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Blue carbon science, management and policy across a tropical urban landscape

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HIGHLIGHTS

- There is large but under-recognised potential for blue carbon in urban landscapes.
- Singapore is used as a case study for urban blue carbon science and policy.
- Singapore's blue carbon ecosystems store 577,227 tonnes of carbon.
- Blue carbon is increasingly incorporated into urban planning and policy.

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ABSTRACT

The ability of vegetated coastal ecosystems to sequester high rates of "blue" carbon over millennial time scales has attracted the interest of national and international policy makers as a tool for climate change mitigation. Whereas focus on blue carbon conservation has been mostly on threatened rural seascapes, there is scope to consider blue carbon dynamics along highly fragmented and developed urban coastlines. The tropical city state of Singapore is used as a case study of urban blue carbon knowledge generation, how blue carbon changes over time with urban development, and how such knowledge can be integrated into urban planning alongside municipal and national climate change obligations. A systematic review of blue carbon studies in Singapore was used to support a qualitative review of Singapore's blue carbon ecosystems, carbon budget, changes through time and urban planning and policy. Habitat loss across all blue carbon ecosystems is coarsely estimated to have resulted in the release of ~12.6 million tonnes of carbon dioxide since the beginning of the 20th century. However, Singapore's remaining blue carbon ecosystems still store an estimated 568,971 – 577,227 tonnes of carbon (equivalent to 2.1 million tonnes of carbon dioxide) nationally, with a small proportion of initial loss offset by habitat restoration. Carbon is now a key topic on the urban development and planning agenda, as well as nationally through Singapore's contributions to the Paris Agreement. The experiences of Singapore show that

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coastal ecosystems and their blue carbon stocks can be successfully managed along an urban coastline, and can help inform blue carbon science and management along other rapidly urbanizing coastlines throughout the tropics.

1. Introduction

Coastal urbanization has exerted a strong influence over a substantial proportion of the world's coastlines, with the global footprint of coastal and marine infrastructure estimated to be at least 32,000 km^2 (Bugnot et al., 2020). Human population growth in the coastal zone and concomitant coastal urbanization has long been associated with rapid habitat loss and environmental degradation along both temperate (Lotze et al., 2006) and tropical coastlines (e.g., Lee et al., 2006; Lai et al., 2015). Coastal urbanization is expected to further increase in the future, as population growth continues to occur disproportionately in the tropical coastal zone (Neumann et al., 2015). As such, we expect tropical coastal ecosystems to continue to experience habitat loss, degradation and pollution if urbanization is not accompanied by sound coastal management and habitat restoration.

Blue carbon has been posited as a potential tool to conserve and restore threatened coastal vegetated ecosystems. Blue carbon currently refers to coastal habitats such as mangroves, seagrasses and tidal marshes that are able to sequester and store disproportionate densities of carbon compared to terrestrial ecosystems over timescales that are relevant to climate change mitigation (Lovelock & Duarte, 2019). Blue carbon ecosystems globally store approximately 33 billion tonnes of carbon, and their large-scale conservation could stop the release of as much as 466 Tg of CO_2 per year (Macreadie et al., 2021).

Much focus on blue carbon has been its role in mitigating or offsetting greenhouse gas emissions at global and national scales (e.g., Herr & Landis, 2016), as this is the scale relevant to international climate change policies, such as Nationally Determined Contributions that are regularly submitted under the Paris Agreement. To complement national scale efforts, there is also increasing interest in blue carbon accounting at sub-national and municipal scales (Kumagai et al., 2020; Wedding et al., 2021), though urban coastal habitats are rarely discussed in the blue carbon context compared to larger contiguous patches of more natural habitat. This is a missed opportunity because cities contribute to greenhouse gas emissions, and are important to global climate change mitigation efforts (Shan et al., 2018; Mi et al., 2019), with several city networks pushing ambitious targets for climate change mitigation. The supply of blue carbon habitats along urban coastlines is also potentially large, with >5000 coastal urban areas across the tropics and sub-tropics containing habitats such as mangroves and seagrasses (Mazor et al., 2021). Studies show that urban reforestation efforts for terrestrial carbon have huge potential (Teo et al., 2021) and blue carbon ecosystems are likely to also have a large potential in urban landscapes (Everard et al., 2014). The high carbon densities of blue carbon ecosystems compared to terrestrial ecosystems mean that even patchy and fragmented habitats along urban coastlines have the potential to store substantial volumes of carbon relative to their small total area.

We investigate the importance and potential contribution of blue carbon science and policy to urban coastal landscape planning. We use the example of Singapore, a heavily urbanized tropical island nation with an extensive coastline. Firstly, we describe the distribution of blue carbon ecosystems in Singapore and the science base for blue carbon along an urban coastline. Secondly, we show how blue carbon stocks and fluxes have changed with historical and future land use changes, including the potential for blue carbon restoration. Finally, we highlight the management, land use decision making and policy opportunities for the incorporation of blue carbon into urban coastal management.

Singapore is an important case study because it has high potential for nature-based climate solutions such as blue carbon, being identified as one of the top urban areas globally for tropical coastal habitat conservation potential (Mazor et al., 2021). We focus primarily on mangroves and seagrasses, as these ecosystems are the only two found in Singapore that match current criteria for inclusion as a blue carbon ecosystem (using the framework proposed by Lovelock & Duarte, 2019). However, where appropriate, we also discuss macroalgae and tidal flats. The evidence for macroalgae as a blue carbon ecosystem is currently mixed, in part because the permanence of sequestered carbon cannot be guaranteed, and several governance challenges exist (Ricart et al., 2022). However, sequestered carbon may be stored over long timescales in some situations, and macroalgae are an important carbon donor to other coastal vegetated ecosystems in Singapore (Saavedra-Hortua et al., 2020) and elsewhere (Ricart et al., 2016). Similarly, tidal flats do not satisfy current definitions of blue carbon, but are discussed here where appropriate because they can be ephemerally vegetated with seagrass, can store carbon in their sediments at densities equivalent to neighbouring seagrass meadows in Singapore (Phang et al., 2015), and have been shown to sequester substantial amounts of carbon (Lee et al., 2021a).

2. Methods

2.1. Screening of relevant literature

To support this Review and ensure that all blue carbon knowledge relevant to Singapore was captured, we conducted a systematic literature review following the procedures recommended in the PRISMA statement (Moher et al., 2009). A screening of primary literature was performed using the Web of Science database (WoS; on 1st August 2022; coverage 1970 - to date), while grey literature such as reports and student theses were captured using the National University of Singapore (NUS) ScholarBank (on 25th May 2021; coverage - to date).

Since blue carbon is a recently emerging topic, the term 'blue carbon' was not used specifically in the search string. Instead terms associated with blue carbon dynamics were used to capture literature that predates the term 'blue carbon'. The following search phrase was used for WoS (across all fields): ("carbon" OR "stock" OR "flux*" OR "biofilm" OR "productivity" OR "emission" OR "sequestration" OR "primary product*" OR "mineralization" OR "sedimentation" OR "export" OR "respiration" OR "decomposition") AND ("mangrove*" OR "seagrass*" OR "macroalgae" OR "marine" OR "coast*" OR "soil" OR "tidal" OR "mud*" OR "*Rhizophora*" OR "*Avicennia*" OR "*Sonneratia*" OR "*Bruguiera*" OR "*Cymodocea*" OR "*Halophila*" OR "*Sargassum*" OR "*Ulva*") AND ("Singapore").

2.2. Data compilation

The WoS search returned 2272 results and the two ScholarBank searches returned 138 and 218 results. All abstracts were screened using the following criteria: (1) were original primary research conducted in Singapore, and (2) were primarily focused on the blue carbon, stocks, fluxes or productivity of a marine ecosystem. Literature was excluded if it was a duplicate record, if it focused on non-target ecosystems such as coral reefs or phytoplankton communities, if it was not from Singapore, or if it was a non-data article (such as a review). The final screened dataset consists of 23 original research papers and theses published between 1982 and 2022. The full articles were then extracted and separated into different categories (ecosystem type, aspect of blue carbon, key finding, sites) based on the information contained in them (Figure S1, Table S1).

3. Status and distribution of Singapore's blue carbon ecosystems

3.1. Mangroves

Thirteen percent of Singapore's original land area was once covered by mangrove forest (Corlett, 1992). This estimated 75 km^2 of mangroves in the 1800s had declined to 63.4 km^2 by 1953 (Hilton & Manning, 1995) due to aquaculture, small coastal developments and some minor land reclamations along the Singapore River. Mangrove loss accelerated rapidly between the 1960s and 1990s, primarily due to land reclamation and the conversion of mangrove-fringed estuaries into freshwater reservoirs.

In total ~95 % of Singapore's original mangrove forests have been lost, with only 8.1 km^2 of mangrove forest remaining, mostly on the north coast of the main island of Singapore, and the offshore islands of Pulau Ubin and Pulau Tekong (Gaw et al., 2019; Fig. 1). Though sparse in size, these mangrove forest patches contain 35 "true" mangrove vegetation species, roughly half of the world's mangrove species diversity (Yang et al., 2013).

3.2. Seagrasses

While records are insufficient to accurately estimate Singapore's historical seagrass extent, herbarium records show that they were present in at least 32 separate locations around Singapore. Substantial seagrass loss has occurred due to extensive coastal development and land reclamation on shallow sloping intertidal surfaces where seagrasses can be found, alongside chronic stresses such as sedimentation due to dredging activities (Yaakub et al., 2014).

Today, seagrasses cover approximately 2.2 km^2 (0.41 km^2 as seagrass meadows, 1.89 km^2 as mixed seagrass and algal cover), found along the coast of both the main island of Singapore and its offshore islands (Lai et al., 2022; Fig. 1). The three largest seagrass meadows remaining – Cyrene Reef, Pulau Semakau and Chek Jawa – collectively account for ~17 % of the total seagrass area in Singapore (Yaakub et al., 2013). Remaining seagrass meadows are distributed across estuarine, coastal and reef-associated settings. Twelve species of seagrasses have been recorded, with *Halophila beccarii and H. spinulosa* found only in Singapore's turbid northern shores, and *Cymodocea serrulata* restricted to the southern offshore islands (Yaakub et al., 2013). The relative distribution of seagrass species and areal cover also varies temporally, with substantial inter- and intra-annual variation (Bramante et al., 2018).

3.3. Other coastal ecosystems

Tidal flats were estimated to cover 33 km^2 in 1922 (Hilton & Manning, 1995), but have reduced to approximately 5 km^2 by the early 2000s (Lai et al., 2015). Large areas of tidal flats along Singapore's southern coast were among the earliest sites to be reclaimed for housing and port development. Tidal flat extent is expected to decline further in the future with planned reclamation works in northeast Singapore. Singapore's remaining tidal flats (Fig. 1) are important areas for benthic biodiversity (Tan et al., 2015) including large populations of horseshoe crabs (Cartwright-Taylor et al., 2011), and are an important feeding area for migratory birds travelling on the East Asian-Australasian Flyway (Lim & Posa, 2014).

Little is known about the historical distribution of macroalgae in Singapore, with previous efforts focusing instead on documenting

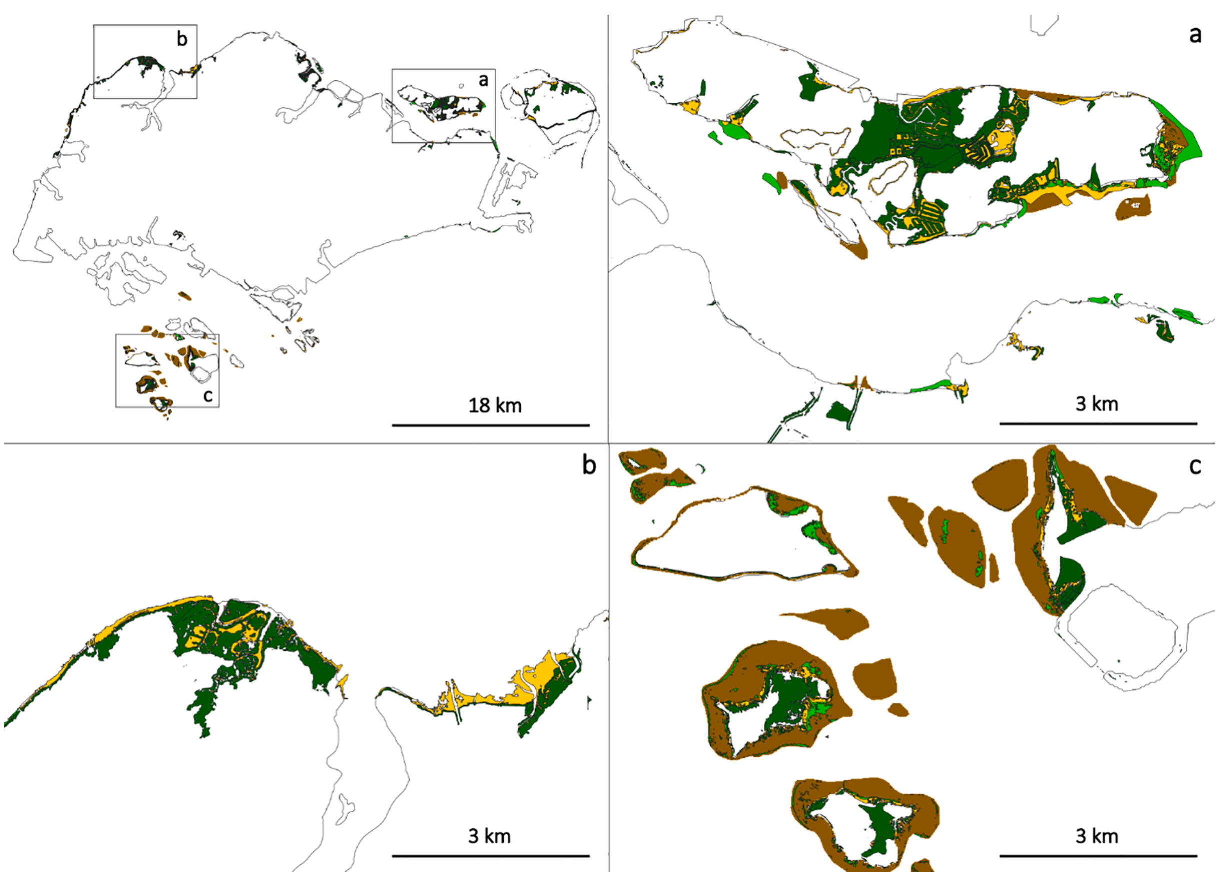

Fig. 1. The distribution of major blue carbon habitats in Singapore (a), and their distribution in Pulau Ubin (a), Sungei Buloh Nature Park Network (b) and the Southern Islands (c). Different colours indicate mangroves (dark green), seagrasses (light green), mudflats (light brown) and maximum macroalgal extent (dark brown). Data provided by the National Parks Board and Kwan et al. (2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

species diversity (Wee, 1978, 1994; Kwan et al., 2021). However, it is expected that macroalgal distribution has reduced substantially due to land reclamation, and reduced depth range due to increased water turbidity in the case of reef-associated macroalgae (Yip et al., 2018). Current macroalgal extent has been mapped at 5.85 km^2 (Kwan et al., 2022; Fig. 1), comprising 286 species (Phang et al., 2016). 12.5 % of this area is dominated by *Ulva,* mostly in the north of Singapore at Pulau Ubin, Pasir Ris and Changi, while *Sargassum* is abundant across 87.5 % of Singapore's national macroalgal extent, mostly in the offshore southern islands (Kwan et al., 2022). Depending on species growth habit, macroalgae can be found on artificial structures, the intertidal zone, reef flat, down to the upper reef slope (Lee et al., 2009; Low et al., 2019). Both *Ulva* and *Sargassum* exhibit distinct temporal and spatial variation, and may be influenced by anthropogenic activities that increase macroalgal biomass; for example, increased nutrient availability from fish farms may encourage macroalgal growth, but may also indicate eutrophication (Teichberg et al., 2010).

4. Urban blue carbon science in Singapore

The blue carbon budget (Fig. 2) is dynamic and contains a number of carbon pools and fluxes that need to be quantified. We present known information on Singapore's blue carbon stocks (*Section 4.1*), ecosystem productivity (*Section 4.2*), gaseous emissions (*Section 4.3*), dissolved fluxes (*Section 4.4*), and decomposition (*Section 4.5*), as well as gaps in research to be addressed in order to improve our understanding of the overall blue carbon budget for Singapore. When quantifying aspects of the blue carbon budget, there are some additional considerations to be quantified that are specifically relevant to urbanised coastlines, particularly the influence of patch size (with urban coastal ecosystems often more fragmented), anthropogenic disturbance gradients, adjacent ecosystems, and geomorphic setting.

4.1. Blue carbon stocks

Blue carbon represents the net accumulation of carbon inputs from biomass and sediment accumulation, minus outputs such as gaseous emissions, dissolved organic carbon export, and loss of particulate matter. Carbon stocks are often split into various pools; biomass, necromass, and sediment carbon, and these pools have been measured for mangroves, seagrasses, and tidal flats at multiple spatial scales, from the local site to the (urban) landscape scale.

Local-scale comparisons across mangrove and seagrass habitats highlighted the wide variation in carbon stocks within and between blue carbon ecosystems (Table 1). Comparatively, mangroves stored substantially greater amounts of carbon per unit area in their living biomass (36.57 Mg C/ha to 226.90 Mg C/ha; Phang et al., 2015; Friess et al., 2016) and in the soil (mean: 307.4 Mg C/ha to a depth of 1 m; Friess et al., 2016), compared to seagrass biomass (mean: 0.52 Mg C/ha; Alemu et al., 2022; Phang et al., 2015) and soil (mean: 155 Mg C/ha to a depth of 1 m; Phang et al., 2015; Alemu et al., 2022) stocks. Carbon stocks for tidal flats ranged between 95.13 and 143 Mg C/ha (Phang et al., 2015; Alemu et al., 2022).

Within ecosystems, variability in carbon stocks also reflects the influence of geomorphic setting, landscape configuration and urbanisation impacts on the coastal landscape (Rovai et al., 2018; Gorham et al., 2021). For instance, seagrass habitats associated with other coastal ecosystems such as mangroves and coral reefs seem to trap and accumulate more carbon than meadows located in naturally depositional and deltaic environments (Alemu et al., 2022). Likewise, less disturbed and contiguous mangroves accumulate more carbon compared to disturbed and restored mangroves, although this may improve with time (Friess et al., 2016).

At the landscape scale, blue carbon assessments in Singapore have only been conducted for mangrove habitats, where carbon storage is estimated to be 450,572 Mg C (Friess et al., 2016). For other blue carbon ecosystems, landscape scale carbon estimates are extrapolated per hectare to the areal extent of the habitat, from the best available site based carbon estimates (Table 1). Consequently, seagrass habitats are expected to store between 31,685 – 39,491 Mg C, tidal flats 86,514 Mg C and macroalgal beds between 200 and 650 Mg C across Singapore's coastal landscape. With these combined approaches, we estimate that Singapore's coastal ecosystems store between 568,971 Mg C and 577,227 Mg C, equivalent to 2,088,124 to 2,118,423 tonnes of CO_2.

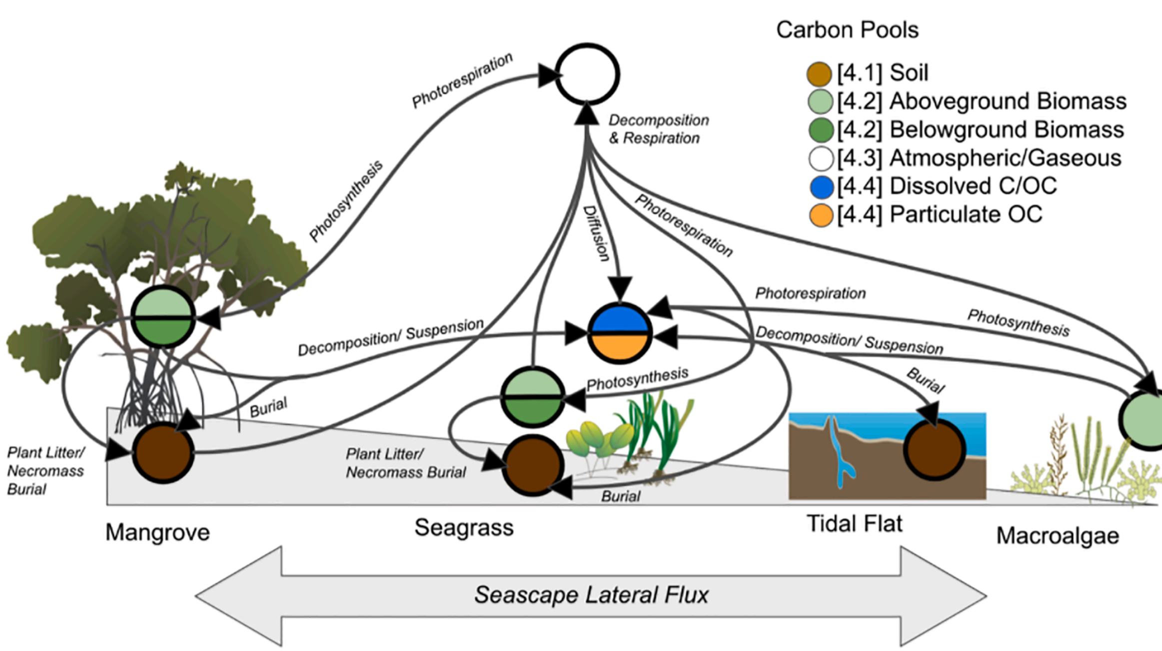

Fig. 2. A conceptual diagram of the blue carbon pools, fluxes, and processes in Singapore's seascape (mangroves, seagrasses, tidal flats, macroalgae). Coloured circles represent carbon pools, labelled lines indicate fluxes and underlying processes. Seascape lateral flux arrow is an overarching indicator of lateral movement of carbon between all systems. Bracketed numbers indicate the associated section in this text. Images for Fig. 2 courtesy of IAN Image Library. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Summary of ecosystem blue carbon stocks and selected blue carbon fluxes in Singapore's urban environment. All total carbon stock numbers rounded.

BLUE CARBON STOCKS (national extent)					**SELECTED BLUE CARBON FLUXES (per unit area)**	
Ecosystem	**Average carbon stock (Mg C/ha)**	**Estimated areal extent (ha)**	**Estimated total carbon stock across Singapore (Mg C)**	**Method of calculation**	**CO_2 emissions (mmol CO_2 m^{-2} d^{-1})**	**Dissolved Organic Carbon (mg l^{-1})**
Mangrove	469.4[a]	960[a]	450,572[a]	Remote sensing of biomass, value transfer of soil carbon field measurements	6–79[f]	2–3.8[f]
Seagrass	138[b]–172[c]	229.6[d]	31,685–39,491	Value transfer of field measurements	ND	2.5-3[f,g]
Tidal flat	124[b] (sandflat) 143[b] (mudflat)	235.6 (sandflat)[d] 400.7 (mudflat)[d]	29,214 57,300	Value transfer of field measurements	4–73[f]	2.2–4.1[f]
Macroalgae	1.1[e]	585[e]	200-650[e]	Linear mixed effects model		
Total		**2410.9 ha**	**568,971 – 577,227 Mg C (2,088,124–2,118,423 Mg CO_2e)**			

[a] Friess et al., 2016.
[b] Phang et al., 2015.
[c] Alemu et al., 2022.
[d] Lai et al., 2022.
[e] Kwan et al., 2022.
[f] Saavedra-Hortua et al., 2020.
[g] Saavedra-Hortua & Gillis, *unpublished data*.

4.2. Ecosystem productivity

Primary productivity represents an important input into an ecosystem's total carbon pool. This flux is often characterized by vegetated areal extent, tree density and forest structure, vegetation health indices (such as Normalised Difference Vegetation Index, or NDVI), or net primary productivity (biomass estimated from allometry and/or leaf litter). Aspects of productivity have been measured for mangroves, with some of the most productive mangrove patches (as determined by NDVI), located in the relatively undisturbed offshore islands of Pulau Tekong and Pulau Ubin. Less productive mangrove patches were located on the main island in areas associated with prior human disturbance (Lim, 2019). Recent efforts to characterize Singapore's mangrove forest structure indicate mature mangrove forests are dominated by trees in the *Rhizophora, Avicennia,* and *Bruguiera* genera with adult tree density (multiple species combined) ranging between 1,453 and 4,323 individuals per ha, and an average plot density of 2,290 individuals per ha (van Breugel et al., *unpublished data*). Singapore's mangroves show clear patterning of species distribution controlled by gradients of tidal inundation, with the pioneer species *Avicennia alba* and *Sonneratia alba* dominating at lower elevations, and more complex species assemblages found at higher elevations.

The productivity of seagrass meadows is highly dependent on the seagrass species present and habitat type. In general, productivity is regulated by photosynthetically active radiation (PAR) availability, temperature, nutrient levels and sediment substrate type. These environmental controls differ with habitat type (McKenzie et al., 2016; Collier et al., 2017). *Halophila ovalis* is the most common seagrass in Singapore, and is able to establish in a wide range of environments, resulting in highly variable morphologies and biomass (Waycott et al., 2004). Being a fast growing plant with high turnover, *H. ovalis* has the lowest standing (3.5 – 8.7 g DW m^{-2}; Ow et al., *unpublished data*) and below-ground biomass (11.7 – 23.9 g DW m^{-2}; Ow et al., *unpublished data*) amongst all species present in Singapore. Another commonly encountered species is *Enhalus acoroides*, which is one of the largest seagrasses found in the tropics (Yaakub et al., 2013). *Enhalus acoroides* exhibits one of the highest plant above-ground biomass production (79.5 $\pm$ 0.6 g m^{-2} to 130.4 $\pm$ 0.7 g m^{-2}; median $\pm$ 1 standard error) amongst species in the region (Bramante et al., 2018). However, their slow growth rate makes it hard for this species to recover from large-scale disturbances. For example, by 2021 the *E. acoroides* meadow at Pulau Semakau has yet to recover from a die-back event between 2006 and 2013 (Bramante et al., 2018).

Ulva is found on the mudflats and sandflats along the Johor Straits (Kwan et al., 2022). An opportunistic and fast-growing algae, its productivity is primarily driven by nutrient availability (Teichberg et al., 2010). As such, blooms can be expected to occur during the Northeast monsoon, where nutrient levels in the Straits are elevated due to increased discharge from the Johor River, introducing more terrestrial runoff into the Straits (Sin et al., 2016). In the south of Singapore, coral reef flats and crests along the Singapore Strait can be covered by up to 30 % in macroalgae, contributed mainly by the brown macroalga *Sargassum* (Low et al., 2019; Low & Chou, 2013). *Sargassum* is the largest canopy-forming alga in the tropics and subtropics, typically growing on rocky substrata or as floating aggregations (Fidai et al., 2020). Globally, *Sargassum* forests can have a high average biomass of 840.5 Mg ha^{-1} (Gouvêa et al., 2020). *Sargassum* is a 'pseudoperennial' alga which can exhibit marked seasonality (Fulton et al., 2014), with most species retaining perennial holdfasts while lateral axes grow and crop almost completely over the season. Vesicles keep detached *Sargassum* thalli buoyant for approximately 30 days (Kokubu et al., 2019), facilitating export from coastal habitats to the deep sea via sea-surface currents. The growth of *Sargassum* in Singapore is driven primarily by sea surface temperature, which is influenced by monsoonal variations, despite the small annual temperature range of 2.6°C (Low et al., 2019; Low & Chou, 2013). *Sargassum* size reaches its minimum in the month of May (thallus length 9.88 $\pm$ 0.48 cm) when sea surface tempreature is high at ~30 °C, and is greatest in December (thallus length 110.39 $\pm$ 2.37 cm) when sea surface temperature is low at ~28.5 °C (Low et al., 2019). The distribution of *Sargassum* exhibits site and depth variation, which may be driven by differences in photosynthetically active radiation (Low et al., 2019; Low & Chou, 2013).

4.3. Gaseous fluxes

Gaseous emissions refer to when gases are exchanged between sediments, water, or plant material and the atmosphere. Blue carbon systems are known to be efficient stores of carbon, but a proportion of these stores can be re-emitted back into the atmosphere (Houghton, 2014; Saavedra-Hortua et al., 2020). Blue carbon ecosystems are also subject to tidal flooding, thus creating anoxic conditions in their soil which produce not only CO_2, but also CH_4 and N_2O (Martin et al., 2020; Krithika et al., 2008).

Saavedra-Hortua et al. (2020) first quantified CO_2 emissions at the sediment-air interface across multiple coastal ecosystems (mangrove, tidal flat, seagrass) along Singapore's urbanized coastline. Blue carbon ecosystems in Singapore had CO_2 emissions that ranged from 4 to 79 mmol CO_2 m^{-2} d^{-1} (Saavedra-Hortua et al., 2020). This compares to Vinh et al. (2019), who found that CO_2 emissions at the sediment-air interface varied from mean values of more than 128 to 520 mmol CO_2 m^{-2} d^{-1} (depending on air temperature) in a mature, rural *Rhizophora*-dominated mangrove forest in Vietnam, whereas seagrasses in Chilika Lagoon, India reported CO_2 fluxes at the water–air interface that varied from –33.9 to 376 mmol CO_2 m^{-2} d^{-1} across dry and wet seasons (Banerjee et al., 2018). Dry and wet seasons lead to variations in CO_2 emissions due to the waterlogged conditions of the mangrove soils that limit the decay of organic matter (Vinh et al., 2019). Additionally, higher CO_2 emissions tend to be recorded during periods of warmer temperatures (Burkholz et al, 2020; Chen et al., 2012). Chen et al. (2012) also found that high levels of eutrophication at their study site in Hong Kong contributed to higher CO_2 emissions. This could explain the lower CO_2 emissions profile from the mangrove forests of Singapore compared to that of Vietnam, even though they share similar climatic conditions, as the mangrove forest in Vietnam is located in the Can Gio Estuary which receives input from three rivers that are likely to have high levels of runoff (Vinh et al., 2019). More studies looking at soil characteristics, differences between dry and wet seasons, and cooler and warmer periods, should be conducted to better quantify the CO_2 emissions in Singapore and provide a stronger base of comparison with other blue carbon ecosystems in the region.

4.4. *Aqueous fluxes and ecosystem connectivity*

Exchange of nutrients and reduction of wave energy across tropical coastal vegetated ecosystems has a positive impact in terms of sediment retention and reducing erosion at the seascape, which ultimately will influence blue carbon stocks in the sediments. Carbon exported from a donor ecosystem could be later retained and accumulated by adjacent ecosystems. The sustained capturing and storing of carbon *in situ* depends on local seascape characteristics such as geomorphic setting (Huxham et al., 2018). Such fluxes are an important component of the coastal carbon cycle; on average, Dissolved and Particulate Organic Carbon (DOC and POC) represent approximately 20 % of the carbon net primary production exported from mangrove forests (Bouillon et al., 2008). In seagrass meadows, DOC represents approximately 7 % and POC 18 % of net primary production (Duarte & Krause-Jensen, 2017).

In Singapore, connectivity has been mainly explored in terms of the exchange of particulate organic matter (POM) across coastal vegetated ecosystems coupled with terrestrial ecosystems; and the export of dissolved organic carbon (DOC) with ebb tides from mangrove forests to adjacent ecosystems (Saavedra-Hortua et al., 2020). This study showed that the POM contributions of different ecosystems as donors and recipients of carbon was influenced by local geomorphic setting and characteristics such as the size of mangrove forest or terrestrial catchment area. Additionally, the importance in terms of percentage of contribution to the POM of some primary producers such as mangrove trees (10 to 50 %), macroalgae (10 to 20 %) and terrestrial plant ecosystems (5 to 40 %) was shown to be higher compared to seagrass (5 to 10 %). DOC has only been measured on ebb tides. DOC in Singapore's northern mangroves forests ranged from 2 to 4.1 mg/l. Seagrass meadows in Chek Jawa (northeast) and Cyrene reef (south) ranged from 2.5 to 3 mg/l, showing similar values across northern and southern meadows (Saavedra-Hortua & Gillis, *unpublished data*). These results highlight the importance of connectivity across the seascape in Singapore blue carbon, as different ecosystems act as donors and recipients of particulate organic carbon (Fig. 2).

4.5. *Decomposition*

Decomposition and respiration are important processes for carbon efflux from coastal ecosystems (Fig. 2). Respiration is performed by both macro- and micro-organisms in which organic carbon is released as CO_2, with microbes largely driving decomposition processes. Decomposition encompasses diverse metabolic pathways that occur aerobically and anaerobically, transforming carbon over time with its eventual release to the atmosphere (primarily as CO_2 and CH_4).

The first step to understanding decomposition processes is to characterise microbial communities in blue carbon ecosystems. Fungal communities in mangrove (*A. alba* and *Sonneratia alba*) and seagrass (*E. acoroides* and *H. ovalis*) ecosystems are known to exhibit biogeographical patterning across Singapore and Peninsular Malaysia due to differences in environments and limits to dispersal (Wainwright et al., 2019a; Lee et al., 2019, 2020; Quek et al., 2021). The transition between the terrestrial and marine environments also influences fungal communities, with communities on aerial organs of the mangrove pioneer species *Sonneratia alba* possessing a stronger terrestrial fungal signature (Lee et al., 2020). Additionally, differences in fungal community composition are associated with specific plant structures (Wainwright et al., 2019a, Lee et al., 2020), with implications for carbon cycling, as different seagrass structures vary in their carbon composition. Fungal communities are even more diverse within the soil column, as sediments associated with *Sonneratia alba* (mangrove), *E. acoroides* (seagrass) and *Sargassum ilicifolium* (macroalga) all have a large proportion of unidentified fungi (Wainwright et al., 2019a, Wainwright et al., 2019b; Lee et al., 2019, 2020).

Bacterial communities are more metabolically diverse than eukaryotes, and their metabolism is linked with many important carbon cycling processes (Jing et al., 2015). Knowledge of bacterial communities associated with coastal ecosystems is generally rudimentary, though several studies are beginning to shed light on bacterial and archaeal diversity (which include the key methane producers) in Singapore's coastal habitats. The microbiome associated with the common macroalga *Sargassum ilicifolium* has been characterised from several locations transecting Singapore's southern islands, with a high proportion of Gram-positive bacteria (Firmicutes and Actinobacteria) on the thallus and vesicle (but not holdfast), which is uncommon in marine niches (Oh et al., 2021). Recent data on seagrass-associated microbes show that plant structures generally have more similar microbial communities and diversity compared to the surrounding sediment (Rabbani et al., 2021, Yan et al., 2021), suggesting there is strong selection of microbial taxa in living tissues. However, community distinction among plant parts differs between species. In particular, below-ground parts (i.e., rhizome and root) tend to host more similar communities than those that are above-ground in *E. acoroides* (Rabbani et al., 2021), but the communities in the leaves, roots and rhizomes of *H. ovalis* are not significantly different from one another (Yan et al., 2021). Below-ground microbes (i.e. in roots, rhizomes and sediment) comprise more bacteria that play important roles in nitrogen fixation, carbon cycling and degradation of complex organics (Yan et al., 2021).

While local knowledge on microbial community composition is available, the contribution of these microbial communities to blue carbon dynamics in urban coastal ecosystems such as Singapore is still largely unknown. It is important to calculate blue carbon decomposition rates in urban settings as disturbances (e.g. nutrient loading, sediment disturbance) have a strong influence on microbial communities and carbon cycling at the microscale. For example, dynamic sulphur, carbon and oxygen gradients within the mangrove rhizosphere fuel and select their microbial communities, and such gradients may differ between undisturbed and disturbed settings. Studies from Singapore have shown that disturbances such as pollution can substantially influence bacterial communities and their metabolism in the mangrove rhizosphere (Jing et al., 2015), so concomitant impacts on blue carbon cycling would be expected.

5. Blue carbon change through time

5.1. Long-term historical changes in blue carbon

Temporal changes in blue carbon stocks in Singapore can be attributed to various factors which differ in their degree of influence on carbon accumulation over different scales of time. Across millennial timescales, the influence of changes in relative sea-level (RSL) on blue carbon ecosystems is more pronounced, as variations in the rate of RSL change can result in the landward or seaward movement of mangroves (Rogers et al., 2019; Saintilan et al., 2020). Palaeo sediments from blue carbon ecosystems can thus be expected to be found where palaeo shorelines existed, which due to previous RSL changes may not line up with the modern shoreline. Such studies are further complicated by natural processes such as erosion that can prevent palaeo sediment accumulation during periods of Holocene RSL change (Bird et al., 2004; Woodroffe et al., 2016). They are further complicated along urbanised coastlines by land reclamation and coastal development that can remove or bury palaeo sediments, while anthropogenic degradation and remineralisation can alter organic carbon content in these sediments over time (Woodroffe et al., 2015). As a result, long-term historical changes in blue carbon have rarely been assessed in an urban coastal environment.

Despite these challenges, palaeo mangrove sediments have been found in heavily urbanised and reclaimed locations along the downtown coast of Singapore, such as Marina South and Kallang (Bird et al., 2004; Bird et al., 2010; Chua et al., 2021). Carbon accumulation occurred at rates of 0.91 MgC ha^{-1} yr^{-1} in Kallang between 4970 and 6210 cal yrs BP and 1.7 MgC ha^{-1} yr^{-1} in Marina South between 8315 and 8540 cal yrs BP, based on radiocarbon dates calibrated using IntCal98 (Bird et al., 2004). These sample ages have been subsequently re-calibrated, leading to revised carbon accumulation estimates of 0.73 MgC ha^{-1} yr^{-1} in Kallang between 4836 and 6392 cal yrs BP, and 0.83 MgC ha^{-1} yr^{-1} in Marina South between 8174 and 8636 cal yrs BP (Chua et al., 2021). Holocene carbon accumulation rates have not yet been established for seagrass ecosystems in Singapore due to the low preservation potential of seagrass tissue and pollen in the palaeo record (Reich et al., 2015).

5.2. Historical and contemporary land use change

Across more recent decadal timescales, Singapore's urban blue carbon has been less influenced by physical factors such as RSL change, and more by human interventions such as land use change and ecosystem rehabilitation (Fig. 3). Singapore's coastline has undergone dramatic changes as it has rapidly urbanised, with land reclamation increasing total coastline length from 480 km in 1993 to 505 km in 2011, of which 83 % is artificial or built, e.g., seawalls and artificial beaches (Lai et al., 2015). Based on historical topographical maps of mangroves and tidal flats (Hilton & Manning, 1995), as well as historical reconstruction of seagrasses (Yaakub et al., 2014), an estimated 85 % of mangroves and tidal flats, and 43 % of seagrass meadows have been lost, mostly since 1953. We estimate that this corresponds to an approximate 85 % loss in blue carbon stock across Singapore, equivalent to total emissions of 12,632,347 Mg CO_2-e (3,442,056.40 Mg C). Due to their high rates of loss and high carbon densities, mangroves alone accounted for ~70 % of this carbon loss, followed by tidal flats (~10 %, using the average carbon stock of tidal flats) and seagrass meadows (~3%) (Fig. 3). Unfortunately, long-term changes in macroalgal extent are not available to make similar calculations.

5.3. Coastal habitat restoration

To offset habitat losses, Singapore's coastal ecosystems have seen repeated restoration efforts since the 1990s, with concomitant benefits

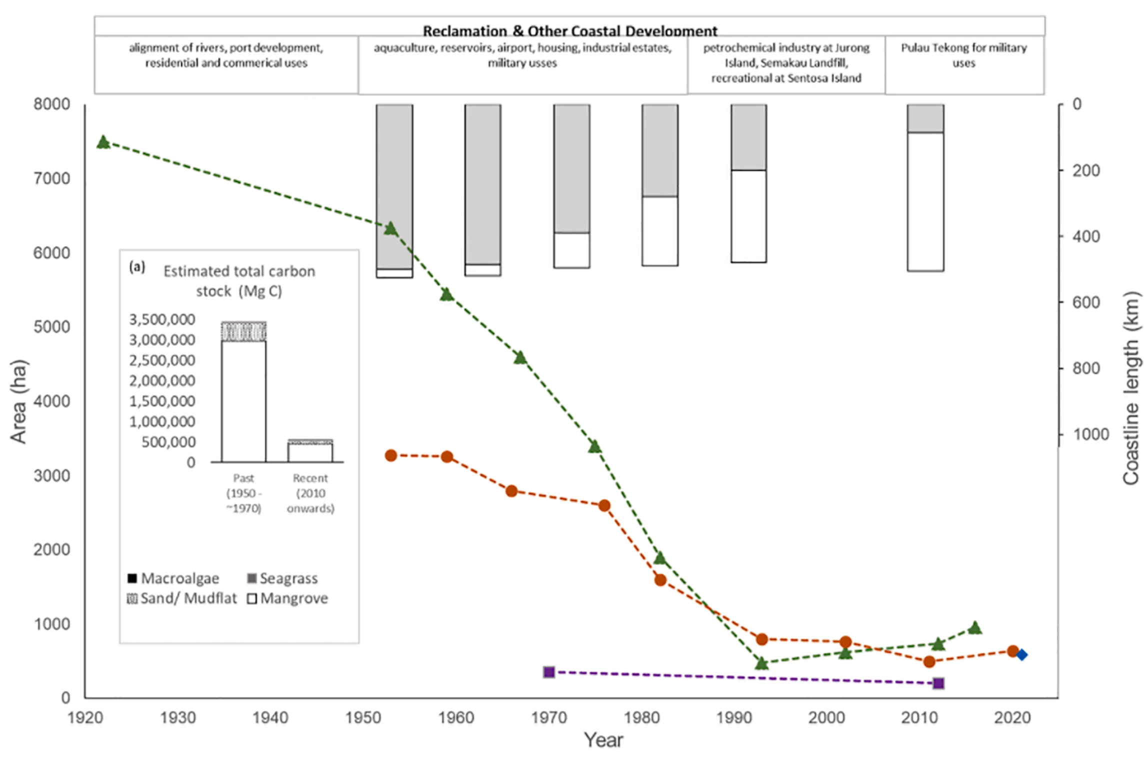

Fig. 3. Estimated loss of mangroves, seagrasses and tidal flats from 1920s onwards, with corresponding reduction of the natural coastlines. Inset (a) shows the estimated loss in carbon stock from these ecosystems (including macroalgae, historical extent unknown). This was calculated based on the areal estimates of mangroves and tidal flats (1953), that of seagrasses (prior to 1970) and the average carbon stock for each ecosystem provided in Table 1. (Data from Hilton & Manning, 1995; Yaakub et al., 2014; Lai et al., 2015; Friess et al., 2016; Kwan et al., 2022).

for blue carbon sequestration and storage. Restoration efforts have mostly focused on mangrove forests (see Friess, 2017 for a summary of all restoration projects to date). A range of restoration approaches have been trialled across Singapore, including natural regeneration, plantations and hybrid engineering, and a conceptual framework has been created to consider the key decision points at which a restoration approach can be changed to increase the ecosystem service provision and adaptive capacity of a restoration project (Ellison et al., 2020). Mangrove restoration is usually undertaken along rural coastlines, so some of these mangrove restoration approaches have needed to be adapted to urban settings, for example regrading of previously reclaimed land, or the incorporation of mangroves into artificial structures.

The Pasir Ris mangroves in northeast Singapore were the earliest documented effort of human-assisted mangrove restoration, after foreshore reclamation in 1978. Subsequent regrading of the reclaimed land in 1989 promoted natural recolonization along the river (Lee et al., 1996), with ecological succession to a more established mangrove community seen today (Jamari, 2021). Replanting at Pulau Semakau in 1999 aimed to replace mangrove habitat lost to land reclamation for a landfill (Tanaka et al., 2004), with high density seedling planting conducted on 13.6 ha of reclaimed area.

Despite the benefits of mangrove restoration, the aboveground mangrove biomass for restored mangroves of Pasir Ris and Pulau Semakau (36.6 and 105.45 Mg C/ha respectively; mangrove age approximately 20–25 years) were lower than that of natural mangroves in Singapore (163.72 –226.9 Mg C/ha), with similar trends for belowground biomass (Friess et al., 2016). In terms of the soil carbon pool, studies from other regions show that soil carbon storage in restored mangroves can resemble reference sites within 20 years following restoration (Osland et al., 2012). Our knowledge of Singapore-specific rates of soil organic carbon recovery is nascent, though mangroves that had naturally regenerated in abandoned aquaculture ponds over the last 13 years on Pulau Ubin were still able to store soil organic carbon at densities of 411 $\pm$ 41.9 Mg C/ha (How, 2020).

A unique challenge for urban coastlines is how to conduct mangrove restoration when much of the shoreline has been hardened through coastal engineering to protect urban assets. While most habitat increases in Singapore are due to rehabilitation of 'natural' ecosystems, coastal artificial structures have provided some novel opportunities for ecosystem establishment of sedimentary environments along an urbanised coastline. Human-assisted recruitment of mangroves within coastal structures was conducted on Pulau Tekong in 2010, with a hybrid engineering approach chosen to reduce shoreline erosion by anchoring mangrove saplings in PVC pots within an engineered sea wall structure (Cheong et al., 2013).

The restoration of seagrass is substantially more challenging to achieve at scale compared to mangrove restoration, due to the dynamics and physical processes found in the subtidal and lower intertidal zones, external stressors such as water quality inhibiting success, and poor knowledge of suitable planting techniques (Katwijk et al., 2016). Seagrass meadows have not been the target of active restoration in Singapore, though research projects have previously been funded that have investigated the potential for seagrass planting in Singapore's waters. However, there is ample evidence for natural regeneration of seagrasses, particularly along new artificial and reclaimed coastlines along the east coast of Singapore over the past 30 years (Yaakub et al., 2014). These seagrass meadows have formed in shallow, sheltered sedimentary environments behind seawalls or submerged rock bunds, indicating the potential for ecologically-friendly engineering designs that reduce hydrodynamics to facilitate natural establishment of seagrass. Although these recent engineered or naturally recruiting blue carbon habitats support smaller stores of carbon, there may still be potential for them to become blue carbon reservoirs in the longer term.

6. Urban planning, management and policy for blue carbon ecosystems

Several authors (e.g., Salon et al., 2014; Rivas et al., 2022) have identified a range of motivations and enabling factors that can increase the success of municipal actions to reduce climate change, many of which are apparent in Singapore. These include the capacity of a municipality to provide financial support, prior data and monitoring capacity (*Sections 4, 5*), governance structures and policies in place that allow the rapid deployment of management actions (*Section 6.1*), co-benefits of management actions (*Section 6.2*), and the involvement of stakeholders (including the public, *Section 6.5*). Singapore has the added enabling factor of the international and regional governance context (*Sections 6.3, 6.4*), that creates incentives to consider blue carbon within carbon accounting frameworks beyond the municipal level.

6.1. *Urban planning and policies relating to blue carbon*

Singapore's urban development trajectory is guided by a number of strategic and statutory land use planning instruments. Singapore has a long history of incorporating environmental concerns into urban planning (particularly increases in vegetation cover), as planning philosophies from the 1970s onwards were framed as the "Garden City" and "City in a Garden" (Tan et al., 2013) towards today's philosophy of planning a "City in Nature". Singapore's approach to environmental management is now guided by the Singapore Green Plan 2030 (SGP 2030), a whole-of-government approach to advance Singapore's sustainable development agenda. A key objective of the SGP 2030 is to strengthen commitments to the Paris Agreement and position Singapore to achieve its net-zero greenhouse gas emissions targets (MSE, 2021). The conservation and restoration of Singapore's remaining blue carbon habitats can make a small but meaningful contribution to this agenda.

The SGP 2030 has led to a range of initiatives related to blue carbon habitats. For example, Singapore's OneMillionTrees movement, launched in April 2020. This initiative will lead to the planting of a million more trees across Singapore by 2030 under the City in Nature pillar of the SGP 2030 (NParks, 2021), and a substantial proportion of trees planted so far have been mangroves. Carbon and the role of vegetation in climate change mitigation has been listed as a key driver of this initiative (NParks, 2021) and the planting of a further million trees across the island could absorb another 78,000 tonnes of CO_2 (MSE, 2021). Extensive urban tree planting programmes have been developed for numerous cities around the world (e.g., Eisenman et al., 2021), and coastal cities within suitable climatic zones would be able to incorporate mangroves into such initiatives. The restoration of other blue carbon habitats could also be supported if tree planting initiatives were expanded to include non-forested ecosystems such as seagrasses or salt marshes.

The SGP 2030 also calls for 50 % more land to be set aside for nature parks by 2030 and a 1000 ha increase in green spaces by 2035 (MSE, 2021). A number of newly announced parks to meet this target have incorporated blue carbon ecosystems. In 2018, the Singapore marine advocacy community launched the most recent Blue Plan, which proposed the protection of several key marine areas on Singapore's mainland and offshore islands (Jaafar et al., 2018), many of which contain mangroves, seagrasses, tidal flats and macroalgal beds. Since that report, a number of intertidal areas have been designated by the government as nature parks or areas with other protected status. In 2018, the gazetting of the 72.8 ha Mandai Mangrove and Mudflat Nature Park was announced, protecting mangroves, ephemeral seagrasses, and some of the most extensive tidal flats in Singapore (NParks, 2018). This will be joined by the new 18 ha Lim Chu Kang Nature Park. Together, these new parks will be joined to the existing Sungei Buloh Wetland Reserve through the Singapore Nature Park Network (Min, 2020). Other planned parks include the new 40 ha Khatib Bongsu Nature Park, containing mangroves and tidal flats along the northeast coast of Singapore (Tan, 2020). There are other mangrove areas across Singapore which are within State Land but not under a nature park that may also benefit from this added designation.

6.2. Links between nature-based solutions for both climate change mitigation and adaptation

Blue carbon ecosystems provide a wide range of ecosystem services beyond their ability to sequester and store carbon for climate change mitigation, including provisioning services such as fish and fuel, regulating services such as coastal protection, shoreline stabilization and pollutant assimilation, and cultural services such as recreation and spiritual value (e.g., Mukherjee et al., 2014; Nordlund et al., 2016). Ecosystem services have been quantified for some of Singapore's blue carbon habitats; for example, an expert elicitation exercise qualitatively assessed the range and state of ecosystem services provided by seagrasses (Nakaoka et al., 2014). A number of mangrove ecosystem services have been quantified through field and modelling methods, including the ability of Singapore's mangroves to reduce the energy of short waves by 75 % (Lee et al., 2021b).

Incorporating additional ecosystem services may provide stronger justification for including blue carbon ecosystems into planning and policy. In addition to their blue carbon benefits, Singapore's mangroves and seagrasses are now seen as a key nature-based solution to coastal protection and climate change adaptation. In August 2019, the Singapore government made a bold announcement about the cost and scale of interventions required to protect Singapore's coastline, with a cost up to USD 72.6 billion to the end of the century (Chang, 2019). Nature-based solutions are expected to be a key component of future adaptation measures under this funding (Tan & Fogarty, 2019). A number of government agencies and commercial contractors have now shown an interest in piloting nature-based solutions along Singapore's coastline to reduce wave energy impacts and stabilise shorelines. The solutions range from the regeneration of natural mangrove stands to the incorporation of coastal flora and fauna into hard structures through hybrid engineering. These options will all have co-benefits of blue carbon sequestration and storage, to differing extents. While a small number of pilot studies exist (e.g., *Section 5.3*), there were no clear design criteria for the large-scale deployment of nature-based solutions. In response, in 2022, government agencies and advisory bodies published guidelines to implement coastal nature-based solutions in Singapore's context (Lai et al., 2022).

6.3. Singapore's regional contributions as a blue carbon financing hub

Cities such as Singapore can play a key economic role in promoting blue carbon conservation both within and beyond their urban boundaries. Singapore has established or is involved in several green finance initiatives such as the Asia Sustainable Finance Initiative, to support institutions to implement environmental, social and corporate governance, and all companies listed on the Singapore Stock Exchange must now report their sustainability objectives (Durrani et al., 2020) and climate-related disclosures.

Utilizing its experience and reputation as a commodity trading hub, Singapore recently established a regional carbon exchange called 'Climate Impact X' (Yin, 2021). The exchange is founded by several banks, investment portfolios and the Singapore Stock Exchange. There is substantial global interest in blue carbon credit projects, which have the potential to generate US$1.2 billion per year in carbon credit sales for mangroves alone (Zeng et al., 2021). It is expected that blue carbon projects will be an important carbon credit category traded on the Climate Impact X, bolstering the conservation and restoration of blue carbon ecosystems throughout Southeast Asia. However, the success of such initiatives will be determined by whether key financial and governance constraints to blue carbon projects can be overcome, such as the funding gap in many existing blue carbon projects, and the tension between commercial and national accounting (Friess et al., 2022).

Singapore is also involved in the Integrity Council for the Voluntary Carbon Market (ICVCM), with representatives on the Council's Governing Board, Expert Panel and Distinguished Advisory Group. The ICVCM's mission is to establish a set of Core Carbon Principles, which will set new threshold standards for high-quality carbon credits globally (ICVCM, 2022).

6.4. International policies relating to blue carbon

While international carbon policies have generally been the preserve of nation states, there has been increasing discussion on how subnational actors can supplement national structures and contribute to larger debates on greenhouse gas emissions reductions. Their large volume of emissions and their importance for GDP generation means that cities have been considered to be at the core of climate mitigation efforts (Mi et al., 2019). Numerous cities have developed municipal climate mitigation plans. For example, 684 cities in the US (accounting for 26 % of the national population and 23 % of national emissions) had set emissions reduction targets by 2007 (Lutsey & Sperling, 2008). City and mayoral networks such as the C40 Cities Climate Leadership Group have been established to share knowledge and coordinate climate mitigation efforts across almost 100 urban areas (including Singapore). Thus, the city scale can be an appropriate scale with which to undertake meaningful climate change mitigation.

Singapore is also unique as a city state in that it also has obligations to national-scale greenhouse gas emissions reporting under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC). Blue carbon has been heavily discussed in this context (e.g., Herr & Landis, 2016) and is seen as an important contributor to emissions reduction in several small island states such as the Seychelles (Hickey & Baez, 2020). Estimation of emissions and removals from mangroves has been included as part of the land-use category 'Forest Land' in Singapore's biennial reporting of greenhouse gases to the UNFCCC. While Singapore has been reporting a net carbon source in its Land Use, Land-use Change and Forestry (LULUCF) sector for the last two biennial reports, the contributing net emissions from this sector is less than 0.5 %. Nonetheless, there are concrete plans to enhance greening efforts across Singapore to mitigate these emissions further, including to actively conserve and restore mangrove areas such as Mandai Mangrove and Mudflat Nature Park. Such efforts to use carbon sequestration and storage to strengthen Singapore's climate resilience are cited in the nation's Long-term Low Emissions Development Strategy (NCCS, 2020).

Seagrasses, tidal flats and macroalgae are currently not included in the land use categories as the IPCC 2006 Guidelines for National Greenhouse Gas Inventories preclude it. In that respect, Singapore has not considered estimates from seagrass meadows, tidal flats or macroalgae as part of its reporting regime to the UNFCCC at this time. However, the IPCC 2013 Wetlands Supplement does include guidance to estimate emissions and removals from seagrass meadows when they are linked to anthropogenic activities or management practices, but does not include estimation of emissions and removals from seagrass meadow as a coastal wetland type as a whole (IPCC, 2014). There is the potential for non-forested ecosystems to be better incorporated into Singapore's Nationally Determined Contributions if robust blue carbon accounting methods can be generated for use in small islands and city states that supplement existing terrestrial carbon accounting approaches.

6.5. Blue carbon as an educational and communication tool

Climate change has often been considered a concept that many people find difficult to engage with and understand (Moser, 2010). It has been suggested that the increase in accessibility to information on climate processes has been one of the factors influencing the rise of climate-based social movements and citizen action groups (Anderson, 2017), which can lead to effective development and implementation of climate policies (Rhodes et al., 2014; Kythreotis et al., 2019).

Blue carbon ecosystems such as mangroves have historically experienced a number of negative perceptions, related to assumptions that wetlands were reservoirs of disease, places of danger, or landscapes of low value that can be converted to human use (Rippon, 2009). Such perceptions and their legacy can still exist today, even within the blue carbon conservation community. Such continued messaging can undermine public support for conservation and restoration efforts. One way to reverse such perceptions is to communicate the benefits of blue carbon ecosystems to the public.

The role that blue carbon in particular plays in climate change mitigation and the high level of scientific understanding is now widely communicated on a global level, even if the development of policy and management actions are still in their infancy. Such a lag is perhaps not surprising, given that the term 'blue carbon' was only introduced to the scientific literature in 2009 (Nelleman et al., 2009). In Singapore, the term is often communicated in a way which highlights conservation success stories, particularly in the news media (e.g. Hwang, 2020). The topic of blue carbon has an increasing visibility both in Singapore's news media and online; mentions of the importance of preserving natural habitats for both biodiversity and carbon storage have increased in frequency in the Straits Times (Singapore's national newspaper) online platform, with 292 articles containing "mangrove" AND "carbon" within the last three years, 136 of those in the last year alone. The search term "blue carbon" returned 18 articles within the last three years, 9 of those within the last year.

The increase in accessible communication on the importance of blue carbon in Singapore's mainstream media sources may already be having a positive impact on how people in Singapore view and understand its role in climate change mitigation. In a recent survey of 1500 people nationwide conducted by the authors, respondents were asked to rate the importance of Singapore's nature in providing carbon storage. 56.5 % of respondents ranked carbon storage as either an extremely important or very important ecosystem service to the nation. Although this study did not differentiate blue carbon in particular, the results are useful in that they indicate a broader or pervasive understanding of carbon storage being important in Singapore's urban context.

7. Conclusions

Research in Singapore shows that the high carbon densities of blue carbon ecosystems can play a role in carbon sequestration and storage in urban environments, even though they are fragmented, disturbed and smaller in extent compared to blue carbon ecosystems that are commonly found along rural coastlines. Singapore is able to store a maximum of 577,277 Mg C (2,118,423 Mg CO_2-e) across only 2410.9 ha, highlighting the importance of carbon-dense coastal ecosystems for site- and landscape-scale climate change mitigation and adaptation efforts.

While Singapore is perhaps one of the more studied urban coastal settings for blue carbon research, substantial knowledge gaps still remain. Knowledge of mangrove blue carbon stocks is relatively well developed for Singapore, though our understanding of blue carbon dynamics in seagrasses, and the potential for tidal flats and macroalgal beds to contribute to blue carbon are generally lacking. Similar to regional and global trends, blue carbon research in Singapore has focused on blue carbon stocks or short-term measurements of fluxes, and longer-term measurements of gaseous and dissolved fluxes are required to incorporate temporal variation in such processes.

For management and policy, experiences in Singapore show that blue carbon is beginning to influence perceptions of coastal ecosystems, and how they are valued by decision makers, even if evidences for this are hidden or indirect. Singapore has also shown how a city (particularly in its capacity as regional financial hub) can influence blue carbon conservation beyond its immediate urban limits, and urban areas such as Singapore can provide knowledge to influence management and planning in other coastal cities. However, while blue carbon has had a broad influence on how we view and manage our coasts, concrete links between blue carbon science and policy are still nascent. One aspect that would help science inform policy further is emissions factors specific to urbanization, which is required for carbon accounting.

It is clear that there is large potential globally, and particularly within the tropics, for blue carbon ecosystems to play a role in climate change mitigation along urban coastlines. The urban coast of Singapore shows the myriad interdisciplinary opportunities for urban blue carbon, from the scientific quantification of blue carbon dynamics, to its influence on land use planning, the financing of blue carbon conservation, and implications for international contributions to policies such as under the Paris Agreement. Thousands of urban areas contain at least one blue carbon habitat within their boundaries, and they will all face different challenges, constraints and opportunities in quantifying their blue carbon stocks and fluxes, and creating regulations and enabling conditions to facilitate the conservation and restoration of blue carbon habitats. However, the Singapore experience provides a road map for how other cities can integrate blue carbon data collection into assessments of land use development, habitat restoration and city-scale policies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104610.

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