Introduction to the Southern Islands Biodiversity Survey, Singapore, 2020–2022

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ABSTRACT. We provide an introduction and background to a survey of terrestrial and intertidal flora and fauna on and around the southern islands of Singapore. Data from field surveys conducted at 17 islands and one patch reef, as well as from literature for various sites, were combined to prepare databases of species records. Sixteen papers published within the same volume then describe the results for various taxa and landscapes.

Keywords. Conservation, inventories, tropical islands, methodologies

Introduction

The main island or 'mainland' of Singapore (earlier known as Pulau Ujong, or Temasek) was just one of more than 80 islands governed collectively by Singapore when it first became independent in 1965 (NUS, 2002). Some of those islands have been merged through land reclamation, others now lie beneath the waves, and new islands have also been created. The majority of our remaining islands lie to the south of mainland Singapore, in the Singapore Strait, and have been known collectively and informally as "the southern islands". Although they share geographical, physical and biological similarities, one subset of these has been grouped together by the Urban Redevelopment Authority (URA) under the "Southern Islands" planning area, while others are subsumed under the "Western Islands" and "Bukit Merah" planning areas. However, for the purpose of the current publication, we take the term "Southern Islands" to refer to all islands and reefs in the Singapore Strait with the exception of Jurong Island, Pulau Damar Laut, Pulau Samulun, and Sultan Shoal. These four are excluded because they lie further west in waters with heavy industrial activity. Our geographic definition of the Southern Islands is illustrated further down in Figure 1, and the chapters in this current publication refer to surveys carried out in 2020–2022 at those islands labelled in red, as well as secondary data for the islands overall.

The Southern Islands' position to the south of mainland Singapore means that salinity is higher and the waters less turbid than at islands to the north, owing to the greater distance from terrestrial sources of sediment such as rivers and from urban runoff. As a result, the vast majority of Singapore's coral reefs were found here even prior to urbanisation, and this remains the case today. Extensive tracts of coastal forest, mangrove forest and seagrass meadow are also found on and around the islands, habitats that have become increasingly rare in recent decades (Turner & Yong, 1999; Tan et al., 2022).

Today, these islands serve a variety of uses, ranging from industry, military, municipal services, to research and recreation. Busy shipping lanes and anchorages crisscross this tiny archipelago, as one third of the world's container trade passes through the Straits of Singapore (Lee, 2022). Mooring can accommodate up to 800 vessels in the waters south of mainland Singapore, awaiting loading, unloading or trans-shipment. Singapore is the world's largest hub for trans-shipment of goods and handles the world's second largest bulk of container traffic (after Shanghai), by 2023 amounting to some 39 million TEU (twenty-foot container

equivalent units) per annum. The same processes of reclamation and erosion that have changed the face of Singapore's coastlines have also played out here. Yet despite all this activity, the Southern Islands (together with the natural coastlines of the East Johor Straits and West Johor Straits) form one of Singapore's three main centres for coastal and marine biodiversity. Collectively, the islands contain almost all of Singapore's remaining coral reefs, most of our mature coastal forests and seagrass meadows, substantial patches of pristine mangroves, and a full spectrum of other coastal habitats such as mudflats, sandflats, sandy beaches, and rocky shores. This makes them a priceless repository of Singapore's natural heritage and biodiversity; it is therefore essential to understand what is found on these islands if we are to conserve this for future generations.

Habitats of the Southern Islands

Although small, the Southern Islands contain a wide diversity of coastal and marine habitats which are home to diverse flora and fauna. On land above the high tide mark, there are coastal forests which are never immersed by the sea but harbour vegetation which can persist in saline, nutrient-poor soils. Further down the intertidal zone are mangroves, sandy beaches, rocky shores, seagrass meadows, mudflats, sandflats, seagrass meadows, and intertidal coral rubble. Many of the islands are fringed by extensive intertidal flats or patch reefs that host a mix of these habitats, which are fully or partially immersed during high tides and exposed during low tides. Species that inhabit these areas must be able to cope with harsh conditions, such as desiccation and high temperatures from the wind and sun when the tide is low, and sudden drops in salinity during heavy rainfall. At the seawards edge of the intertidal flats are subtidal coral reefs, which may have their reef crests exposed during extremely low spring tides. Beyond these lie the open sea and deep seabed.

Coastal forests

Coastal forests thrive above the high-tide line, comprising plants adapted to nutrient-poor, saline soils and the challenges posed by strong winds and storms. Flat, sandy areas often support faster-growing pioneer species, while steep, rocky regions tend to favor slow-growing specialists. Many of the plant species in these forests are unique to the coast and are threatened in Singapore by habitat loss. Their role in erosion and storm protection has not been studied as extensively as that of mangroves. These forests provide vital nesting sites for large, charismatic birds like herons and raptors, as well as habitat for forest-dwelling animals such as macaques and bats. Today, the Southern Islands are a refuge for this habitat and many threatened coastal plant species which are rare on mainland Singapore.

Mangroves

Mangrove forests are highly productive wetlands located along estuarine rivers and low-lying coasts. Growing within the upper intertidal zone, mangroves contribute to coastal protection by attenuating waves and shield seagrass meadows and coral reefs from siltation caused by land runoff. The complex habitat formed by their trunks, stilt roots and pneumatophores (breathing roots) is a nursery ground for many fish and crustacean species. This in turn supports a rich diversity of larger animals such as birds, snakes, otters and even crocodiles. Traditionally, mangroves provided essential resources like food (fish and shellfish), fuel (firewood), fibre and medicine (from medicinal plants) to coastal communities. In modern Singapore's context,

they are popular sites for research, education, recreation and eco-tourism, and also help support good marine water quality and recreational fisheries. While the mangroves of the Southern Islands are not the largest, they are species-rich and unique in their geomorphology. While mangroves on mainland Singapore and the northern islands of Ubin and Tekong are associated mainly with mudflats, those in the Southern Islands lack major river systems while forming dense stands together with seagrass meadows and coral reefs.

Rocky shores

Rocky shores are characterised by rocks, outcrops, and boulders covered in algae. These are inhabited by animals like molluscs, sea stars, and crabs that are adapted to dealing with direct sunlight and high temperatures, such as by hiding in crevices or retreating into watertight shells. The uneven and irregular shapes of the rocks create rugosity, offering nooks and crannies for shelter and helping to reduce wave energy. Broadly speaking, there are two types of rocky shore in Singapore: granite boulders in the north (such as at Pulau Ubin, Pulau Sekudu, and Changi), and sedimentary cliffs in the south, of which Labrador Nature Reserve is the last surviving example on the mainland. This makes the visibly stratified rocky shores and bare cliff faces of the Southern Islands especially precious as examples of Singapore's geological heritage.

Sandy beaches

These stretches of bare sand, extending from the high-tide mark to the low spring-tide mark, have low resident biodiversity. Nonetheless, they play a vital role as nesting grounds for endangered species like sea turtles and horseshoe crabs. The beaches of many of the Southern Islands are popular spots for recreational activities such as water sports, swimming, and picnics.

Mudflats

Exposed at low tide, mudflats are typically located near mangroves but in areas too deep for them to thrive. These habitats consist of anoxic fine sediments teeming with burrowing worms and bivalves, which in turn support migratory shorebirds that stop in Singapore to refuel. Mudflats are also home to various crustaceans and fish, including mudskippers, which are hunted by waterbirds like herons and egrets. While the Southern Islands lack large riverine systems delivering soft sediment, patches of mudflat are still found in association with mangroves and migratory shorebirds (e.g. whimbrels) have been sighted.

Sandflats

Only exposed at low tide, sandflats may appear lifeless but are home to animals like clams, crabs, sea stars, sand dollars, and snails that burrow beneath the surface. Shorebirds may frequent these areas to forage for food. Prior to land reclamation along the East Coast of mainland Singapore, extensive sandflats with areas of seagrass extended from Tanjong Rhu to Changi Point, providing rich fishing grounds. This habitat is now increasingly rare on the mainland, but can still be found on some of the Southern Islands.

Seagrass Meadows

Seagrasses are flowering plants that play crucial roles in the marine environment. They provide food for large herbivores such as dugongs and green sea turtles, while seagrass meadows serve as nurseries for juvenile crabs, shrimp, and fish. The structural complexity

of these meadows fosters rich biodiversity, supporting high populations of echinoderms, molluscs, and crustaceans; this makes them popular spots for intertidal walks. Seagrass meadows can also sequester significant amounts of carbon in their sediments and contribute to wave attenuation when they grow densely. The Southern Islands are host to some of the largest and most diverse seagrass meadows remaining in Singapore, and are critical for their long-term survival. These are also regularly visited by dugongs, as evidenced by frequent sightings of feeding trails.

Coral Reefs

The Southern Islands are home to almost all the natural coral reefs in Singapore which persist to the present-day. Despite intense urban development in our compact city-state, they continue to support a rich diversity of marine organisms. More than 250 species of hard coral, over 200 species of sponges, 120 species of reef fish and myriad other species of soft corals, nudibranchs, and other invertebrates have been recorded, some of which are still undocumented and possibly new to science. Charismatic megafauna such as the hawksbill and green sea turtles as well as black-tipped reef sharks are not uncommon. A coral reef can be subdivided into three parts: the reef flat, reef crest and reef slope. The reef flat is typically shallow and exposed during low tides; hence it comprises lower live coral cover than the other parts of the reef. However, the coral rubble (comprising the skeletons of dead coral) still serve as important shelter for a diverse number of species, and is often interspersed with seaweed and seagrass. The reef crest is typically submerged, with the uppermost parts exposed only during the lowest of spring tides; it is the richest and densest with marine life due to the availability of sunlight. As the reef slopes towards the seabed, the density of hard coral cover and other marine life declines and the community shifts to species adapted to lower light conditions. The seabed is typically sandy or silty; however, sea fans, sea whips, and colourful cave corals often grow where rocks occur. Coral reefs attenuate wave action, support Singapore's recreational fisheries, and are actively used for research, recreational diving, and intertidal walks.

Open sea and Seafloor

The most extensive but least studied marine habitats in Singapore, the open sea and seafloor are home to megafauna such as dolphins, game fish (e.g. giant trevally), and pelagic birds (e.g. terns and raptors). The ecology of many of these is poorly studied in Singapore. Anecdotes from recreational fishermen also indicate the presence of large elasmobranchs such as the honeycomb whipray and shovelnose ray on Singapore's seafloor, and have recently been verified by eDNA sampling (Ip et al., 2021). Results from the earlier Comprehensive Marine Biodiversity Survey (2010-2015) suggest that the seafloor is heterogeneous, hosting high densities of sea cucumbers, feather stars, basket stars, or barrel sponges in certain areas, and reaching to as deep as 200 m. More research to understand the ecosystems of the open sea and seafloor is needed.

Previous work

As early as the colonial period, collections of both terrestrial and marine flora and fauna were made in the Southern Islands and their associated reefs. The accounts below give an idea of the wealth of intertidal biodiversity that had long been recognised:

> *"At low water spring tides, the whole of these reefs are uncovered, so that by lying on the reef, one can look down into a depth of from 4 to 9 fathoms, like as a school boy does on a wall and looks at the objects below, which here are living corals of many and wondrous shapes, with tints so beautiful that nothing on earth can equal them. While the lovely coral fish, vying with their abodes in the liveliness of their colours, are to be seen peeping out of every crevice, which at full tide has but a few feet of water to cover it"* – Little (1848: 585), describing Pulau Blakang Mati (Sentosa).

> "[Cyrene] *Shoal… presents a brilliant appearance at low water, being covered with live corals and shells, many of the most brilliant colours. It is a favourite hunting ground for conchologists*." – Dennys (1894: 99), describing Terumbu Pandan (Cyrene Reef).

Since then, researchers have continued to study the biodiversity of the islands, with many scientific publications produced since the 19th century. From 2010 to 2015 the National Parks Board (NParks) and the National University of Singapore (NUS) co-organised a Comprehensive Marine Biodiversity Survey, when local and international experts sampled extensively the marine biodiversity around Singapore including the Southern Islands. The results were published as special supplements of the Raffles' Bulletin of Zoology (Tan & Goh, 2015; Tan & Goh, 2016) and produced more than 100 new species records for Singapore and more than 30 species new to science. Investigations into the terrestrial biodiversity of some of the islands have also been made, such as with Koh et al (2002), Chua (2011), Teo et al (2011), and Hung et al (2017a, 2017b, 2017c). Such efforts over many decades have built up a strong body of knowledge of the fauna and flora of the islands, but much remains to be done. While extensive records have been published involving the marine biodiversity of the islands, significantly less work has been done for their terrestrial biodiversity. There is also no aggregated database of species records across all the islands for the various taxonomic groups.

Current survey

In 2019, NParks decided to initiate a Southern Islands Biodiversity Survey (SIBS) as part of a continuing national effort to fill in gaps in knowledge of biodiversity. Preliminary field visits and preparatory planning began in October 2019, leading up to the official announcement of SIBS on 28 November 2019.

Objectives

The objectives of SIBS were:

a. To document the terrestrial flora, terrestrial fauna, and intertidal biodiversity of selected Southern Islands through field surveys;
b. To assemble a database of species records for individual islands based on literature reviews and the internal records of the National Parks Board (NParks) and the Sentosa Development Corporation (SDC); and
c. To briefly report on the cultural and geological heritage of the Southern Islands.

While the initial announcement also indicated that surveys would be done of shallow seafloor areas between 10m and 20m depth, these were subsequently cancelled as safe-distancing restrictions on fieldwork throughout the Covid-19 pandemic from April 2020 to August 2021 made them logistically impractical.

Duration
Most field surveys were carried out between October 2019 and Mar 2022; this was longer than the originally planned period of 2 years due to delays imposed by the Covid-19 pandemic.

Administration
A secretariat was formed within NParks under the supervision of Karenne P. P. Tun, comprising Y.H. Jonathan Tan, Bryan P.I. Leong, Lua Hock Keong, and Dillen Ng.

SIBS carried out three types of field surveys: terrestrial flora, terrestrial fauna, and intertidal. They were conducted concurrently, with one to ten team visits per island. Surveyors comprised NParks staff and volunteers, as well as members of partner nature groups. The team also conducted extensive reviews of published literature as well as internal NParks and Sentosa Development Corporation records to piece together a comprehensive database of species records for individual islands.

Geographical coverage
A summary of the physical characteristics of the Southern Islands is given in Table 1. Of these, a total of 18 sites were surveyed during SIBS (Figure 1), comprising 17 islands and one patch reef (Terumbu Pandan/Cyrene Reef). However, it should be noted that surveys of Pulau Semakau also included the associated patch reef Terumbu Semakau to its north, and that Pulau Berkas has more or less eroded into an intertidal patch reef. Of the unsurveyed islands, Pulau Bukom, Pulau Sebarok, and the merged island of Pulau Bukom Kechil, Pulau Busing, and Pulau Ular are highly urbanized and thus were not included in fieldwork. Pulau Anak Bukom was also not surveyed due to its tiny size and close proximity to Pulau Bukom. No opportunities to survey Pulau Sudong, Pulau Pawai and Pulau Senang occurred during the study period.

Each site, including those not covered by fieldwork during SIBS but with secondary data available, is assigned a location code within the survey database. For the purposes of the report, some sites may be subsumed under a larger umbrella. Pulau Hantu Besar and Pulau Hantu Kechil sit on a single intertidal platform and are reported as one island, Pulau Hantu. Terumbu Pempang includes all the Pempang reefs, such as Terumbu Pempang Laut, Terumbu Pempang Tengah and Terumbu Pempang Darat. Several database locations are subsumed under Sentosa, such as Mount Imbiah, Serapong (including Mount Serapong, Serapong reef, and Berhala Reping), the former Pulau Selugu, and Siloso (including Mount Siloso and Tanjong Rimau). For marine and terrestrial fauna, Big Sister's Island and Small Sister's Island were grouped as one site, but considered two separate sites for terrestrial flora. The same approach applies to Lazarus Island and Pulau Seringat, because the two original islands were merged by reclamation work but remain floristically distinct. Finally, depending on the data source, entries for the patch reefs adjacent to Pulau Semakau i.e. Terumbu Semakau, Terumbu Raya, Terumbu Bemban and Beting Bemban Besar, may be listed individually, clustered as one site (Semakau patch reefs), or grouped together with Pulau Semakau.

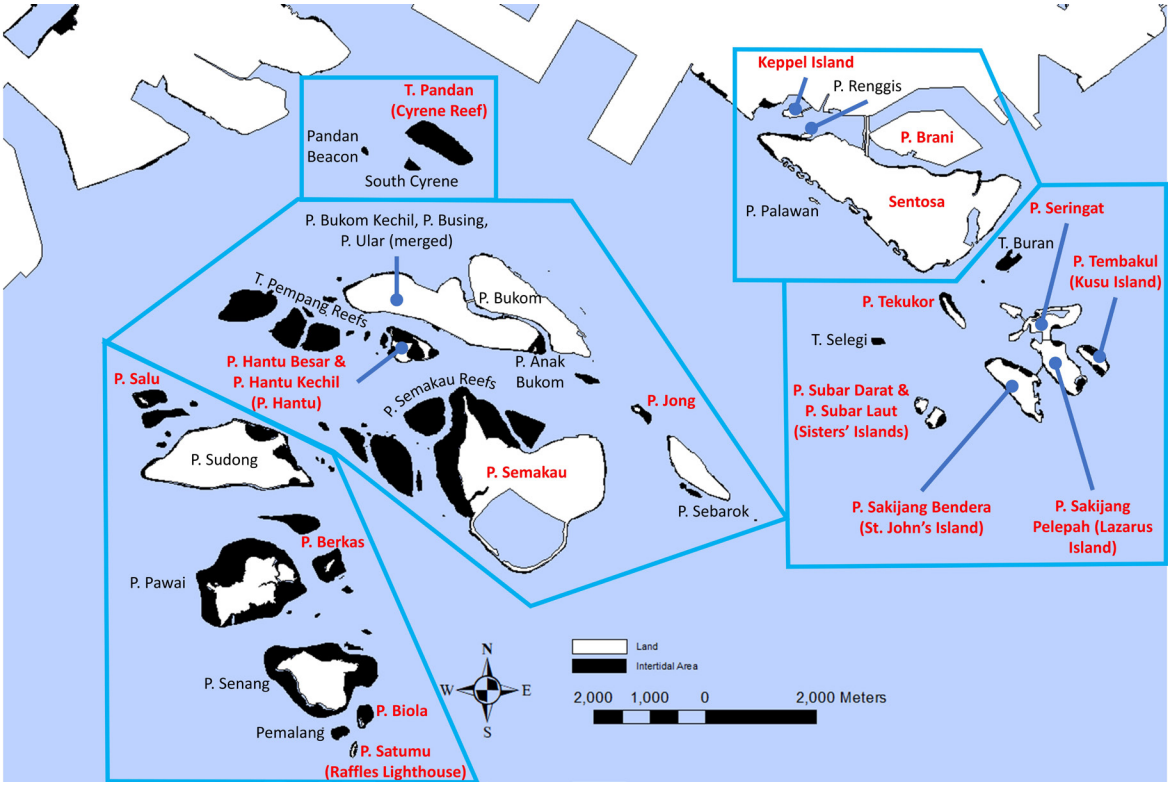

Figure 1. The Southern Islands and its associated reefs. P. = Pulau (island) and T. = Terumbu (patch reef). Red indicates that the site was surveyed during SIBS. For ease of reference, these can be further grouped into five geographical clusters, starting from the top right in a clockwise manner: Greater Southern Waterfront, St John's Cluster, Southern Islands Live Firing Area, Semakau Cluster, and the Cyrene Reefs.

Table 1. Physical characteristics (approximate) and total surveys conducted of the Southern Islands and reefs, grouped by geographical cluster. *Italics* indicate patch reefs associated with the island listed above them in **bold**.

Cluster	Island/Reef	Land area (ha)	Intertidal Area (ha)	Coastline Length (m)	Max. Elevation (m)	SIBS Surveys
Greater Southern Waterfront	**Pulau Brani**	124.6	0.8	5,068	42	1
	Pulau Keppel (Keppel Island)	5.4	0.3	1,031	19	2
	Pulau Palawan	0.6	0.8	386	4	-
	Pulau Renggis (Terumbu Renggis)	-	<0.1	-	-	-
	Sentosa (including Imbiah, Siloso, Selugu, Serapong)	480.5	45.6	15,536	87	18
St. John's Cluster	**Midway Reef**	-	0.3	-	-	-
	Pulau Sakijang Bendera (St John's Island)	43.6	16.6	4,879	35	9
	Pulau Sakijang Pelepah (Lazarus Island)	42	17.6	4,332	51	10

Table 1. Continuation.

Cluster	Island/Reef	Land area (ha)	Intertidal Area (ha)	Coastline Length (m)	Max. Elevation (m)	SIBS Surveys
	Pulau Seringat, (including Pulau Seringat Kechil, and Kias Island)	37.2	14.7	7,035	5	-
	Pulau Subar Darat (Small Sister's Island)	3.4	2.7	975	24	2
	Pulau Subar Laut (Big Sister's Island)	5.4	6	1,253	21	-
	Pulau Tekukor	6.5	9.4	1,477	26	7
	Pulau Tembakul (Kusu Island)	8.9	9.3	2,311	28	3
	Terumbu Buran	-	9.3	-	-	-
	Terumbu Selegi	-	2.9	-	-	-
Semakau Cluster	**Pulau Anak Bukom**	0.5	-	367	-	-
	Pulau Bukom	150.5	8.5	6,791	7	-
	Batu Kopi	-	<0.1	-		-
	First Bukom Beacon	-	<0.1	-		-
	Third and Fourth Bukom Beacons	-	0.2	-		-
	Terumbu Bukom	-	4.7	-		-
	Pulau Bukom Kechil, Pulau Busing and Pulau Ular	210.7	31.7	8,358	15	-
	Busing Beacon	-	0.6	-		-
	Terumbu Busing	-	2.0	-		-
	Pulau Sakeng and Pulau Semakau (Semakau Landfill)	329.1	160	15,899	9	7
	Beting Bemban Besar	-	56.4	-	-	-
	Terumbu Bemban	-	14.9	-	-	-
	Terumbu Buntal	-	0.1	-	-	
	Terumbu Menalung	-	1.9	-	-	-
	Terumbu Raya	-	37.5	-	-	-
	Terumbu Semakau	-	25.6	-	-	-
	Other unnamed reefs	-	4.5	-	-	-

Table 1. Continuation.

Cluster	Island/Reef	Land area (ha)	Intertidal Area (ha)	Coastline Length (m)	Max. Elevation (m)	SIBS Surveys
	Pulau Hantu (Pulau Hantu Besar & Pulau Hantu Kechil)	14.3	26.8	4,199	10	3
	Terumbu Hantu	-	2.8	-	-	-
	Other unnamed reef	-	0.1	-	-	-
	Pulau Jong	0.8	5.5	342	23	4
	Pulau Sebarok	47.7	6.5	3,364	10	-
	Monggok Sebarok	-	0.2	-	-	-
	Terumbu Jambi	-	3.4	-	-	-
	Terumbu Pempang Reefs					
	Beting Pempang		1.5	-	-	-
	Terumbu Pempang Darat	27.5	27.5	-	-	-
	Terumhu Pempang Kecil	-	1.0	-	-	-
	Terumbu Pempang Laut	44.6	44.6	-	-	-
	Terumbu Pempang Luar	-	1.9	-	-	-
	Terumbu Pempang Tengah	28.5	28.5	-	-	-
	Other unnamed reef	-	<0.1	-	-	-
Southern Islands Live Firing Area	**Pemalang**	-	5.9	-	-	-
	Other unnamed reef	-	0.1	-	-	
	Pulau Berkas	-	24.3	-	-	1
	Terumbu Berkas Besar	-	20.6	-	-	-
	Terumbu Berkas Kecil	-	1.8	-	-	-
	Other unnamed reef	-	0.2	-	-	-
	Pulau Biola	0.5	9.7	393	21	5
	Pulau Pawai	86.4	149.2	7,817	44	-
	Other unnamed reefs	-	0.9	-	-	-
	Pulau Salu	1.0	14.6	489	12	4
	Terumbu Salu	-	15.4	-	-	-
	Terumbu Salu Kecil	-	1.3	-	-	-

Table 1. Continuation.

Cluster	Island/Reef	Land area (ha)	Intertidal Area (ha)	Coastline Length (m)	Max. Elevation (m)	SIBS Surveys
	Pulau Satumu Raffles Lighthouse)	1.2	1.9	745	7	1
	Pulau Senang	83.1	104.3	4,865	35	-
	Other unnamed reefs	-	3.6	-	-	-
	Pulau Sudong	215.8	58.2	8,033	14	-
	Terumbu Palat reefs	-	1.8	-	-	-
	Other unnamed reefs	-	2.4	-	-	
Cyrene Reefs	**Pandan Beacon**	-	1.4	-	-	-
	South Cyrene Beacon	-	4.1	-	-	-
	Terumhu Pandan (Cyrene Reef)	-	44.7	-	-	2
TOTAL						82

Databases

Separate databases were created in Microsoft Excel for flora and fauna species. This was to deconflict between scientific names of plants and animals. For example, *Ficus variegata* refers to both a species of fig snail and the common red stem fig. The fauna database contained Animalia and Protista, while the flora database contained Plantae, Fungi, Chromista and Bacteria (Cyanobacteria).

A comprehensive literature review of over 190 sources, dating back to 1978, was used to populate the database initially, followed by results from the current field surveys. Compilation of the records was performed by the authors of the various papers in this volume, taxon specialists listed in Table 2, and by the staff members of NParks, interns and volunteers listed in the Acknowledgements. The literature included peer reviewed papers, online sources such as Wild Singapore (Tan, 2008) and Lee Kong Chian Natural History Museum's Singapore Biodiversity Records Archives (NUS, 2021), as well as unpublished records from various stakeholders and researchers investigating the islands over the years. Records from large survey projects and expeditions such as the Comprehensive Marine Biodiversity Survey (CMBS), Nature Areas Survey Team reports (2005–2007) and Rapid Biodiversity Assessment surveys conducted by staff of the National Biodiversity Centre were also compiled and added to the database.

The species checklists for each taxon are laid out in the appendices of each paper, and the year of the most recent published record or NParks internal record is noted for each species, morphospecies or other lower taxonomic classification within the tables. These

years are not necessarily the year of the species observation in question, but the year of publication or internal record, and, as such, may be indicative of an observation made prior to the indicated year. For instance, a 2020 publication could be presenting a 1980 recorded observation of a species at the site.

Field surveys

The database was supplemented with groundwork surveys including intertidal surveys, flora and fauna transect surveys and camera trapping, conducted up to March 2022. These surveys varied in number per site due to the differing natures of the islands being surveyed. Factors included accessibility, size, number of biomes present, availability of previous data and governmental restrictions.

Terrestrial flora survey

Surveys of the terrestrial flora were conducted from October 2019 to March 2022 by NParks staff, with the assistance of SDC staff for Sentosa. Transect surveys were conducted to investigate the various habitats present on each island and cover most of its area (Figure 2A).

The survey team consisted of five to eight individuals who took approximately three hours per visit. During the surveys, leaf specimens of each vascular plant species were collected and bagged, using a pole pruner to reach higher branches (Figure 2C). These were labelled and passed to the Singapore Botanic Gardens Herbarium (SING) to confirm their identity. All the entries were then collated by the National Biodiversity Centre into the Southern Island Flora database.

Bryophytes and fungi were collected opportunistically during flora surveys (Figure 2B, 2D). Photographs were taken before collecting the specimen and the substrate on which it was growing was either collected or noted down when a collection was deemed impractical. Both photographs and specimens were then sent to the respective taxon expert at SING to be identified.

Terrestrial fauna survey

A total of 33 fauna surveys were organised from February 2020 to March 2022, a number conducted in conjunction with flora surveys. Surveyors included NParks staff, SDC staff, as well as volunteers from partner organisations such as the Herpetological Society of Singapore and Nature Society Singapore. Fauna surveys were done through a variety of techniques depending on the taxonomic groups, and further details are given in taxon-specific papers in this volume. Most were visual surveys along transects during the day. Other survey techniques included insect nets and malaise traps for the insect taxa, leaf litter surveys for herpetofauna and nocturnal surveys for birds and mammals. Camera traps were also used on certain islands, the cameras installed approximately 30 cm above ground and maintained over a period of 6.5 months. The species recorded by all these methods were added to the fauna database.

Figure 2. (**A**) Sketch of the size flora transect routes taken to survey Lazarus Island, each coloured line representing a separate survey. (**B**) Efforts were taken to collect fruiting bodies of fungi together with its substrate and mycelium. (**C**) A pole pruner was used to obtain leaf specimens from high or difficult to reach areas. (**D**) Bryophyte specimens, like other plants, were bagged and photographed before being sent to SING for identification

Intertidal survey

Substantial areas of intertidal habitats including seagrass patches, rocky and sandy shores and coral reefs were surveyed between August 2020 and March 2022. The surveys were conducted at low tide on days when timing was appropriate, typically in the early morning (06:00–10:00) or in the evening (16:00–20:00). A reconnaissance trip was organised for each site to identify suitable areas for laying out transects that would encompass a wide diversity of intertidal habitat types and maximise species encounters, and GPS coordinates were recorded. Each survey involved a team of approximately 10-20 people (this varied due to Covid-19 restrictions as well as the accessibility of the site) comprising NParks staff/interns, NParks volunteers, and members of the Wild Singapore survey team.

During each survey, a 30m line perpendicular to the shoreline was laid across the intertidal zone based on the previously recorded GPS coordinates. Three sets of 25 m line transects were then identified parallel to the shore, with one set each within the zones 0–10m, 10–20m and 20–30m from the shoreline. This was to ensure sampling covered the upper, middle, and lower shore, with at least 5m between each set of transects. Each transect set/shore level was then surveyed by a team of 3-5 surveyors, and for each transect five quadrats (50cm by 50cm) were placed along either side of the transect tape at intervals determined via a random number generator (Figure 3A). Quadrats were photographed for record keeping (Figure 3C), and seagrass, seaweed and living intertidal species in the quadrat were preliminarily identified to the lowest possible taxonomic level and photographed for later confirmation. Morphospecies spotted outside the quadrats were also opportunistically recorded and photographed for later identification.

One more team of 5-10 surveyors would separately patrol the intertidal zone beyond the vicinity of the transects Another team of 5-10 surveyors separately patrolled the intertidal zone beyond the vicinity of the transects to take photographs of as many species as possible for later identification (Figure 3D). Suitable macroalgae specimens were collected and taken to SING for pressing, identification, and vouchering (Figure 3B).

Data Scrubbing

As the data was compiled several resources were used to standardise taxonomy. The World Register of Marine Species (WoRMS, 2024) was used for marine species, Plants of the World Online (POWO, 2024) for vascular plants and Integrated Taxonomic Information System (ITIS, 2017) for the remaining species, further supplemented by Biodiversity of Singapore (NUS, 2021) and National Center for Biotechnology Information (NCBI, 2024). We have also attempted to standardise with the taxonomy used in the 3rd edition of the Singapore Red Data Book (Davison et al., 2024). If conflicting identifications arose, expert opinion was sought and agreed names standardised throughout the database. Global status of the species was taken from the IUCN Red List (IUCN, 2023). Local conservation status of a species was taken from Davison et al. (2024). Sources such as Biodiversity of Singapore (LKCNHM, 2021), Wild Singapore (Tan, 2008), FishBase (2024) and the Checklist of the Flora of Singapore (Lindsay et al., 2022) were used to determine the residency status if there was uncertainty. Entries not identified to species level were not assigned a resident status, local status, or global status. Entries were also categorised into several functional groups such as seagrasses, macroalgae and epiphytes for flora, and marine worms, soft corals, and fish for fauna.

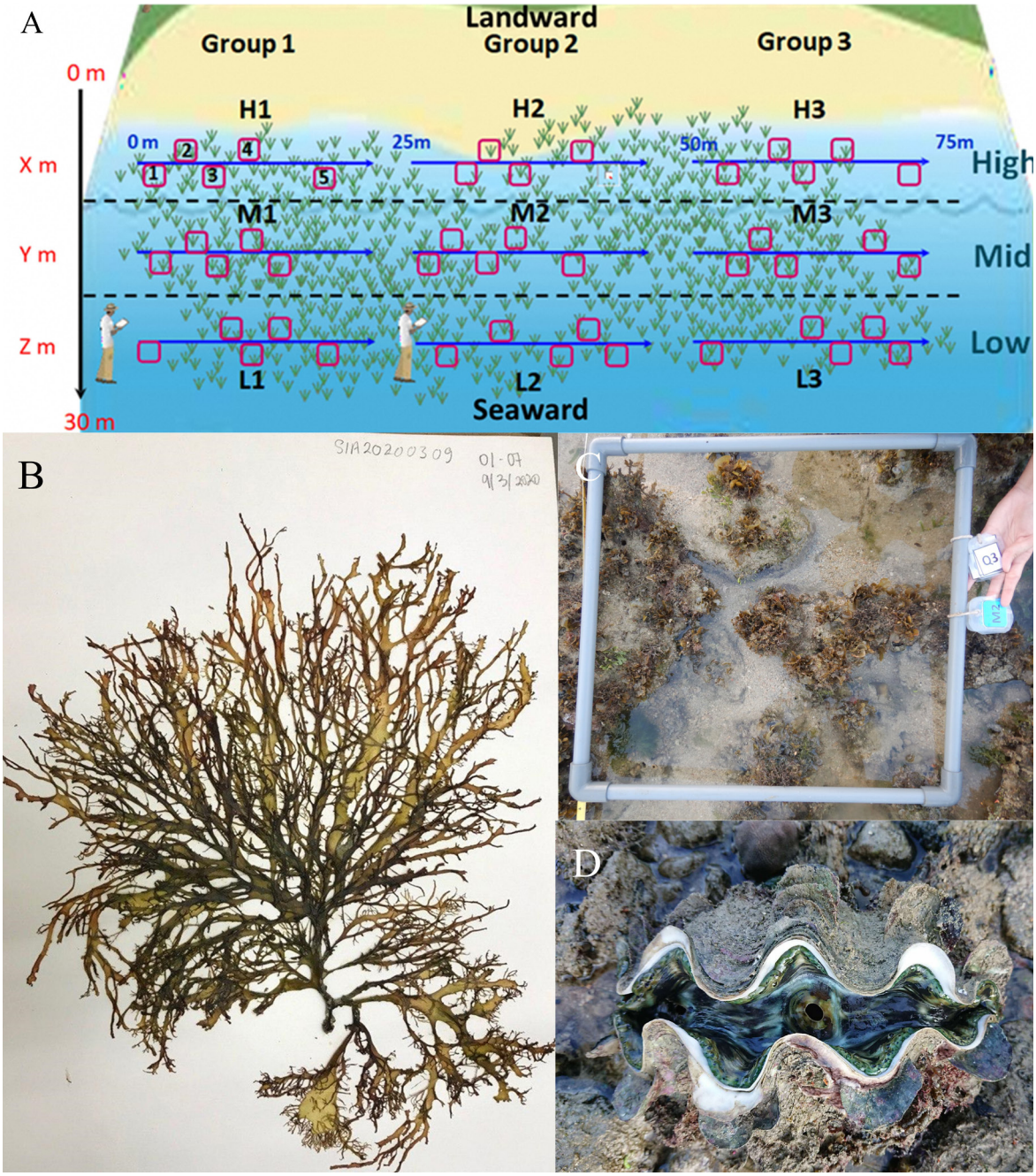

Figure 3. (**A**) Visual representation of a transect survey layout. Coordinates at which the transects (X,Y,Z) and quadrats (1 to 5) were to be placed were randomised. (**B**) A pressed red seaweed specimen of the genus Halymenia, collected from Terumbu Semakau and curated at SING. (**C**) A picture of a quadrat taken at the start with its corresponding transect and quadrat identification (in this case M2 Q3). (**D**) Organisms with sparse distribution and hence unlikely to occur within small quadrats, were often spotted and recorded by the BioBlitz team. One example is the fluted giant clam Tridacna squamosa.

Results

The Southern Islands Biodiversity Survey resulted in 14 taxon-based papers including five on flora (vascular plants, mangroves, seagrasses, bryophytes and fungi) and ten on fauna (mammals, birds, herpetofauna, lepidopterans, dragonflies, insects, sponges, molluscs, echinoderms and marine worms). Quantitative data that was collected during intertidal transect surveys is not reported here.

Groups not covered by papers included an array of terrestrial arthropods such as spiders, dipterans, hymenopterans, ants and termites, as well as the soil fauna. Some of these groups would have required specialized collecting methods, or nocturnal surveys, or pose problems in identification and taxonomy that are beyond current capacity to handle. As the emphasis of this project was on the terrestrial and intertidal biodiversity of the islands, some major marine groups that would require substantial subtidal surveys to properly cover (such as cnidarians, marine arthropods, macroalgae, and fish) also do not have chapters on them; however, checklists of their distribution have been compiled in the appendix for reference. The full database that SIBS has compiled is available at https://go.gov.sg/sibs

The flora database included records of more than 1,500 plant, fungi, and macroalgae taxa. More than 9,000 specific locality records were included in the database, an average of about 6 records per taxa but this included duplicates. Coverage of the vascular flora was thorough, but coverage of the other groups such as macroalgae, and especially bryophytes and fungi, would be less complete due to the relative difficulty of identification and collection.

The fauna database included approximately 5,000 taxa. More than 20,000 specific locality records were included in the database, an average of about 4 records per taxa. The naming of species was straightforward for well-known taxa such as mammals and birds, but some morphospecies for poorly known taxa could not be named even to genus or family level. For example, there were records of 111 morphospecies of Platyhelminthes but only 36 of them were named to species level. There were records of 179 morphospecies of Porifera, 110 of them named to species level. The morphospecies to which a species-level name could not be attributed were given an informal designation, for example among Platyhelminthes, Order Polycladida, Suborder Acotylea were species “sp 1” to “sp 26”; some of the informal designations had already been devised during previous work by specialists in published work, they were therefore unique to a recognized taxon or morphospecies already encountered elsewhere. Such names can be linked to museum specimens, SIBS photographs or other information via the database. The checklists compiled for the taxon-based papers and appendices are primariy focussed on species or morphospecies-level records. However, the full database also contains numerous taxa records identified only to higher levels, and it is recommended to refer to that for a fuller picture of the diversity recorded. For some animal groups (e.g., birds) coverage was incomplete because the timing of surveys did not include all seasonal migrants. For others (e.g., marine bony fish) coverage may have been comprehensive in terms of total species listed, because of the geographical spread of surveys and the quantity of literature records, but coverage island by island was not comprehensive because of limited time spent in the vicinity of any given island.

In addition to the 14 taxon-based papers, there were additional contributions on geology and the history, heritage and land use of the various islands. All are included in the current volume.

LIMITATIONS

One critical limitation to note is that the amount of survey effort per island for the respective surveys was highly variable. Some islands were surveyed less due to their inaccessibility, e.g. lacking jetties for boats to dock and reachable only by amphibious landing with smaller boats. The Covid-19 pandemic also overlapped with the survey period from Apr 2020 onwards. Safe-distancing rules meant that many survey trips had to be postponed and/or reduced in the number of surveyors allowed, and the final number of trips was not as many

as had been hoped for. The involvement of NParks staff, volunteers, and partners such as academics and nature groups all had to be scaled-back due to the public health considerations imposed by the pandemic. This also meant that certain taxonomic groups did not receive as much attention, with relatively limited data collected. We have tried to supplement this by conducting extensive review of internal NParks records as well as published literature such as books and journal papers, but we acknowledge that there are likely many other sources of information (e.g. museum records, grey literature, and unpublished data from non-government organisations or universities) that we have not been able to include due to time and resource constraints. Nonetheless, we are confident that the work presented here represents one of the the largest-scale attempts to-date to document both the terrestrial and marine biodiversity of Singapore's Southern Islands.

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