro Colorado Island in Panama by the Center for Tropical Forest Science (CTFS) of the Smithsonian Tropical Research Institute (Hubbell & Foster, 1983; Losos & Leigh, 2004). A 50-ha permanent plot was set up at Pasoh and yielded a large amount of information about forest dynamics in tropical forest (Kochummen et al., 1990). This has since become part of the growing ForestGEO network of ecological permanent plots, now in 75 localities in 28 tropical and temperate countries, including the Bukit Timah Nature Reserve in Singapore where two 2-ha permanent plots have been established (Chua et al., 2013; Davies et al., 2021).

While global networks of distributed permanent forest plots contribute immensely valuable data to the management of forest at the global scale, a single plot in its specific locality is limited in terms of the information it can yield for the purpose of forest restoration and management within the local landscape. This is because a single plot cannot capture the range of forest types and seral stages, especially in heterogeneous landscapes with a mosaic of past land-use histories. Furthermore, there are also localities that are not focused on forestry and do not have previously established permanent sample plots. Therefore, there is a need to establish local and not just global networks of permanent forest plots to provide timely data on forest ecological dynamics for the monitoring of populations and the formulation of restoration and management strategies catered for local or national contexts.

Located 1° N of the equator, Singapore is an example of a tropical city-state where much of its remaining forests exist today in small fragments amidst a largely urban landscape. By the early 1900s, less than 2% of the original forest cover remained due to land conversion for agricultural crops such as gambier, pepper, rubber and pineapples (Corlett, 1992). And yet, although primary forest comprised only 0.2% of the total land area of Singapore by the end of the 20th century, with another 4% of native-dominated mature secondary forest (Yee et al., 2011, 2016), the majority of recorded native plant species in all major taxonomic groups are still extant (Lindsay et al., 2022). Many of the patches of primary and mature secondary forests occur as small remnants within the Bukit Timah Nature Reserve (BTNR), Central Catchment Nature Reserve (CCNR) and the Singapore Botanic Gardens (SBG). Despite the importance of understanding forest dynamics and responses to surrounding land-use changes for the conservation and restoration of these small rain forest remnants, permanent forest plots were not established until the 1990s. This could be attributed to the absence of a substantive planned forestry sector in Singapore's early history of development.

This paper traces the history of ecological permanent forest plots in Singapore and summarises some of the key findings from these plots over the years. We lay out the need to re-establish the historical plots in CCNR, as part of a core network of Long-Term Forest Ecological Monitoring plots in Singapore that include existing plots at the Mandai and Nee Soon areas of the CCNR as well as four Nature Parks. These plots will supplement other on-going long-term forest dynamics studies, e.g., the ForestGEO plots in BTNR and regular surveys of the SBG Rain Forest. This will yield critical information about forest growth, structure, composition, recruitment and mortality over time across the primary forest and native-dominated secondary forest patches of different seral stages and land-use histories. These permanent plots also offer opportunities to monitor the faunal species composition of these forest fragments and to undertake studies to improve our understanding of plant dispersal syndromes and interaction networks. Finally, we describe the approach taken to re-establish the CCNR permanent plots and explain the data that will be collected.

History of forest plots in Singapore

The use of forest plots as a research tool in Singapore was driven by four broad areas of study from the 1970s through to today: (a) ecology of Singapore's forest tree communities and vegetation types; (b) conservation value of small rain forest fragments; (c) regeneration capacity of rain forests affected by natural and anthropogenic land-use disturbances; (d) resilience of the rain forests against climate change.

Laying the foundation for understanding forest tree communities and vegetation types

There has been a long history of botanical collection and the study of plant systematics in Singapore, led by the botanists of SBG since the 19th century (Middleton & Turner, 2019). Singapore is today the most densely collected country in Southeast Asia, with a botanical collection density of over 5721 specimens per 100 km^2 (Middleton et al., 2019). In comparison, Peninsular Malaysia has about 200 specimens per 100 km^2 (Middleton et al., 2019). Plot-based botanical studies in Singapore, however, had a comparatively later start.

Early plot-based studies

The earliest published study of forest in Singapore that can be considered to have used a 'plot'—in the sense of an area within which plants were identified and counted—was conducted by I.H. Burkill (Burkill, 1919), then-Director of SBG, in December 1918. It was not stated exactly where the plot was located, but it was a 30-year-old secondary forest patch of about 2 acres (about 0.8 ha) within the grounds of SBG, which was slated to be removed for the Gardens' development. Burkill took the opportunity to measure the height and girth at breast height (gbh) of all the large trees and also identify all other species in the patch. He also attempted to count all of the plants in the undergrowth in two parts of the patch, comprising a total area of 1/3 of an acre. In 1933, another SBG botanist, E.J.H. Corner, enumerated trees in two 'plots', each in primary freshwater swamp forest at Jurong and Mandai (Corner, 1978). H.B. Gilliland laid out two of what he termed 'transects' of 1000 by 6 feet (c. 300 by 1.8 m) in two parts of the forest in the MacRitchie area of CCNR near Lornie Road. Although he called them transects, they are effectively narrow plots. One of these was in a patch of *Adinandra* 'belukar' (Gilliland, 1958) and the other was in logged-over lowland mixed dipterocarp forest (Gilliland & Wantman, 1959). While these studies provided some early reference points for the relative abundance of trees per unit area in these vegetation types, the plot methodology limited their use for broader generalisations, e.g., plots of unequal area (except for Gilliland's) and too few replicates.

Wong Yew Kwan established the first set of highly replicated, equal-area forest plots at BTNR between June 1974 and January 1978 (Wong, 1987). This was undertaken as an activity of the Singapore Branch of the Malayan Nature Society. Wong was formerly the Deputy Chief Research Officer of FRIM and was appointed the Commissioner for Parks and Recreation in Singapore from 1974 to 1982. A total of

20 clusters of circular plots were set up in BTNR, each cluster comprising four 0.04-ha (0.1 acre) circular plots, i.e., the total area of each cluster was 0.16-ha (0.4 acre). The intent was to record the composition of the tree species and their distribution in the Reserve. The results of the survey confirmed that the forest composition conformed to that of a coastal hill dipterocarp forest type (sensu Symington, 1942) dominated by *Rubroshorea curtisii* (Dyer ex King) P.S.Ashton & J.Heck (= *Shorea curtisii* Dyer ex King). At that time, Bukit Timah was the southernmost known extent of this forest type. Aside from the numerical dominance of Dipterocarpaceae trees (125 individuals out of 889 trees), the largest numbers of tree genera (11) and species (22) were from the Euphorbiaceae as then defined, including genera now placed in Phyllanthaceae (Wong, 1987). Of significance is the fact that this was the first known proper quantitative survey of primary forest trees in Singapore, along with the fact that the work was undertaken by volunteers!

It should be noted that Frederick Swan, who was on sabbatical leave at the Department of Botany, National University of Singapore, established two 60 by 40 m (0.24-ha) plots in primary forest at BTNR from 1982–1983, one of them in Fern Valley and the other about 250 m away in Jungle Fall Valley (Swan, 1988). He used these plots to study the tree distribution patterns along an elevational gradient. Swan's study showed that the shallower depth of the granitic bedrock at Fern Valley may have resulted in a forest structure and floristic composition distinct from that found at Jungle Fall Valley, i.e., 20% fewer species, 44% fewer stems and 23% lower basal area than in the Jungle Fall Valley plot (Swan, 1988).

To understand forest succession after degradation by past agriculture, Corlett (1991) surveyed 15 plots of 50 × 20 m distributed around today's CCNR where he measured and identified all plants more than 2 cm diameter at breast height (DBH). Prior to this, Hill (1977) proposed three types of secondary vegetation based on observations of this area: grass and scrub, low secondary, and tall secondary based mainly on vegetation height. From his own study, Corlett (1991) instead proposed four successional stages and described the stages in greater floristic and ecological detail. Sim et al. (1992) surveyed a plot of 20 × 20 m and six 15 × 15 m plots in patches of *Adinandra* 'belukar' around Singapore, all outside of the CCNR but with a plot within the BTNR. The flora and vegetation structure would have corresponded to Corlett's Stages 2 and 3, which in turn correspond to Hill's low secondary forest type. The soils of *Adinandra* 'belukar' were also found to be exceptionally acidic and low in nitrogen and phosphorus, which explain the dominance of *Adinandra dumosa* Jack and other species that are elements of disturbed heath forests elsewhere in Peninsular Malaysia (Sim et al., 1992). Unfortunately, the Wong (1987), Swan (1988), Corlett (1991) and Sim et al. (1992) plots were not physically marked and the details of their exact locations were too imprecise in these publications for the plots to be relocated for re-survey.

'Wong Yew Kwan plots' in the Central Catchment Nature Reserve

Following the formation of the National Parks Board (NParks) of Singapore in June 1990 to manage the national parks (comprising SBG and Fort Canning Park) and the nature reserves, Wong Yew Kwan, who by then had retired, was commissioned by

NParks to undertake an ecological survey of the tree communities in CCNR in 1991. Up till that point, there were only the quantitative ecological studies by Gilliland and Corlett but no known comprehensive survey of the trees in CCNR. The forest was stratified into four forest types (FT), according to the interpretation of relative canopy height, tree crown size, and canopy uniformity (Wong et al., 1994; Turner et al., 1996a), as follows: FT1—open vegetation with few scattered trees, corresponding to Corlett's Stage 1 and partly corresponding with Hill's 'grass and scrub' vegetation type; FT2—generally closed canopy vegetation with many small trees, 8 to 15 m tall, corresponding to Corlett's Stages 2 and 3 and Hill's 'low secondary forest' type; FT3—vegetation with larger trees, 10 to 20 m tall, and higher density, corresponding to Corlett's Stage 4 and Hill's 'tall secondary forest' type; FT4—vegetation with a continuous canopy, much taller trees, with a multi-storey profile resembling primary rain forest. From 1992 to 1993, using the same study design as that in BTNR, a total of 62 clusters of four 0.05-ha circular plots were surveyed, sampling across the FT2, FT3 and FT4 areas. FT1 was not sampled because of the lack of trees. The survey yielded a total of 7462 trees ≥ 30 cm gbh, belonging to 499 species, 46 of which could not be identified. It also revealed the presence of three *Rubroshorea curtisii* trees, which was then not known to occur in lowland mixed dipterocarp forest (sensu Symington, 1942) in Peninsular Malaysia and Singapore, and also a new record for Singapore of *Shorea ochrophloia* Strugnell ex Symington (Wong et al., 1994).

FT4 was interpreted as primary forest; while densities of Dipterocarpaceae and other species that would otherwise be found in intact forests of Southeast Asia are relatively low in FT4 patches in Singapore, they represent the last remnants of such vegetation in Singapore today and are of the highest conservation priority. Analysing the survey results further, Turner et al. (1997) showed that the 16 FT4 plots contained 340 tree species, more than the 281 species recorded from the 43 plots of the two secondary forest types, FT2 and FT3. Three clusters of plots in the Nee Soon Swamp Forest, Singapore's last substantial intact tract of freshwater swamp forest, were included in FT4, but were recognised as having a distinct tree community composition. The mean number of species per plot in the more diverse secondary forest type (FT3) was only about 60% of the primary forest. This secondary forest developed on land that had been abandoned after agricultural use but after even more than 100 years of regeneration and the proximity of contiguous primary forest patches, it was still substantially less diverse than the primary forest and was not accreting species rapidly. This provided early evidence of arrested succession in secondary forests on land formerly used for agriculture (sensu Goldsmith et al., 2011).

The rich ecological information obtained from the initial surveys of the CCNR plots influenced Singapore's nature reserve management policy for the next three decades. Amongst the older members of the research community and NParks nature reserve management staff in Singapore, the CCNR plots were remembered as the 'Wong Yew Kwan plots'. Fortunately, unlike the BTNR Wong (1978) plots, the centre of the CCNR plots were marked by a thick plastic pole, and detailed maps were drawn by Dennis 'Paddy' Murphy showing the locations relative to nearby landmarks. In 2008, Chew Ping Ting, one of Wong's original team members, led a new team of NParks staff to relocate the plots. Most plots could be relocated with the help of the maps, plastic poles and surviving trees from the original survey, except for two clusters of plots. The locations of the plots were then logged with a Global Positioning System receiver to facilitate future efforts to relocate the plots. However, even though the plots were relocated, there was not an accompanying comprehensive re-survey of the trees in the plots to include identification and measurement of new recruits, data critical to understand forest dynamics and succession.

Demonstrating the value of small rain forest fragments

The early 1990s saw an upward trend in studies on habitat loss and fragmentation worldwide (Anderson et al., 2021). Such studies also began to gain traction in the tropics, although most of the studies were focused on birds with little attention given to plants (Turner, 1996). This was also the period when studies on the value of small rain forest fragments began to take shape in Singapore (Er et al., 2022). This was critical because small forest fragments were often the only patches of intact habitat left in urban landscapes, such as in Singapore.

Singapore Botanic Gardens Rain Forest inventory

To understand the long-term effects of habitat fragmentation on local plant diversity in tropical rain forests, in 1994, Ian Turner and Hugh Tan, who were then at the Department of Botany at the National University of Singapore, undertook a complete enumeration of woody plants ≥ 5 cm DBH in the 4-ha remnant patch of primary rain forest in SBG. This was formerly known as the Gardens' Jungle and is today called the SBG Rain Forest. This was akin to the setting up of a 4-ha permanent plot. Comparing this inventory of the plants to the historical collection in the herbarium, Turner et al. (1996b) reported that about half the original plant species continued to persist, despite more than a century of isolation. This suggested that small rain forest fragments could be important refugia for plant species and that there is a time-lag in extinctions. It was also noted that half of the tree species present in the forest in 1994 were represented by only one or two individuals, with *Calophyllum ferrugineum* Ridl. unusually dominant, constituting about 25% of all woody stems. This highlighted the challenges of regeneration in small rain forest fragments. The SBG Rain Forest has continued to be monitored, with complete re-enumeration of the woody plants in 2009–2012 and again in 2019–2021.

Bukit Timah Nature Reserve ForestGEO (CTFS) plots

At around the same time as the plant inventory of SBG Rain Forest, the CTFS established a regional headquarters in Singapore at the National Institute for Education of the Nanyang Technological University (NTU) in 1993 (Davies et al., 2021). The partnership with NTU, now through the recently formed Asian School of the Environment, continues today. Two 2-ha plots were set up within BTNR. One plot was established within the primary forest in 1993 and re-surveyed in 1995–1996, 1997, 2003, 2007–2008, 2012 and 2018. Another plot, almost adjacent to it, was added in predominantly secondary forest in 2004 and re-surveyed in 2007, 2012 and 2019

(LaFrankie et al., 2005; Lum & Ngo, 2021). All woody stems ≥ 1 cm DBH in the plots were surveyed, which was the smallest minimum threshold to be systematically applied for inclusion in plot-based studies and provided the opportunity to explore the dynamics and compositional change of smaller stems. A number of findings have resulted from analyses of the plot surveys over the years. Firstly, the results have shown that there has not been a loss of species within the plots, but rather an addition of new species via recruitment of young saplings from outside of the plots (Ercelawn et al., 1998; Ngo et al., 2016). Secondly, mortality and recruitment rates tended to be higher than those reported for more pristine lowland rain forest sites elsewhere in Southeast Asia (Ngo et al., 2016). Thirdly, there did not appear to be any significant major losses of large trees as would be expected from a small rain forest fragment due to edge effects (Ngo et al., 2016). Fourthly, the plot in the secondary forest, which had been left to regenerate for at least 56 years, was structurally and floristically distinct from the primary forest plot, with 30% of the stem density, 58% of the basal area, and 26% of the species richness of the primary forest plot (Chua et al., 2013). In essence, these results suggested that the rain forest fragment at Bukit Timah was more resilient to the effects of fragmentation than was previously thought, but regeneration of secondary forest towards primary forest—even when there was primary forest adjacent to it and hence dispersal limitation should not be a major contributory factor—was slow and almost arrested, possibly due to the soil conditions following past land-use disturbance. From 2005–2008, a ‘Bukit Timah Big Trees’ survey was extended to the whole of BTNR and recorded 10,218 trees ≥ 30 cm DBH (Lum & Ngo, 2021), including species that were new records for Singapore (Khoo et al., 2018).

Monitoring the regenerative capacity of disturbed rain forests

With the remnants of the highest quality forests identified for conservation and monitoring, attention then turned to the potential for secondary forests in Singapore to regenerate and recover from past disturbance.

Forest disturbance due to wind tends not to be thought of as a prominent driving force in shaping forest structure and composition in the hurricane-free tropics, although this has been shown to have a significant effect in some localities (e.g., Kelantan in Peninsular Malaysia, Wyatt-Smith, 1954; Kalimantan, Indonesia, Proctor et al., 2001). At the same time, there have been anecdotal observations of increasing frequency of blowdowns and storm-associated treefalls in Singapore’s nature reserves along with concerns of potential implications from increasing frequency of extreme weather events with a warming climate. A major windstorm (wind speed greater than 60 km/h) that brought about extensive tree falls in the part of CCNR north and south of Mandai Road in early 2011 presented a rare opportunity to study the recovery of the forest arising from changes in the short-term abiotic conditions. A set of plots was therefore set up to monitor the vegetation changes.

There was also an increasing recognition of the need for the vegetation surveys in secondary forests that had regenerated following the abandonment of plantations, agricultural land and wastelands. Earlier studies on such post-agricultural secondary succession in Singapore (e.g., Corlett, 1991) focused on areas within BTNR and CCNR, and noted the general absence of non-native, i.e., exotic, species. With variable-sized, non-permanent plots throughout Singapore, Teo et al. (2003) verified the low levels of invasion in CCNR secondary forests compared to 'wastelands' that were dominated by exotic species. These wastelands mostly persisted as remnant patches of land awaiting development in the urbanised landscape but some of which occurred around and in the vicinity of BTNR and CCNR. Eventually, a series of highly replicated plot-based surveys were undertaken by students supervised by Hugh Tan at the National University of Singapore (e.g., Neo et al., 2013; Neo et al., 2014a, 2014b). These surveys ascertained the ecological value and regeneration capacity of these forested patches as 'novel forest ecosystems': forests comprising combinations of previously unassociated species and with abiotic conditions, such as soil characteristics, that are the result of past human activities, and which persist as self-organising, self-sustaining stable states (Hobbs et al., 2006; Lugo, 2009; Neo et al., 2017; Lai et al., 2021).

A separate set of studies examined the relationships between seedlings in quadrats nested within octahedral plots around CCNR, the trees in the plots, and environmental and soil characteristics (Chua et al., 2016: 12 plots; Chua & Potts, 2018: 11 of the 12 plots). The results suggest that legacies of soil degradation from past agriculture were affecting seedling recruitment and forest regeneration.

'Mandai storm forest' plots

Following the severe windstorm event in 2011, Alex Yee and Chong Kwek Yan established a total of 40 plots in what Lai et al. (2022) coined the Mandai storm forest (following Wyatt-Smith's phrase for a similar forest in Kelantan), comprising 26 plots in old-growth and young secondary forests that were affected by the windstorm, and 14 plots in old-growth and young secondary forests that were unaffected. These plots were surveyed annually for 5 years from 2011 to 2015. The surveys showed how the canopy and basal area, as well as the coarse woody debris, in the affected plots recovered to the same levels as the unaffected plots in 1 year. By the second year, the taxonomic and functional diversities had increased beyond the levels in the unaffected plots, with no evidence of a shift in functional composition towards resource-acquisitive strategies such as lower wood density or higher specific leaf area (Yee et al., 2019). In a further analysis of recruitment in the affected plots, Lai et al. (2019) demonstrated that sapling recruitment was moderated by wood density, seed mass and adult stature. Each square plot was small compared to earlier plots in Singapore and the typical plots in tropical forest studies, measuring only 10 × 10 m (i.e., 0.01 ha), and yet could be surveyed rapidly, even when including measurement of stems as small as 1 cm DBH, and—with a carefully planned sampling design and sufficient replication—representative enough of the very challenging fieldwork environment to allow for detailed investigations into the short-term regeneration dynamics following the windstorm (Lai et al., 2022). Plastic pipes had been laid down to mark the corners of the plots, and still remain, but unfortunately the tags on individual trees were removed in 2015 following the end of the project (Lai et al., 2022). These plots may provide an interesting perspective on forest regeneration on a site with past land-use disturbance and natural disturbance, if they continue to be monitored.

Nature Parks plots

Eleven forested patches that were abandoned plantations or wastelands were identified, and five square 20 × 20 m (0.04 ha) plots were installed in each of these patches from 2011–2012 by Louise Neo and Alex Yee. Analyses showed that the plant species richness in these patches were negatively associated with increasing leaf litter and distance to older-growth forest (Neo et al., 2017; Lai et al., 2021). The high soil nitrogen and high soil potassium were found to be correlated with lower native plant species richness (Neo et al., 2017) while higher soil phosphorus was associated with higher diversity of exotic tree species ≥ 5 cm DBH (Lai et al., 2021). Exotic tree species such as *Falcataria falcata* (L.) Greuter & R.Rankin, also known as albizia, and *Acacia auriculiformis* A.Cunn. ex Benth dominated some of these sites. These nitrogen-fixing legumes are highly adaptable and can persist better under an initial phase of being limited by other macronutrients, setting off an autogenic successional pathway. Their high growth rates and nitrogen-fixing properties give them an ecological advantage which has allowed them to out-compete native species in these sites. Interestingly, the results from these forests outside of the nature reserves contrast with those of Chua et al. (2016) and Chua & Potts (2018) which suggested that low soil fertility impeded regeneration of native species in forests within CCNR.

Additional analysis of the 105 'novel forest ecosystems' plots, together with the 40 Mandai storm forest plots, provided evidence for the addition of a new category of 'exotic-dominated secondary forests' to the classification of forests in Singapore (Yee et al., 2016). It also demonstrated the association of sub-categories with past land-use history, with 'abandoned-land forest' and 'waste-woodlands' paralleling *Vismia* versus *Cecropia* dominated succession trajectories in post-pastoral landscapes in the Neotropics (Mesquita et al., 2001). The majority of native-dominated forests are already protected in the nature reserves, while the exotic-dominated 'novel forest ecosystems' in Singapore occur mostly outside of the nature reserves, including some of the Nature Parks that are planned as 'buffer parks' to the nature reserves, e.g., Bukit Batok Nature Park, Windsor Nature Park and Thomson Nature Park. Given the vegetation composition and ecology, a different management strategy is required in these areas, e.g., invasive species management and enrichment planting (Neo et al., 2017; Lai et al., 2021).

These plots were larger than the Mandai storm forest plots, but still small by comparison to the ForestGEO plot at BTNR. Notwithstanding this, the rich insights provided from the analyses of the data demonstrated that with sufficient replication and representative sampling, the most important ecological variations of interest could be captured. In 2014, nested 'sub-plots' of 10 × 10 m were established in one quadrant of each of most of the plots, where smaller stems (1 cm ≤ DBH < 5 cm) were surveyed, in addition to re-surveying the 20 × 20 m plot (A.T.K. Yee, unpublished data). Like the Mandai plots, the corners of the plots and sub-plots were marked by plastic pipes, so future re-surveys will be possible.

Understanding the resilience of rain forests to climate change

In the 2010s, there was increasing attention on both the resilience of forests to withstand impacts from a changing climate, as well as the role of forests as a storehouse of carbon to buffer anthropogenic emissions of greenhouse gases into the atmosphere.

Nee Soon plots

A key vegetation type of particular interest in the context of climate change is wetland, or swamp, forest. Such forests contain unique biodiversity given the adaptations required to survive and thrive in the waterlogged environment and given the special hydrological conditions could be particularly sensitive to, e.g., changes in precipitation regime due to a changing climate. For Singapore, the Nee Soon Swamp Forest is exceptionally high value in terms of animal (Ng & Lim, 1992) and plant (Turner et al., 1997; Chong et al., 2018) diversity. NParks therefore commissioned a series of studies in the part of CCNR containing the Nee Soon Swamp Forest.

The first ten 15 × 15 m plots (Q1 – Q10) were established in 2011. The number of plots were then increased to 40 and each was expanded to 20 × 20 m in 2013 (Chong et al., 2018, 2021); the intention was to match the dimensions of the plots in the novel forest ecosystem study (Neo et al., 2017; Lai et al., 2021; Table 1). Analyses of the 40 Nee Soon plots by Chong et al. (2021) found that soil was a major factor structuring ecological communities, similar to findings by Neo et al. (2017) and Lai et al. (2021) for exotic-dominated secondary forests, but also showed that soil and hydrological effects on vegetation are difficult to decouple.

The plots were then re-surveyed and an extended area of 40 × 40 m around each plot was surveyed for 'big trees' (defined as ≥ 30 cm DBH) in 2018. At the end of this study, dendrometer bands were installed on selected big trees, including those ≥ 30 cm DBH in the core 20 × 20 m plot. Soil cores at least 1.5 m deep were taken from all plots and dipwells with piezometers were installed in the 21 'wet' plots for monitoring changes in the water table. The piezometers were removed from most plots in 2021 but may be re-installed if required.

When the plots were re-surveyed for a third time in 2020, sub-plots of 10 × 10 m were also established in one quadrant of 16 of the plots and in which 'saplings' (1 cm ≤ DBH < 5 cm) were surveyed; four 'quadrats' of 1 × 1 m were established in 37 of the plots where 'seedlings', defined as < 1 cm DBH but ≥ 20 cm height, were surveyed; and the dendrometer band readings were taken for the first time. Additional side-projects were conducted as student projects to study leaf litter production (Lam et al., 2022), decomposition (Lam et al., 2021), tree fecundity (Lam et al., in preparation), and plant functional and anatomical traits (Lam et al., in review).

Whole-life cycle demographic modelling made possible with the seedling-to-fruiting nested study design in these later projects in Nee Soon is a proof-of-concept of how well-designed permanent plot studies can provide valuable data for development of powerful predictive modelling capabilities for scenario-based simulations to identify alternative trajectories and pinpoint areas where management intervention is required (Lam et al., in preparation). The litter production study by Lam et al. (2022) also demonstrated a way to link community composition to ecosystem function,

Table 1. Plot design of recent square plot-based vegetation studies in Singapore. *For the plots in the Nature Parks set, there were five plots in each of the four forest patches at Bukit Batok Nature Park, Bukit Batok Town Park, Windsor Nature Park, and Thomson Nature Park.

Plot set	Dimensions	Size cut-off	*n*	Year(s) surveyed (20--)												Key reference(s)
				11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	
Mandai storm forest	10 × 10 m	≥ 1 cm DBH	40	✓	✓	✓	✓	✓								Yee et al. (2019)
Nature Parks	20 × 20 m	≥ 5 cm DBH	20*	✓		✓										Neo et al. (2017); Lai et al. (2021)
	10 × 10 m	1 cm ≤ DBH < 5 cm	20*			✓										A.T.K. Yee, unpublished
Nee Soon	20 × 20 m	≥ 5 cm DBH	40			✓					✓		✓			Chong et al. (2021)
	40 × 40 m	≥ 30 cm DBH									✓		✓			Chong et al. (in prep.); Lam et al. (in prep.)
	10 × 10 m	1 cm ≤ DBH < 5 cm	16										✓		✓	Lam et al. (in prep.)
	1 × 1 m	Height ≥ 20 cm, DBH < 1 cm	37×4										✓	✓	✓	Lam et al. (in prep.)

via the estimation of 'specific' productivity, i.e., per unit basal area canopy primary productivity intrinsic to each species that can be scaled up to the stand level through basal area. Although specific canopy primary productivity is lower for swamp-adapted species, the litter produced decays much slower (Lam et al., 2021) leading to carbon accumulation. From the soil cores, soil organic carbon was found to be three times higher in the 'wet' plots compared to the 'dry' plots (Chong et al., in preparation).

Singapore Carbon Accounting ('SINCA') plots

As part of national monitoring of carbon stocks associated with the land sector for regular reporting of Singapore's greenhouse gas inventory to the United Nations Framework Convention on Climate Change (UNFCCC), since 2015 NParks has also established about 120 permanent plots throughout Singapore. Of the 120 plots, 18 plots are located in forested areas in nature reserves and nature parks. These plots have been re-surveyed once, in 2020, and will be revisited at 5-year intervals. The plot dimensions and size thresholds are similar to the core and extended plot areas of the earlier plots (Tables 1 and 2), except that the area where trees ≥ 5 cm DBH are being measured are nested as four 10 × 10 m through the diagonal of the 40 × 40 m extended plot.

Towards long-term ecological monitoring of forests in Singapore

Plot-based sampling is one of the basic approaches to the study of vegetation and forests. A simple yet highly impactful modification of the plot is to make it permanent. Permanent plots were considered by Chytrý et al. (2019) to be among the six most important developments in vegetation science over the past 30 years. By re-surveying the same plots at an appropriate frequency over a sufficiently long duration, insights into vegetation change and hence the dynamic relationships can be gained on top of comparisons across gradients in space. Within plots, individual plants such as trees can also be tagged to allow the tracking and quantification of individual-level demography and fitness, such as mortality, growth and fecundity. These are important parameters that, when studied across multiple species in plots together with the environmental parameters also measured across time, allow for building mechanistic and process-based individual-based models with a higher degree of granularity as demonstrated in the Nee Soon plots (see also Lai et al., 2022), compared to plots that do not tag individuals.

Despite the successes of the small but highly replicated and distributed Mandai storm forest plots, the novel forest ecosystem plots, and the Nee Soon plots, these sets of plots were narrowly focused for particular objectives. The Mandai and Nee Soon plots also focused only on a segment of CCNR. The Wong Yew Kwan plots are the earliest set of plots that span across the various seral stages of Singapore's forests (Fig. 1) and with a large sample size (e.g., compared to Chua et al., 2016). Therefore, in addition to re-surveying and maintaining the plots in Table 1 that were discontinued previously, the Wong Yew Kwan plots in CCNR should also be re-established and the

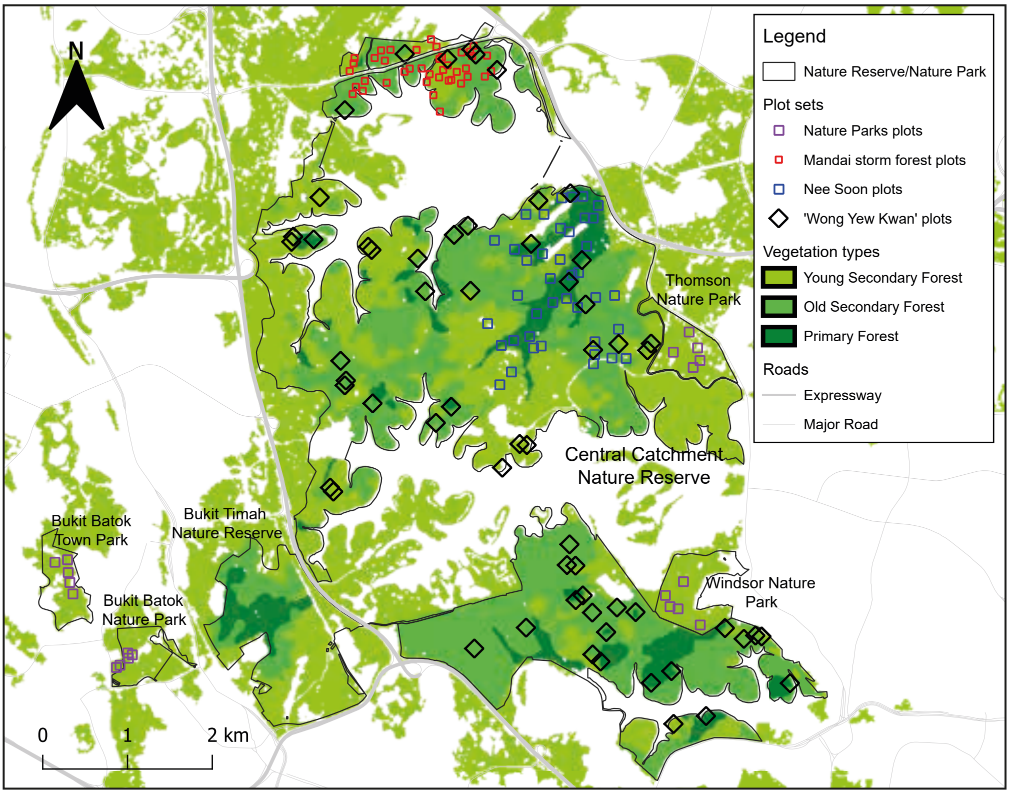

Fig. 1. Permanent forest plots included in the Long-Term Forest Ecological Monitoring plot network. Vegetation types from Yee et al. (2011).

plot and survey design harmonised with the other three sets of plots (Fig. 2). In addition, the timing of future re-surveys will be on a fixed schedule (Table 2). Collectively, the Mandai, Nature Parks, Nee Soon and Wong Yew Kwan plots will form NParks' Long-Term Forest Ecological Monitoring (LTFEM) network of plots (Fig. 1). The LTFEM plot network will provide the fundamental research infrastructure to coordinate forest ecology research in Singapore and will be complemented by the SBG Rain Forest Inventory and BTNR ForestGEO plots, as well as the forested SINCA plots. Together, these will be representative of most of the major inland forest types of Singapore, especially the remaining primary forest. The undertaking of this effort by NParks, a statutory agency, will increase the likelihood that the long-term investment can be sustained. At the time of writing, all 60 Wong Yew Kwan plots have recently been re-established, and the seedling quadrats and sapling sub-plots in Nee Soon have been re-surveyed again. In addition, camera trapping and bird surveys are being conducted in the Wong Yew Kwan plots. Surveys of seedlings in quadrats in each of the 60 Wong Yew Kwan plots and re-surveys of the Nature Parks plots and the Mandai storm forest plots will be conducted in 2023. Tree phenology and seed/litter-trapping will soon commence, but for only a subset of the Wong Yew Kwan plots that are most easily

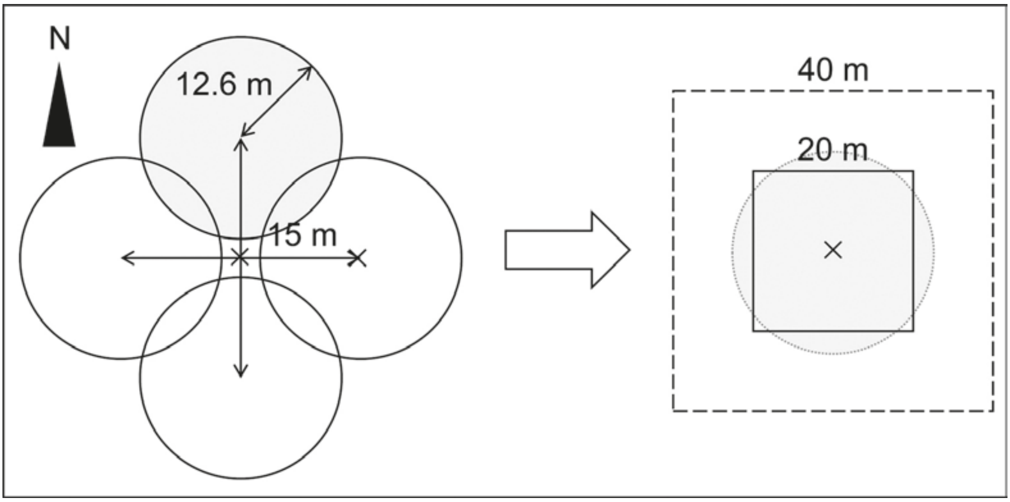

Fig. 2. Harmonisation of the Wong Yew Kwan plot-cluster design (left) to the design of other LTFEM plots (right). The typical cluster of Wong Yew Kwan circular plots are arranged in cardinal directions 15 m away from a cluster centre, with each plot 12.6 m in diameter (which resulted in a slight overlap between plots). One of the plots at each of 60 of the 62 clusters would be converted to a square plot.

Table 2. Permanent plot design in the Long-Term Forest Ecological Monitoring project.

Sampling hierarchy	**Dimensions**	**Terminology for individuals measured**	**Size threshold**	**Frequency of re-measurement**
Extended plot area	40 × 40 m	Big trees	≥ 30 cm DBH	Dendrometer bands: annual; otherwise together with core plot
Core plot (or just 'Plot')	20 × 20 m	Trees	≥ 5 cm DBH	Every 4(–6) years
Sub-plot	10 × 10 m	Saplings	1 cm ≤ DBH < 5 cm	Every 2(–3) years
Quadrat (NE, SE, SW, NW)	1 × 1 m	Seedlings	Height ≥ 20 cm, DBH < 1 cm	Annual

accessible and can be covered as clusters in a fortnightly schedule of fieldwork. While such work is highly laborious, the data are extremely valuable and long-term studies of phenology and canopy primary production are still very rare in the tropics. This will be carried out for two years (2023–2024), before a review is conducted on whether it should be continued. These surveys of seedlings, wildlife, and also measurement of seed rain, litter production, and environmental variables including soil and microclimate, which are recognised shortcomings of the ForestGEO network where most plots do not have such data (Davies et al., 2021), are a feature of the LTFEM study design. The LTFEM plot network may be expanded in the future to include other forest patches in other parks, such as Kent Ridge Park and Telok Blangah Hill Park where the *Adinandra* 'belukar' was studied by Sim et al. (1992), as well as Mount Faber Park, Coney Island Park, etc., which represent remaining inland forest types that are less diverse in terms of native species and more disturbed and isolated but may provide information on the regeneration dynamics of such forests in a densely urbanised landscape matrix.

As demonstrated through the much more geographically restricted set of Nee Soon plots, we envisage that the data from the LTFEM plot network will lead to the development of predictive capabilities that can identify bottlenecks of forest regeneration and possible threats to the persistence of Singapore's precious remaining primary forest species, and form a baseline for development, testing, and refinement of novel strategies to enhance forest ecological resilience. Given the resource-intensiveness of ground, in-person data collection, there is every intention to improve the efficiency of plot surveys including through the use of technology, e.g., through satellite- or drone-based imaging, LiDAR, ground-based sensors, automation and digitisation. Our vision is to encourage collaboration by researchers of Singapore's forests to use these plots for their studies so that layers of data can be built on the same localities to maximise potential synergies.

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