Ecosystem Services 76 (2025) 101774

Contents lists available at ScienceDirect

Ecosystem Services

journal homepage: www.elsevier.com/locate/ecoser

Full Length Article

The pluralistic natural capital values of a tropical city

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https://doi.org/10.1016/j.ecoser.2025.101774
Received 23 February 2025; Received in revised form 3 August 2025; Accepted 3 September 2025
Available online 16 September 2025

ARTICLE INFO

Keywords:
Natural Capital Assessment
Ecosystem services
Tropical city
Regulating services
Climate change

ABSTRACT

Nature in cities is essential for human well-being. Quantifying and valuing the goods and services provided by nature to city dwellers is missing in tropical contexts. Yet, as cities worldwide face similar challenges, understanding the services provided by tropical urban ecosystems becomes imperative for effective management. Here, we present the first Natural Capital Assessment of a tropical city, unveiling three critical insights. Firstly, we demonstrate the vital reliance of a developed tropical city on nature, particularly for climate change mitigation through regulating services. Secondly, we identify intact natural areas as Singapore's most valuable assets, stressing the significance of the quality of urban greenery in enhancing ecosystem services. Lastly, we highlight the importance of nurturing connections between urban residents and nature, fostering relational values crucial for sustained care and conservation of nature.

1. Introduction

Urban nature plays a pivotal role in enhancing quality of life in cities and promoting human health and well-being (Elmqvist et al., 2019; Hunter et al., 2019). The significance of this role was underscored during the global COVID-19 pandemic, when access to green spaces emerged as critical factor for the physical and mental wellbeing of urban residents (Acuto et al., 2020, Grima et al., 2020, Kleinschroth et al., 2024). It has also been echoed in high-level policy documents, such as the Convention on Biological Diversity's Kunming-Montreal Global Biodiversity Framework (GBF) and the United Nations' Sustainable Development Goals (SDG), both of which highlight the rich biodiversity harbored in cities and the diverse benefits that it provides to citizens (Soanes and Lentini 2019, Spotswood et al., 2021). Specifically, Target 12 of the GBF aims to significantly increase "the area and quality, and connectivity of, access to, and benefits from green and blue spaces in urban and densely populated areas", while SDG 11 calls for the creation of inclusive, safe, resilient, and sustainable cities, alongside universal access to green spaces (General Assembly of the United Nations, 2015).

Natural capital assessment (NCA) aims at measuring and valuing the goods and services that nature provides to people. The process is increasingly recognized as essential for integrating the full value of urban nature into public policies and management practices (Guerry et al., 2015, Bateman and Mace 2020). As stressed by the IPBES values assessment report (Pascual et al., 2022), it is essential not only to assess the instrumental value of natural assets, but also their intrinsic and relational values. Achieving this, however, requires a pluralistic approach to valuing ecosystem services, one that combines monetary methods for assessing their economic value (both market and non-market value) with socio-cultural techniques (e.g., public opinion surveys and participatory mapping) (Jacobs et al., 2018) for revealing their importance to the community. These diverse techniques provide distinct insights into the importance of ecosystem services and collectively equip policymakers with the tools and knowledge needed to identify critical ecosystem services and highlight geographic areas where their provision may be lacking or irreplaceable.

Rather few NCAs have been conducted at a national level, partly because of the complexity of such work and the large data requirements (Bateman et al., 2013). However, NCAs are now widely applied in urban areas, including in major cities such as London (Northridge et al., 2020), New York (Sutton and Anderson, 2016) and Toronto (Green Analytics Corporation, 2020). An analysis of 221 published studies of urban ecosystem services from around the world revealed a strong geographical bias towards temperate regions (Richards et al., 2019), which is a notable deficiency, given that tropical cities differ considerably in both the supply of, and demand for, naturally produced goods and services. Many tropical cities are situated within biodiversity hotspots and support species-rich ecosystems, including numerous endemic and endangered species (Cincotta et al., 2000). Furthermore, these natural and semi-natural areas provide a broad range of ecosystem services, whose relative importance often contrasts with those found in temperate cities (Grêt-Regamey et al., 2020). For example, tropical cities derive critical benefits from regulating services that help mitigate high temperatures, tropical storms, erosion, storm surges, and cyclones (Lugo 2014). As extreme weather events are becoming more frequent even in temperate regions (Bastin et al., 2019), insights from tropical urban systems may offer valuable lessons for planners in temperate cities seeking to develop effective climate adaptation strategies.

Here, we present an NCA of Singapore, a city-state with a population of over 6 million, located one degree north of the equator. Historically, the island was covered by primary rainforest, which in 1819 covered 90 % of the land area (Corlett 1992) and has since declined to less than 0.2 % (Gaw et al., 2019), resulting in profound losses of native biodiversity (Castelletta et al., 2000, Brook et al., 2003, Theng et al., 2020). Similarly, intertidal and marine ecosystems have suffered drastic reductions and degradation due to extensive land reclamation and shoreline development (Lai et al., 2015, Chng et al., 2022). However, Singapore now recognizes natural assets as crucial for both economic prosperity and urban livability (Tan et al., n.d., URA, 2019, Chan et al., 2021), and in recent years has explicitly incorporated ecosystem service principles into land use planning (Friess, 2017). Guided by planning visions of a "City in a Garden" and a "City in Nature", great efforts have been made to increase the canopy cover of tall trees, increase the extent and accessibility of green spaces, and conserve and promote urban biodiversity (Tan, 2023). In addition, Singapore now spearheads tropical urban ecosystem services research, motivated in part by its need to find solutions to problems such as rising urban temperatures (Lourdes et al., 2021), increased frequency of flash floods (Chow et al., 2016a,b), and the threat of sea-level rise (Velegrakis et al., 2007).

To our knowledge, this is the first NCA for a large, densely populated city in the humid tropics, and is also one of the most comprehensive assessments anywhere, both in the range of ecosystem services evaluated and in its methodological diversity. The NCA's scope and approach were shaped by three key decisions made at the outset. First, the system boundary was defined as the national territory of Singapore, which comprises approximately 730 km^2 of land area and 714 km^2 of territorial waters. This meant that only local food and water production were included in the analysis, despite Singapore's substantial reliance on imports of these resources. Second, a dynamic systems perspective was adopted, treating the city as a system in which ecosystem services are co-produced by nature and humans (Tan et al., 2020). We therefore assessed all aspects of Singapore's natural assets, including natural terrestrial, tidal and marine ecosystems, human-managed parks and gardens, and highly engineered elements such as roof gardens and green walls. Third, we employed a pluralistic approach to valuation, with the aim of capturing the multiple values associated with natural assets in a city with an ethnically and culturally diverse population. Specifically, the NCA methods were designed to assess: 1) the supply of ecosystem services at a national scale, 2) the spatial distribution of key ecosystem services across Singapore, 3) public preferences for those services, and 4) the economic value of selected services. To achieve these goals, we leveraged diverse data sources, including cadastral data, land-use plans, satellite imagery, social media photographs, nationwide tree inventories, street view images and mobile phone data. In the following sections, we present key findings from the NCA, most of which have been described in greater detail in specialist publications. The resulting information serves as a baseline for assessing the impacts of management and development strategies, aligned with defined objectives for environmental exploitation, protection, maintenance, and restoration. The concluding section discusses the broader policy implications of our findings for both Singapore and other large cities.

2. Methods

The study was designed to encompass the core requirements for an NCA as specified by the Natural Capital Coalition and Keynes (2016) and the Natural Capital Committee (2017). These include measurement of the extent, condition and diverse values of natural assets, and of the services they provide. The key components and workflow of the NCA are illustrated in Fig. 1.

An important preliminary step was to develop an ecotope map of Singapore showing the distribution of main habitat types. For this, we classified Worldview and QuickBird satellite images using random forest machine learning to generate 12 terrestrial categories (Gaw et al., 2019) and used remote sensing to quantify coastal and marine habitats (Tan et al., 2023). Of the 30 resulting land and water cover classes, artificial impervious surfaces (14 %), buildings (7 %) and young secondary forest (9 %) were the dominant land cover types. In contrast, primary forests, native-dominated secondary forests, and mangrove forests each accounted for less than 1 % of Singapore's land area (Fig. 2 and Table 1 Supplementary Information). Another preliminary step was to determine, together with local experts, which ecosystem services were likely to be most important in Singapore, classified into provisioning, cultural, and regulation & maintenance services. This consultative process resulted in a list of 17 services, including several regulating services that experts considered especially important for their role in conferring resilience to climate change and other physical and environmental hazards. The methods used to quantify and value these assets and services are outlined below; further details are available in various publications resulting from the NCA.

2.1. Quantification of natural assets and ecosystem services

The 17 ecosystem services were quantified, both in terms of their supply and their economic and social demand (see next section on pluralistic valuation). Each service was measured using an indicator proxy to estimate its supply and/or demand. The categorization into provisioning, cultural, and regulating & maintenance is based on the CICESv5.2 (Haines-Young and Potschin-Young, 2018) and the related codes are provided for each ecosystem service. The models used to assess these ecosystem services are summarized below.

Temperature reduction (#2.3.6.2): We assessed the impact of various ecosystem types on ambient air temperature by regressing air temperature on surrounding landscape characteristics. Details are provided in Masoudi et al. (2021), and in the code is given in Richards, Tan et al. (2020). As cooling is a benefit that must be directly experienced, we sampled the national air temperature reduction maps to quantify it in two contexts: (1) air temperature reduction in the neighborhood of people's homes (within a 10-minute walk from their home building), and (2) within all public park areas. We quantified the mean air

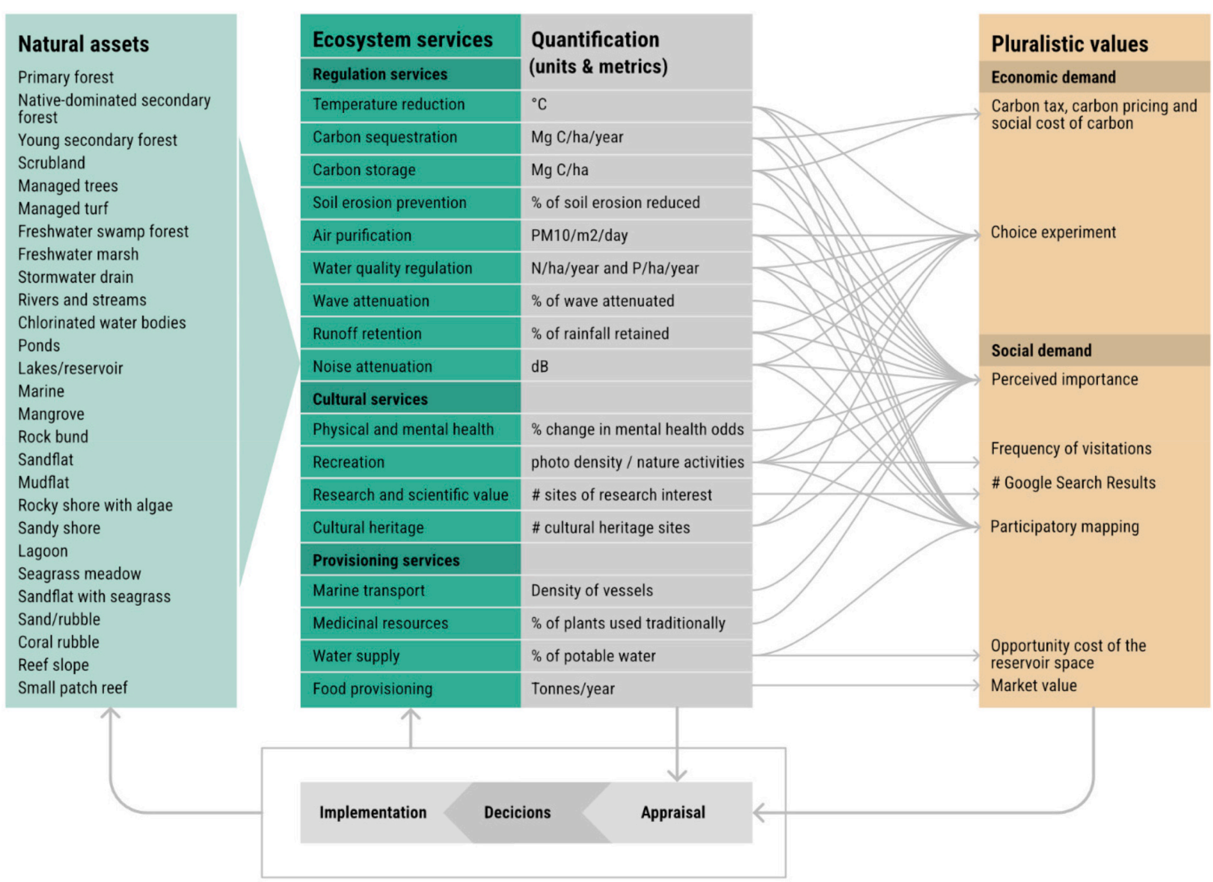

Fig. 1. Key components and workflow of Singapore's Natural Capital Assessment, highlighting the flow from environmental production (left) to pluralistic valuation (right). The first column identifies the natural assets that support ecosystem services essential to human wellbeing. In a first step, ecosystem services are quantified. These are then valued through a range of methods with some ecosystem services being assessed using multiple approaches, as indicated by the arrows. The resulting pluralistic valuation serves to inform policy decisions and guide the sustainable management of natural assets.

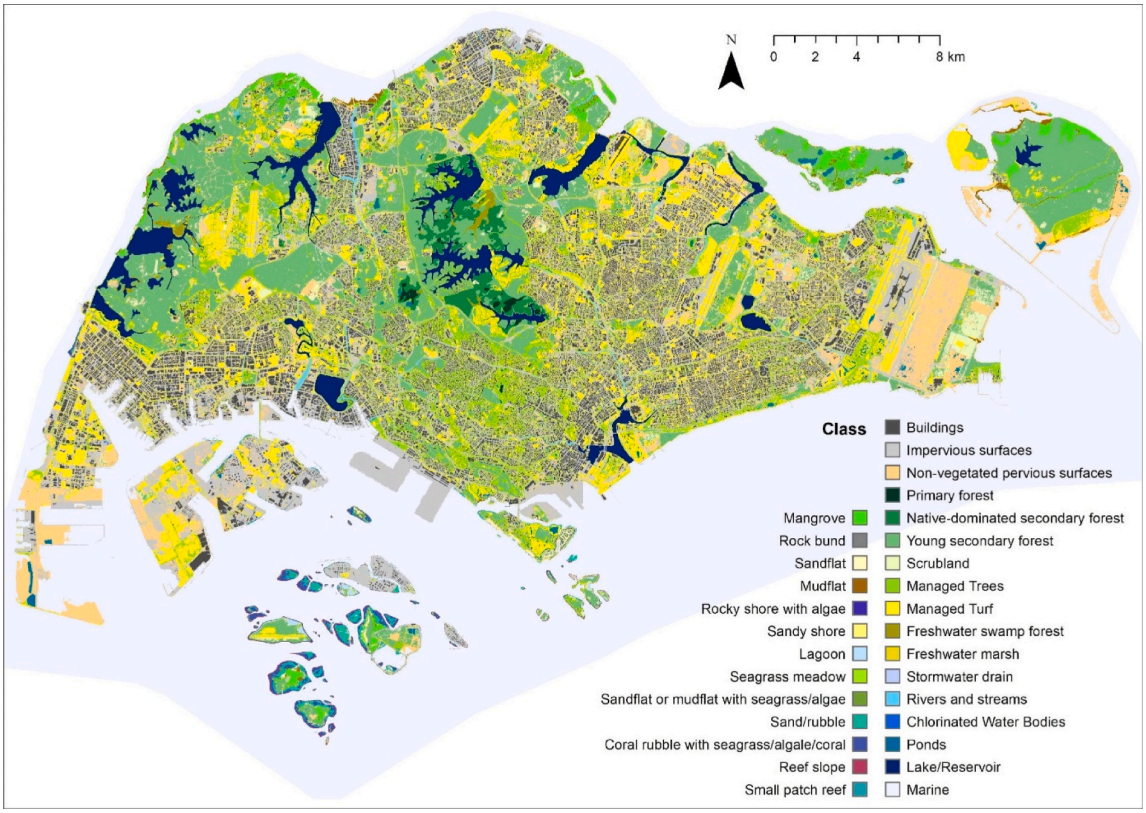

Fig. 2. Ecotope map of Singapore in 2018 based on Gaw et al. (2019).

temperature reduction due to ecosystems within an 800 m buffer around each inhabited building, representing a ca. 10 min walk, as suggested by Wibowo and Olszewski (2005). Census data at the building level was not available, so we estimated the population within each building by applying a dasymmetric mapping downscaling approach, as suggested by Holt et al. (2004), using subzone-level citizen and permanent resident population data from 2016 downloaded from the data.gov.sg archive and building data (Dissegna et al., 2019). Very large buildings – defined as buildings with a volume (area × height) above the 99th percentile – were excluded from the analysis, as they were more likely to be industrial than residential. The population within each subzone was averaged across the total volume of residential buildings present in the subzone, thereby assuming that the living space for each resident was the same.

Air purification (#2.3.6.1): We modelled the removal of particulate matter (PM_{10}) by vegetation over the course of 24 h using a dry deposition model developed by Nowak et al., 1998 and Manes et al. (2016). Details of our air purification assessment are provided in Tan et al. (2015). Input data included canopy cover, air pollution concentration, leaf area index (LAI) and deposition rates. We assumed no precipitation and relatively high ambient PM_{10} conditions of 84 μg per m^3, based on the median annual 99th percentile daily mean between 1994 and 2014. LAI was parameterized using a national map we developed using remote sensing, described in To estimate the improvement in air quality, we estimated the proportional daily removal of PM_{10} by vegetation, aas suggested by Meir et al. (2000). Canopy height data was extracted from a coarse national map of vegetation height that we created from spaceborne stereophotogrammetry. More details can be found in Dissegna et al. (2019). To estimate the improvement in air quality due to the removal of PM_{10} by vegetation, we estimated the proportional improvement in air quality due to the daily removal suggested by Escobedo and Nowak (2009). The mean annual height of the planetary boundary layer in Singapore was extracted from the NCEP GDAS/FNL 0.25 Degree Global Tropospheric Analyses and Forecast Grids dataset (GDAS, 2015), using 2015 as the reference year.

Carbon sequestration (#2.3.6.2): Carbon sequestration was mapped using a benefit transfer approach, in which sequestration values were assigned to each ecotope using a lookup table. For terrestrial ecosystems and mangroves, a systematic review of peer-reviewed scientific journal articles was conducted on Google Scholar (GS) and Web of Science (WOS) to acquire carbon sequestration values. Search terms are provided in the Supplementary Information Table 2. We used the median values for terrestrial ecosystems, because individual values varied widely, and there were several large outliers. For marine ecosystems, all results were reviewed and averaged, and results from sub-tropical and highly arid results were excluded due to the drastically different abiotic and biotic processes. For mudflat and seagrass beds, we measured carbon dioxide flux at low tide using a Li-COR-6800 (LiCOR- Lincoln, USA) with soil dome attachment from four different sites around Singapore (Chek Jawa, Sungei Buloh Wetland Reserve, Sungei Puaka, Labrador Nature Reserve) as a basis for estimating rates of carbon sequestration. At each site, two measurements were made in the interior and one at 8 m from the system edge, and a mean value calculated (Table 1 Extended data).

Carbon storage (#2.3.6.2): Total carbon storage was calculated based on the ecotope map coupled with a look-up table of carbon storage factors specific to each ecotope. For terrestrial ecosystems, we used information on carbon storage provided by the National Parks Board of Singapore. This information had been derived from Pleiades satellite images from 2015 to2017 (spatial resolution 2.8 m) that had been pansharpened to 0.7 m, classified using a Decision Tree, and stitched together to produce a land use map of Singapore. To determine the carbon storage values for each ecotope, a substantial field data collection campaign was conducted, taking on-the-ground measurements of biomass at 127 sites. For land use categories that were not well captured by the sampling campaign, literature values were used. For mangrove ecosystems, we took ecosystem-level carbon storage (both above- and below-ground biomass and soil) estimates derived from field surveys across 49 plots and remote sensing of above-ground biomass. For tidal flat and seagrass ecosystems, averages were derived from field estimates of carbon storage within different geomorphic settings across Singapore, measuring carbon stored in biomass and sediments (methods described in Alemu et al. (2021)).

Water quality regulation (#2.1.1.1): We used total nitrogen and total phosphorus runoff as a proxy for water quality regulation. Details are provided in Alemu et al. (2021). The mass balance approach was based on the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) Tier 1 Nutrient Delivery Ratio (NDR) model described in Sharp et al. (2016). Major model inputs included topography (which we obtained from a map of vegetation height created from spaceborne stereophotogrammetry; Dissegna et al., 2019), annual precipitation, the ecotope map, watershed delineation, and flow and interactions of nutrients between land use types (described in more details in Alemu et al. (2021)).

Soil erosion prevention (#2.2.1.1): Soil erosion prevention modelling was carried out using a modified version of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978, Guerra et al., 2014). Details are provided in Tan et al. (2021). The ecosystem service is defined as the difference in the actual total and hypothetical soil loss that would occur without any vegetation cover. Model inputs specified were rainfall runoff factor, topographic information, soil erodibility factor, vegetation cover, and soil conservation practices. The soil erodibility factor (expressed in SI units; Foster et al., 1981) was calculated using data for soil particle size distribution and clay content obtained from 24 locations and representing all vegetation cover types (Tan et al., 2021). The rainfall runoff factor was taken from a global mapping of erosivity (Panagos et al., 2017). The topographic factor was calculated from the digital elevation model as suggested by Moore and Burch (1986). The vegetation cover factors were derived using our map of LAI creased using remote sensing and street level photographs as described in Richards and Wang (2020), using a conversion from the normalized difference vegetation index, as suggested by Van der Knijff et al. (2000).

Wave attenuation (#2.2.3.2): We used the InVEST 3.2.0 Coastal Vulnerability module (Sharp et al., 2016) to model wave attenuation by mangroves. Details are provided in Lee et al. (2021). We considered two scenarios, one representing average hydrodynamic conditions and the other elevated water levels during a tropical storm event. Data inputs included field surveys at three locations across Singapore (Sungei Buloh Wetland Reserve, Mandai Mangrove and Mudflat, Pulau Ubin) and the Singapore Regional Model in Delft3D provided by Kurniawan et al. (2011).

Runoff retention (#2.2.2.2): We estimated runoff retention using a “curve number” method (USDA, 1986). Details are provided in Tan et al. (2021). Curve numbers were assigned to different vegetation cover types to characterize their runoff retention, with higher numbers indicating greater runoff. Runoff was modelled under extreme precipitation conditions of 110 mm rainfall per hour, as suggested by Chow et al. (2016a, b), and rainfall catchments modelled using a digital elevation model derived from satellite images, as described in Dissegna et al. (2019). To estimate the mean impact of runoff retention services in regulating rainfall in the vicinity of people’s homes, we cross-referenced the catchment map with building-level population data, as described above under temperature reduction.

Noise attenuation (#2.1.2.2): Noise attenuation was modelled using a simple two-dimensional mechanistic model, following the methodology of the System for the Prediction of Acoustic Detectability model (Reed et al., 2012). Details are provided in Tan et al. (2021). The model evaluates four types of noise attenuation over space, including spherical spreading loss, atmospheric absorption loss, topographic and barrier effects over solid barriers, and foliage and ground cover loss due to absorption and scattering of sound waves by vegetation. Reduction of traffic noise by vegetation only provides a service to people in situations where they can experience the reduced noise exposure. We sampled the national traffic noise reduction maps to quantify the benefit experienced by people in two contexts: (1) noise reduction in their home neighborhood (within a 10-minute walk from their home building), and (2) within all public park areas. We quantified the mean noise reduction due to vegetation within a 800 m buffer around each inhabited building to approximate a 10-minute walk, as suggested by Wibowo and Olszewski (2005). The estimation of census data at the building level is described above.

Recreation (#3.1.1.1): The online national survey (described above) was used to determine the frequency of visits to, and use of, nature spaces by Singaporeans and permanent residents. The national survey was complemented by a separate, face-to-face, close-ended survey (N = 407) that was conducted from late January to early March 2020 to ascertain the various types of park usage in ten parks and nature areas in Singapore. In addition, we developed an automated approach to extract and classify the visual content of geo-tagged photographs from the image-sharing platforms Instagram and Flickr, as a means to identify the various uses people make of green spaces. Details are provided in Song et al. (2020a,b). Finally, to study recreational fishing, we conducted surveys (n = 2324 roving creel observations) coupled with a structured questionnaire survey (n = 108) from May 2019 – February 2020 to assess the extent of recreational fishing activities among Singapore residents.

Physical and mental health (#3.1.1.1): We conducted a household survey to assess people’s mental health status. The answers to the General Self-Rated Health questions were compared to respondents’ postcode; satellite imagery was used to ascertain their proximity to green spaces, as characterized by vegetation cover, canopy cover and surrounding park area. Data for visual greenness were derived from Google Street View (GSV), as described in Richards and Wang (2020). More details about the sampling frame and the survey process are described in Zhang et al. (2019) and Zhang et al. (2021).

Cultural heritage (#3.2.1.3): In large cities, sites of cultural importance are often located within or close to green spaces. To explore this association between cultural heritage and natural capital, we extracted and cross-referenced the locations of all monuments, historic sites, and heritage trails from map layers published by the National Heritage Board and Urban Redevelopment Authority. We focused on locations within 100 m distance of nature spaces, as this distance has previously been used to indicate the immediate vicinity of natural assets (Dadvand et al., 2012, Smith et al., 2017).

Research and scientific value (#3.2.1.1): Green spaces and semi-natural areas within cities are often the objects of scientific study, in part because of their proximity to research institutions, and they may therefore have considerable scientific value (defined as contributing to a broader field of knowledge compared to intrapersonal education). We used two approaches to assess the opportunities for scientific investigation, discovery and knowledge, of Singapore’s natural assets. The first used Google Scholar to identify 395 outdoor locations in Singapore that could be attributed to a habitat or ecotope and included the name of a site of interest. The second approach, described in more details in Friess et al. (2020a,b), involved a systematic review of various bibliometric databases (Web of Science, first 1000 returns from Google Scholar, and Scholarbank@NUS) to quantify complementary indicators of scientific values. Six indicators linked scientific value to a specific ecotope, and four of them focused on the scientific value of a particular site, allowing us to show the spatial distribution of scientific value across Singapore’s coastal and marine zones.

Food production (#1.1.1.1): We used the Singapore Master Plan (URA 2019) and the Singapore Land Authority’s Cadastral map to map the distribution of agricultural and aquaculture industries in Singapore. The type of industry was identified based on available data on the Singapore Food Association website (https://www.sfa.gov.sg). Coastal fish farms in Singapore were delineated using high-resolution Google Earth satellite imagery derived from base maps produced by the National Centre for Space Studies and Airbus. Areas with traditional fish farm pens and platforms constructed on wooden stilts (known locally as kelongs), and areas with modern deep-sea fish cages were identified visually and digitized into a polygon vector shapefile. As ground-truthing via field visits was not feasible due to the COVID-19 pandemic, we checked online news articles, maps, fish farm websites and informal interviews with industry experts to ascertain the validity of our identification process. We assessed the role of agriculture and fisheries to Singapore's food security by considering the contribution of local production to consumption for seafood and vegetables from 2008 to 2018 to meet national demand, using data from Singapore Food Agency (2019, 2020).

Medicinal resources (#1.1.1.2): To obtain a list of all medicinal plants species found and used in Singapore, we conducted a rapid evidence review of existing information collated from government websites (i.e. NParks, Data.gov, Ministry of Health, National Heritage Board) and academic research papers relating to traditional medicine in Singapore and abroad (Koh et al., 2009, Siew et al., 2014) (Supplementary Information Table 3).

Water supply (#4.1.1.1): Water is a severely limited resource in Singapore and two-thirds of Singapore's land surface serves as water catchment area, with reservoirs currently meeting around 20 % of Singapore's water needs; the remainder is water that has been imported, reused or desalinated (Irvine et al., 2014). The index of water supply – defined as the fraction Singapore's total area occupied by reservoirs – was quantified using digitized maps of water infrastructure provided by the Singapore Public Utilities Board (PUB Board 2019). The total area of 17 reservoirs is approximately 32.8 km^2 (4 % of Singapore's land area), of which 16 reservoirs are on the main island, with one reservoir on the island of Pulau Tekong.

Maritime transport (#4.1.2.4): To calculate the extent of seaspace used for maritime transport, the geodesic area of anchorages and navigation lanes in the Straits of Singapore were digitized with reference to nautical charts published by Maritime Port Association (Maritime and Port Authority, 2020) and used to construct trends in indicators of seaspace use over the past decade. To assess the intensity of seaspace use, the density of vessels in anchorages and fairways was derived by dividing the number of vessels present on a specific day by the geodesic area of these zones. Data on the numbers of vessels was obtained from a live vessel traffic map (Marine Traffic 2020).

2.2. Pluralistic valuation

2.2.1. Social demand

Preference survey: An online national survey with 1500 participants (adults 18 years and above) was conducted to understand public preferences regarding ecosystem services and to determine the economic value of ecosystem services via discrete choice experiments. The survey was undertaken in May 2019 by a professional market research company and was approved by the National University of Singapore Institutional Review Board (reference code: S-19-094E). Participants were stratified by several criteria (i.e., age, gender, ethnicity) to ensure that the final sample was representative of the Singapore population in terms of standard demographic characteristics. Descriptive statistics of the survey participants are provided in Table 4 of the Supplementary Information. The ecosystem services were rated on a 5-point Likert scale from 1 – "Not at all important" to 5 – "Extremely Important", including the option of "I don't know" for ecosystem services which participants were not familiar with. "I don't know" responses were later treated as "Not at all important", as we assumed that their lack of knowledge for a service would render the service not at all important at the point of assessment. Participants were additionally invited to provide socio-demographic information, e.g., ethnicity, religion, housing type, monthly household income, education level, whether or not they had an environmental or science related education, and their affiliations to environmental groups, to provide an understanding of their socio-cultural backgrounds (Fig. 2 Supplementary Information). We also asked participants for their postal code, which was used to estimate the proportions of different land cover types within 500 m of their residence.

To understand participants' environmental attitudes, we used the 6-item New Ecological Paradigm (NEP) scale and items from the Value-Belief-Norm (VBN) Theory containing the biospheric, altruistic and egoistic components as proxies for environmental worldviews (Stern et al., 1999). NEP scale and VBN have been found to be useful as a proxy for environmental worldviews (Van Riper and Kyle 2014). The scales were rated on a 5-point Likert scale.

Deliberative participatory mapping: To assess shared social values, we conducted a deliberate participatory mapping session with 10 groups of stakeholders, encompassing government agencies, academia, and non-governmental organisations. In this process, stakeholders contributed to creating and mapping geographic or spatial information by incorporating their local knowledge, perspectives and priorities. To minimize participant fatigue (based on our experience in a pilot study), we limited the mapping to five ecosystem services. Each group was tasked to map at a national level area important in the supply of the top five ecosystem services, thereby producing five ecosystem services maps. For each ecosystem service, groups were provided a physical A0 (84.1 cm by 118.9 cm) street directory map of Singapore with most of its offshore islands and had a map scale of 1:35412. Each group was provided 100 coloured stickers to be distributed on the map. The density of the distributed stickers on the map indicated the relative importance of a location for a specific ecosystem service, with higher densities indicating greater importance. Heat maps were then generated using kernel density estimation to produce a circular area of 354 m around each point, corresponding to the map scale of the study. We also conducted a bundling analysis to determine which ecosystem services were grouped together across Singapore. We used the intensity maps produced from kernel density estimation and applied a k-means clustering algorithm in the RSToolbox package in R to determine the ecosystem service bundles.

2.2.2. Economic demand

For services with a market value, e.g., food provisioning and carbon sequestration, we determined their economic values using existing market data on those goods as a proxy. The economic value of food provisioning services was estimated by examining the aggregated value of locally produced vegetables, and seafood from 2011 to 2018 using data from Singapore Food Agency (2019, 2020) and Southeast Asian Fisheries Development Center (2020). All values were converted into Singapore dollars using the average annual exchange rates and controlled for year-on-year inflation rates using the goods and services inflation calculator from the Monetary Authority of Singapore, and with 2019 as the baseline. For carbon valuation, only the valuation of carbon sequestration was considered, since this is the final ecosystem service derived from carbon-related ecosystem functioning. As multiple sources of value for carbon sequestration existed, we calculated a range based on carbon tax, carbon price from emission trading schemes, and social costs of carbon (see Table 5 Supplementary Information). For carbon tax, we used the price set by the government of Singapore ($5 per tCO_2e). To extract the value of carbon from emission trading schemes, we retrieved data from the International Carbon Action Partnership, which contains carbon price for multiple emission trading schemes internationally. We used the prices from each emission trading scheme within a five-year period from January 01, 2015 to December 31, 2019. We converted the prices per tCO_2e from USD to SGD using the average annual exchange rates for each year. Prices were then kept constant (base year = 2019) using the inflation calculator by Singapore's Monetary Authority of Singapore. Once the prices had been adjusted, we took the average of all the prices for each emission trading scheme. The social costs of carbon were based on the mean values of various global social carbon estimates as a proxy for the values of carbon, as well as the mean global social carbon estimate with a 3 % pure rate of time preference. The value of maritime transport was based on the nominal GDP in 2019 and market prices in April 2020 (Maritime Port Association 2020, Singapore Statistics 2020).

We performed discrete choice experiments to study people's marginal willingness to pay for potential ecosystem services from urban neighborhood green spaces, parks, and coastal parks in Singapore. This work formed part of the preference survey described above. Four types of discrete choice experiments were designed: one for neighborhood green spaces, two for parks, and one for coastal parks. Each experiment was designed with seven attributes (air pollution, temperature reduction, noise attenuation, biodiversity, walking distance from home, and service and conservancy charge), organized in an optimal orthogonal design. In total, 375 citizens or permanent residents in Singapore took the survey online. More details about the experiment can be found in Yan et al. (2022). The results of the choice experiments were analysed using mixed logit models. For recreational values of selected green spaces, we used a travel cost method using the origin–destination matrices data of mobile phone users. Demand functions were established for selected parks including the Bukit Timah Nature Reserve and Jurong Lake Gardens (Jaung and Carrasco, 2020).

To quantify the value of vegetation, we developed a hedonic pricing model and estimated tropical homebuyer's preferences for different types of vegetation. Resale data from public housing apartments and private luxury condominium developments were linked to variables and the proportion of vegetation types and sea/fresh water within a buffer around the neighborhood. Regression models were used to investigate the relationships between explanatory variables and property price. Study details and results are presented in Belcher and Chisholm (2018) and Belcher et al. (2019).

3. Results

3.1. Essential ecosystem services of a tropical city

Our analyses highlight the substantial contributions that urban natural assets make to environmental quality and hazard mitigation (Fig. 3). Notably, natural assets were shown to reduce mean air temperature by up to 3.6 °C (Fig. 3 and Table 2 Extended data), improve air quality by removing 3.7 % of PM_{10} within 24 h (Fig. 3 and Table 3 Extended data) and mitigate nutrient runoff, reducing annual nitrogen and phosphorus loads by 87 % and 80 %, respectively, compared to artificial surfaces (Fig. 3 and Table 4 Extended data). These assets also decreased the risk of soil erosion by 80 % annually (Fig. 3 and Fig. 1 Extended data), reduced traffic noise levels by up to 4.8 dB within parks (Fig. 3 and Fig. 2 Extended data), and were estimated to sequester 46′000 Mg of carbon annually (Fig. 3). Additionally, our findings demonstrate the essential role played by these ecosystems in flood mitigation and coastal protection, reducing surface water runoff and attenuating incoming wave energy during storm events by up to 85 % (Lee et al., 2021).

Singapore's natural assets are also important in providing diverse cultural services. These include promoting physical and mental health, providing unique cultural experiences and facilitating religious practices (Fig. 1). For example, we estimated that a 1 % increase in tree cover was associated with a 3.5 % improvement in the likelihood of experiencing good mental health (Table 5 Extended data).

Provisioning services are comparatively limited in Singapore, due to its reliance on imported food. Even so, significant proportions of some

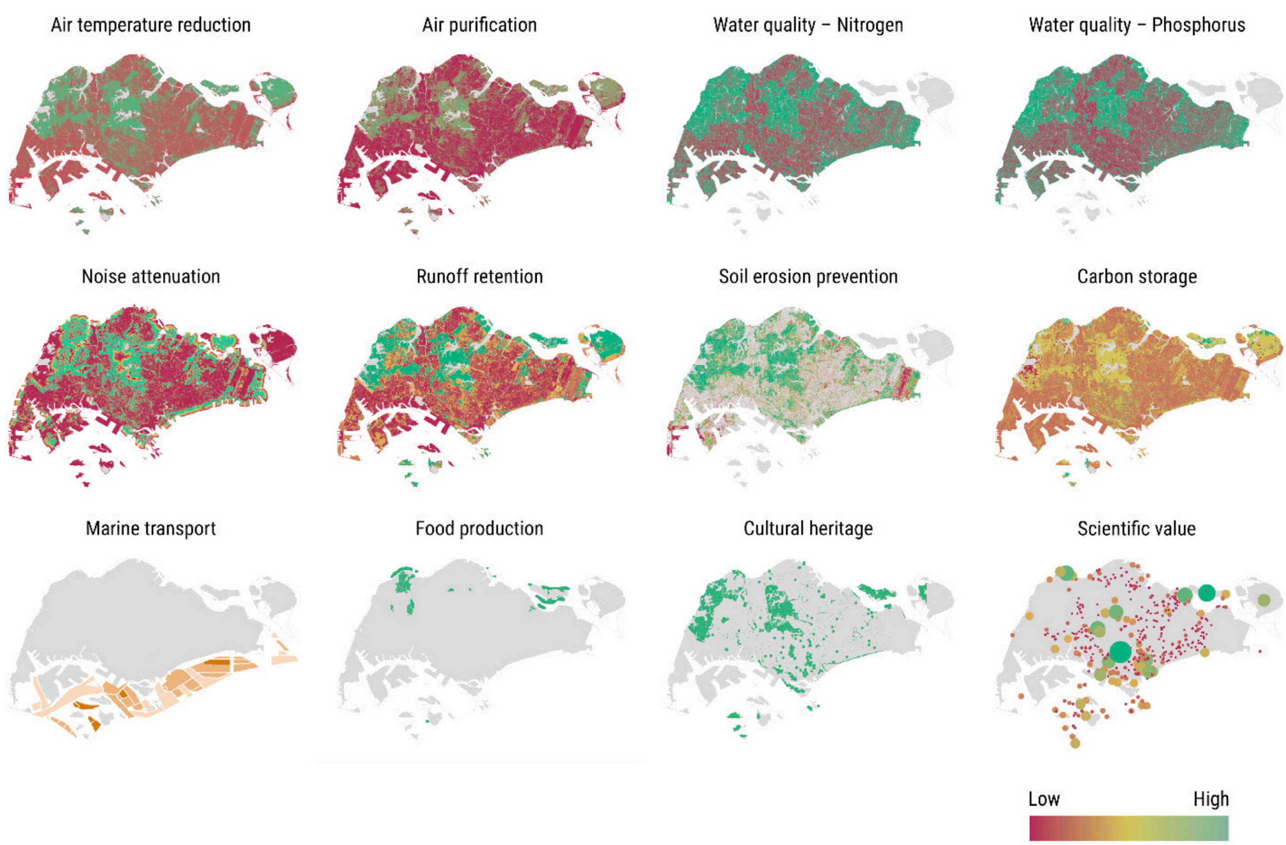

Fig. 3. Modelled supply of ecosystem services provided by Singaporean's natural assets. Air temperature reduction: low = 0°C, high = 5°C; air purification: low = 0 g PM_{10}/m^2/day, high = 0.03 PM_{10}/m^2/day; water quality – nitrogen export: low = 0 g N/ha/year, high = 50 g N/ha/year; water quality – phosphorus export: low = 0 g P/ha/year, high = 20 g P/ha/year; noise attenuation: low = 0 dB, high = 14 dB; Runoff retention: low = 0 %, high = 100 %; soil erosion prevention: low = 0 %, high = 100 %; carbon storage: low = 0 Mg C/ha, high = 180 Mg C/ha; marine transport: low = density of vessels ≤ 1; high = Density of vessels > 6; food production, high = location of agricultural land plots; cultural heritage, high = location of cultural heritage sites; scientific value: low = 0 number of Google scholar search results, high = > number of Google scholar search results.

commodities are produced locally, including 14 % of leafy vegetables (Fig. 3 and Fig. 3 Extended data). Also, 4 % of all vascular plant species in Singapore are used in traditional medicine (Fig. 4 Extended data). Singapore's territorial waters contribute 5 % of the fish and seafood consumed locally, with these amounts increasing strongly in recent years (Fig. 5 Extended data). The maritime industry also relies heavily on sea-space, with 38 % of Singapore's marine waters earmarked for anchorages and navigation lanes to support its maritime industry (Fig. 6 Extended data).

Finally, Singapore's natural assets are highly valued by the international scientific community, serving as key research sites that have significantly advanced scientific knowledge (Fig. 3). As one example, at least 656 articles have been published in the scientific literature (data for 2018) that focus solely on Singapore's coastal ecosystems (Friess et al., 2020a,b).

3.2. Spatial patterns in the supply of ecosystem services

The provision of Singapore's ecosystem services is shaped by the spatial composition and configuration of vegetation, leading to strong spatial patterns in their supply. Larger and more intact forested areas are especially important for providing regulating services (Fig. 3), with primary forests, freshwater swamp forests, freshwater marshes and mangroves having lower land surface temperatures than other vegetation types. More generally, vegetation with a tree canopy has a larger cooling effect than non-tree vegetation and even small patches of wooded vegetation can be effective in lowering lower land surface temperatures, especially if they are simple in shape and highly connected (Table 2 Extended data). We also show that trees with extensive, spreading canopies (e.g., *Albizia saman*) are important for temperature reduction and water flow regulation in built-up areas (Drillet et al., 2020).

Closely correlated with the cooling effect of vegetation is its capacity for air purification. Under conditions of elevated ambient PM_{10}, unmanaged tree canopy vegetation removes nearly twice as much particulate material from the air as managed vegetation (0.013 *v.* 0.007 g/m^2/day; Table 3 Extended data). Natural land use and land cover types are also important for regulating water quality, being highly effective in intercepting pollutants before they reach water bodies. For example, mean export rates of nitrogen and phosphorus from unmanaged grasslands, freshwater marshes and swamps are estimated to be 13 % and 1 %, respectively, of those from artificial surfaces (Table 4 Extended data).

Also correlating positively with temperature and air pollution regulation are carbon storage and sequestration rates (Table 1 Extended data). Managed trees have the highest rates of carbon sequestration (4.29 MgC/ha/yr), exceeding those in coastal ecosystems such as mangroves (1.65 MgC/ha/yr) and seagrass beds (0.49 MgC/ha/yr). In contrast, unmanaged vegetation is more effective than managed vegetation in preventing soil erosion (Fig. 1 Extended data). In the coastal zone, wave attenuation capacity is positively correlated with the width of mangroves, with a 500 m increase in mangrove breadth improving wave attenuation by over 10 % (Lee et al., 2021).

More detailed analyses reveal that the provision of ecosystem services does not scale linearly with green cover but is strongly influenced by urban morphology. One example is the cooling effect of woodland patches, which is modulated by adjacent built-up areas; regression analysis shows that a 10 % increase in building cover leads to a 0.6 °C rise in temperature (Table 2 Extended data), an effect that exceeds by a factor of five the cooling from managed tree-cover. Another is the finding that increasing tree cover in neighborhoods with open, midrise buildings significantly enhances water flow regulation and air quality compared to high-rise building neighborhoods, contrary to what has been found in comparable urban areas in Europe (Grêt-Regamey et al., 2020).

The quality of vegetation is yet another factor influencing the provision of ecosystem services. For example, the capacity of mangrove forest to regulate water quality varies considerably, with more intact patches acting as nutrient retention hotspots, while less intact patches release relatively high levels of nitrates and phosphates into surface waters (Table 4 Extended data and in Alemu et al. (2021)).

3.3. Public perceptions about Singapore's ecosystem services

The results of the online survey revealed strong preferences for several regulating services, particularly temperature reduction, air purification, water quality regulation and noise attenuation (Fig. 4). Respondents also valued highly the mental and physical health benefits associated with nature. Key motivations for visiting nature included 'getting fresh air', 'going for a walk', and 'exercise/sports activities', alongside endeavours aimed at nurturing spiritual and mental well-being, such as 'enjoying the peaceful environment' and 'to feel refreshed' (Fig. 7 Extended data). Some responses reflected the interests of particular groups such as anglers, who stressed both the health benefits and personal enjoyment derived from fishing (Fig. 8 Extended data). Nature also played a notable role in religious observances, with 41 % of respondents having engaged in religious activities in nature over the past year, and 23 % having participated in spiritual contemplation in natural settings (Fig. 9 Extended data).

The importance of Singapore's nature reserves and parks for biodiversity was positively valued, suggesting that they are key sources of non-use value to people; 64 % of respondents ranked the role of nature in "supporting biodiversity" as being 'very' to 'extremely' important. Respondents also mentioned the recreational, inspirational and educational benefits they gained through watching wildlife and on nature walks (Fig. 7 Extended data). Conversely, some aspects of urban nature were considered problematic. For example, although wild birds were recognized as valuable for pest regulation and seed dispersal, some respondents associated them with disease transmission and property damage (Leong et al., 2020); similarly, coastal wetlands were often linked to unpleasant odors, potential dangers, and disease transmission (Friess et al. (2020a,b)).

Accessibility was an important factor shaping people's perceptions of ecosystem services. For example, the perceived value of natural areas was higher where there were amenities such as hiking trails, cycling paths, viewing towers and boardwalks to improve access. Also, respondents appreciated areas where green spaces were linked with cultural heritage sites, monuments and heritage trails, particularly in the intensely urbanized Central Business District, highlighting the opportunities for developing synergistic relationships between cultural heritage and nature.

As expected, provisioning services such as the production of food, fish, and biofuels were ranked low in the national survey. However, community farms and gardens were appreciated as multifunctional spaces, valuable not only for cultivating food and medicinal plants, but also for strengthening social cohesion and building communities (Oh et al., 2022).

A participatory mapping exercise involving NGOs, academics and government demonstrated an alignment between public perceptions and modeled ecosystem services supply (Fig. 10 Extended data). Participants demonstrated a nuanced understanding of nature's diverse values within urban settings, prioritizing intact and unmanaged vegetation for regulating ecosystem services and cultural services, such as aesthetics and inspiration. They also emphasized the importance of landscape naturalization projects such as Bishan-Ang Mo Kio Park, which was developed as part of the Active, Beautiful, Clean Waters (ABC Waters) initiative (Irvine et al., 2014). They recognised the multifunctional importance of such areas, not only in delivering regulating services such as runoff retention, but also in offering recreation, educational opportunities and aesthetic inspiration.

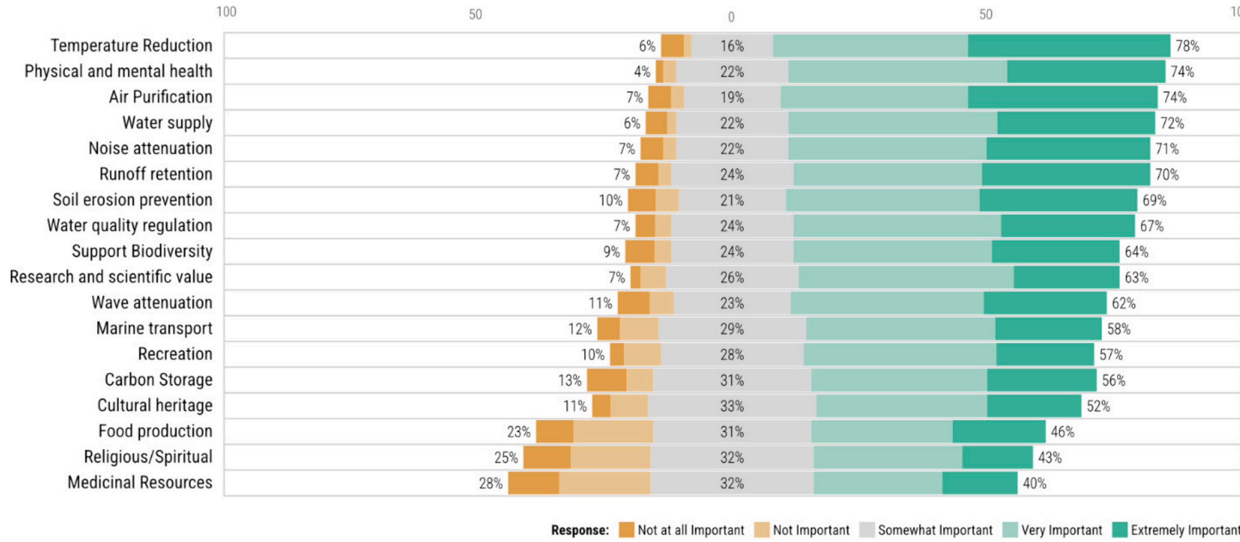

Fig. 4. Essential ecosystem services, including the support for biodiversity, provided by Singapore's natural assets. The percentages are derived from the public social perception survey and represent the importance ratings (n = 1500).

3.4. The economic value of Singapore's ecosystem services

A variety of methods was used to assess the economic value of ecosystem services. These included: (1) assessing market values for services such as food provision and carbon sequestration; (2) using discrete choice experiments to understand public marginal willingness to pay for non-market services; and (3) applying the travel cost method to estimate the recreational value of green spaces.

The results show that some regulating services have a high economic value, aligning with the high scores attributed to these services in the opinion survey. Temperature reduction emerged as a particularly valued service, with a marginal willingness to pay of up to SGD$13 for an additional hectare of neighborhood green spaces per person monthly, and up to SGD$5 for a 20 % to 40 % reduction in air pollution levels monthly (Fig. 11 Extended data). Depending on the valuation method employed, the annual estimated value of carbon sequestration across by Singapore's ecosystems varied widely, from SGD$2 million to SGD$28 million annually.

Cultural and educational benefits were inferred from willingness-to-pay metrics, with values averaging approximately SGD$5 monthly for sea views, nature education programs, and cultural heritage (Fig. 11 Extended Data). Coastal parks were valued as hubs for aquatic pursuits, commanding a relatively high marginal willingness to pay of SDG$18 for activities such as sailing and swimming. The recreational value of parks was also assessed through the travel cost method. Based on data from over 1.5 million visitors, the consumer surplus per visit was SGD$2 for Bukit Timah Nature Reserve and SGD$15 for Jurong Lake Gardens. These figures translate into significant annual recreational benefits for these sites, estimated at approximately SGD$9 million and SGD$66 million, respectively (Jaung and Carrasco 2020).

Hedonic pricing analyses indicate that biodiversity appreciation was weakest in residential areas, where preferences inclined towards non-ecological aspects such as provision of facilities and sea views (Belcher and Chisholm 2018). Concerns about problematic aspects of urban nature were also reflected in the hedonic pricing analyses, particularly in areas of high conservation value (e.g., unmanaged secondary forests), where issues like human-wildlife conflicts (with wild boars, macaques) and poor aesthetics were perceived as potential drawbacks. These results are supported by data on property prices, which show positive correlations with managed vegetation in the neighborhood, but negative correlations with unmanaged vegetation of high conservation value (Belcher and Chisholm 2018).

4. Discussion

In this NCA, currently available data and methods were used to derive policy-relevant information about the ecosystem services provided by Singapore's natural capital. Supplies of regulating services, for example, were estimated by applying generally accepted modelling approaches (e.g., for soil erosion prevention, carbon sequestration) to accessible spatial data, while the preference surveys and economic analyses also followed widely used methodologies. Two limitations of the results should be mentioned at the outset. The first is that the quality and spatial resolution of the analyses varies widely among ecosystem services due to differences in the availability of data and in the predictive power of the various models. The second – inherent in pluralistic valuation – relates to the difficulty of directly comparing the value of individual ecosystem services. Some services contribute to short-term benefits or economic growth and can be evaluated using e.g. market-based methods, while others are tied to ecosystem functions, structures, and processes that require long-term protection, necessitating valuation approaches that recognize nature's intrinsic properties (e.g. participatory mapping). Also, certain values stem from people's relationships with nature and call for methods that capture relational values (e.g. preference survey). Shifting focus from short-term, individual material gains to sustainability-oriented societal values calls for assigning multiple values to a single ecosystem service, rather than simply summing single values for each service to estimate the value of nature (Pascual et al., 2022).

Despite these limitations, we consider that our results provide a reliable snapshot of the supply of, and demand for, important ecosystem services in Singapore, from which three broad conclusions relevant for policy can be drawn. First, Singapore's natural assets provide a wide range of ecosystem services, several of which have considerable value, not only economically but in other ways as well. These include regulating ecosystem services, notably temperature reduction and runoff retention, which were also highly valued in the Southeast Asian city of Kuala Lumpur (Aiman et al., 2022). Valuations in both cities were considerably higher than in the temperate cities of Toronto (Green Analytics Corporation, 2020) and London (Northridge et al., 2020), reflecting greater demand for these services in humid, tropical conditions. Second, Singapore's most valuable natural assets are its remaining intact, unmanaged natural areas. The high value of these areas derives both from their rich biodiversity and their status as the largest contiguous green spaces within the city. Indeed, these areas are especially significant for Singapore, a city state that is devoid of rural hinterlands to supplement its urban ecosystems. Third, most Singapore residents acknowledge and appreciate the benefits they receive from nature, and their perceptions of ecosystem services provision align closely with empirical data. However, some residents express concerns over certain aspects of nature, which they regard as harmful or threatening. Finally, it is worth noting that the relative importance of different ecosystem services has changed as the city has developed; with most food now imported, provisioning services are much less significant than they were a few decades ago (Richards et al., 2019), while cultural and regulating services have become increasingly important for Singapore's residents.

The NCA provided detailed information about the state of Singapore's natural assets and resulted in many suggestions for enhancing the value of specific ecosystem services. The latter can be summarized as general policy recommendations, some of which are relevant not only for Singapore but also for other large cities:

Protect remaining natural and semi-natural habitats. The conservation of remaining natural and semi-natural habitats is imperative. As Singapore advances in its development efforts, the pressures on these areas, and on the high biodiversity they support will inevitably increase. Current projections indicate that by 2030, approximately 47 % of existing tidal flats, 33 % of mangroves, and at least 10 % of intertidal reef flats are at risk of land reclamations (Lai et al., 2015), which would result in a significant loss of ecosystem services. Many other cities, particularly in tropical regions, also harbor patches of natural habitats that have remained undeveloped and are very valuable for the ecosystem services they provide (Edwards 2020).

Integrate nature into the built environment. Even with the most rigorous conservation initiatives, it may prove impossible to fully retain the ecological benefits that Singapore currently obtains from nature. Many green areas have been earmarked for development, posing a significant risk of losing the ecosystem services they provide. To mitigate this, conservation efforts must be complemented by innovative urban design and planning solutions that integrate nature into the built environment (Dobbs et al., 2019). In fact, Singapore has been a pioneer in developing such solutions, exemplified by major projects such as the Bishan-Ang Mo Kio Park and Jurong Lake Gardens. They are an important reason why Singapore continues to be a 'City in Nature', benefitting from a wide range of ecosystem services, despite a nearly three-fold increase in urban density since 1970.

Plan for resilience. Natural assets play a crucial role in enhancing urban resilience in the face of changing environmental conditions. The COVID-19 pandemic highlighted the importance of green spaces, as many residents reported that access to green spaces was critical for their physical and mental wellbeing during that difficult period (Kleinschroth et al., 2023). Similarly, regulating services such as air temperature reduction and runoff retention will become increasingly necessary for mitigating the impacts of climate change, both in Singapore and other tropical cities.

Ensure equitable access to benefits from nature. Given that access to nature is fundamental for human flourishing, policymakers must ensure equitable access to these benefits for all residents. This entails enhancing ecosystem services provision in areas where they are deficient, and ensuring that vulnerable populations, such as the elderly and those with mobility challenges, can access parks and natural spaces. Spatial decision-support tools, such as the NatCap tool developed as part of this NCA, have proved highly instrumental in aiding decision-makers in evaluating spatial trade-offs and overcoming deficiencies in urban ecosystem service provisions (Wicki et al., 2021).

Strengthen awareness about the benefits of nature. It is important to increase public awareness of the benefits derived from nature and strengthen people's emotional connections with the natural world. Our results show that activities such as gardening and horticultural therapy can improve awareness and appreciation of biodiversity (Drillet et al., 2020), foster positive emotions, enhance physical and mental well-being (Ng et al., 2018) and strengthen social cohesion (Oh et al., 2022). In this connection, education has a key role to play; by promoting awareness about urban nature, we can cultivate biospheric values and social norms towards promoting pro-environmental behavior (Oh et al., 2021).

Monitor the state of natural capital. Ongoing climate and socio-economic changes threaten ecosystem quality (Fung et al., 2022). It is therefore crucial to establish robust research and monitoring frameworks to assess the state of Singapore's natural assets and the ecosystem services they provide. The information these produce will be important both for effective decision-making and for conserving Singapore's natural assets.

For those interested in using this NCA as a foundational model for similar work in other cities, several practical aspects merit attention. First, any NCA must be tailored to local needs and circumstances, including the choice of ecosystem services and the methods to measure them. This applies especially to the pluralistic valuation of natural assets, since perceptions about value are likely to vary both regionally and culturally. Thus, the first step in any NCA must be to specify which assets and ecosystem services are considered important in the local context and identify how these contribute to pluralistic value, as shown for Singapore in Fig. 1. Second, such an approach draws upon expertise from many disciplines including environmental science, computer science, social sciences and economics, and necessitates close collaboration with administrative authorities, particularly with those involved in planning and management of the environment. Strong stakeholder engagement is also essential for identifying local priorities and preferences, ensuring that the NCA is relevant to the local context. Managing such a complex project is not easy, but the breadth and depth of insights obtained far exceed what could be achieved through a more siloed approach. Third, any study necessarily builds upon existing data, models and local knowledge. Key data in our study included baseline information on land use and land cover, biodiversity, and socio-economic factors, most of which could be obtained without too much difficulty. However, any NCA is only 'work in progress', constrained not only be the availability of data and choice of methods, but by the researchers' expertise and experience. For example, we assessed public perceptions of ecosystem services using a simple ranking system, but methods such as Q methodology (e.g. (McKeown and Thomas 2013)) might have provided more nuanced insights into the diverse perspectives present within a complex multicultural society.

The NCA generated new data sets and tools that may be useful for conducting similar studies in other urban contexts. One such tool is a freely available, publicly accessible and open-source R-package designed for modelling urban ecosystem services (Richards, Tan et al. 2020), enabling interested stakeholders to leverage existing data sources and models and collaborate with research institutions to extend ongoing efforts and build local capacities. Other tools developed within the project's framework present promising avenues for conducting fine-scale assessments of park provision (Song and Chong 2021). Finally, recognizing the immense pressure on land for housing, infrastructure, and economic activities in Singapore, we co-developed with stakeholders from the Singaporean government agencies a participatory multi-objective optimization tool for navigating the inherent conflicts between urban densification and the provision of urban ecosystem services (Wicki et al., 2021). Besides enabling planners to assess the complex interactions between urban green spaces, ecosystem service provision, and competing land-use demands, the NatCap tool allows also for the inclusion of future transportation nodes and infrastructural developments, facilitating a more holistic assessment of spatial planning scenarios.

5. Conclusions

This study has demonstrated the pluralistic value of Singapore's natural capital, assessed in terms of the delivery of ecosystem services, monetary value, and public perception. More generally, it has confirmed the importance of natural assets as the foundation of people's lives and in contributing to their quality of life in a large, densely populated city. The results support our contention that integrating natural capital within a broader framework alongside human and social capitals is a promising way to uncover conflicting planning visions and foster sustainable urban design, planning and management. Indeed, in its most recent master plan, Singapore proposes a wide range of science-based planning measures and nature-based solutions aimed at enhancing the value of its natural capital (URA, 2025). Many of the policy recommendations from this study also have relevance in other large cities. Some apply mainly to tropical cities such as Jakarta, Lagos or Manaus, which face similar challenges of high temperatures and intense rainfall (i.e., climate analogues, *sensu* Barbu et al., 2024). Others may be useful in rapidly growing cities, as they attempt to find an optimal balance between densification and the preservation of natural capital.

CRediT authorship contribution statement

Adrienne Grêt-Regamey: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Justine Saunders:** Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization. **Peter Edwards:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Data curation, Conceptualization. **Daniel Richards:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jahson I. Alemu:** Writing – review & editing, Methodology, Data curation. **Natasha Bhatia:** Writing – review & editing, Methodology, Data curation. **Roman Carrasco:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation. **Zuzana Drillet:** Writing – review & editing, Methodology, Investigation, Data curation. **Tze Kwan Fung:** Writing – review & editing, Methodology, Investigation, Data curation. **Yan Feng Leon Gaw:** Writing – review & editing, Methodology, Investigation, Data curation. **Wanggi Jaung:** Writing – review & editing, Methodology, Investigation, Data curation. **Andrea Law:** Writing – review & editing, Methodology, Investigation, Data curation. **Rachel Ai Ting Leong:** Writing – review & editing, Methodology, Investigation, Data curation. **Aikeen Youu Ming Lim:** Writing – review & editing, Methodology, Investigation, Data curation. **Mahyar Masoudi:** Writing – review & editing, Methodology, Investigation, Data curation. **Yudhishthra Nathan:** Writing – review & editing, Methodology, Investigation, Data curation. **Rachel Rui Ying Oh:** Writing – review & editing, Methodology, Investigation, Data curation. **Wen Ting Ooi:** Writing – review & editing, Methodology, Investigation, Data curation. **Fairul Edros Ahmad Shaikh Shaikh:** Writing – review & editing, Methodology, Investigation, Data curation. **Xiao Ping Song:** Writing – review & editing, Methodology, Investigation, Data curation. **Claudia L.Y. Tan:** Writing – review & editing, Methodology, Investigation, Data curation. **Puay Yok Tan:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Sergio Wicki:** Writing – review & editing, Methodology, Investigation, Data curation. **Lynn-Wei Wong:** Writing – review & editing, Methodology, Investigation, Data curation. **Yanyun Yan:** Writing – review & editing, Methodology, Investigation, Data curation. **Erik Yando:** Writing – review & editing, Methodology, Investigation, Data curation. **Alex Thiam Koon Yee:** Writing – review & editing, Methodology, Investigation, Data curation. **Jingyuan Zhang:** Writing – review & editing, Methodology, Investigation, Data curation. **Daniel A. Friess:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

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.

Acknowledgments

We thank many experts in government agencies for their time and extensive knowledge, without whom this study would not have been possible. The research was supported by the National Research Foundation, Prime Minister's Office, Singapore, under its Campus for Research Excellence and Technological Enterprise (CREATE) Program (NRF2016-ITC001-013). Richards D was supported by Strategic Science Investment Funding for Crown Research Institutes from the New Zealand Ministry of Business, Innovation and Employment's Science and Innovation Group. Oh RRY acknowledges support from the Commonwealth Government of Australia, the German Center for Integrative Research (iDiv) and German Research Foundation (DFG–FZT 118, 202548816). Fung TK was supported by the Lady Yuen Peng McNeice Graduate Fellowship. We thank Ralph Sonderegger for the support in designing the figures.

Appendix A Extended data

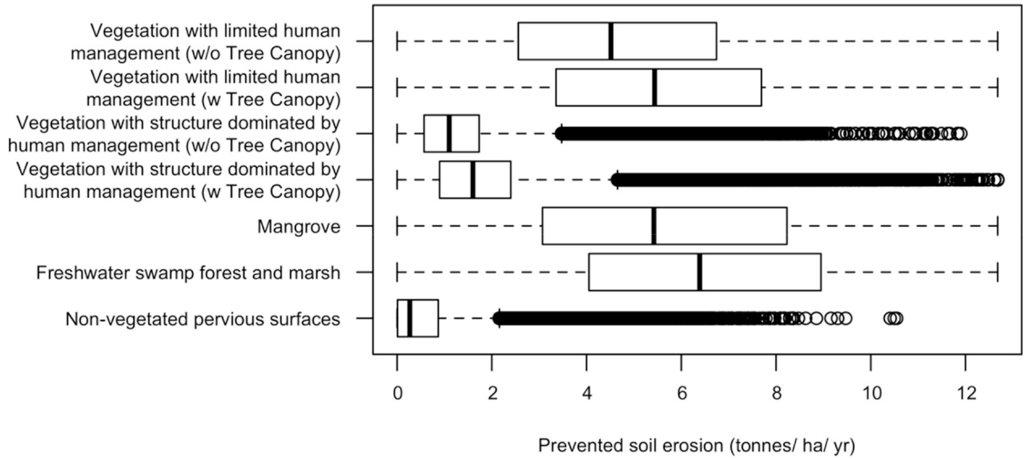

Fig. 1. Prevented soil erosion. Box and whisker plots show the median (bold line), interquartile range (box), and range within 1.5 9 IQR (whiskers). All means are statistically different according to Tukey' least significant difference (LSD).

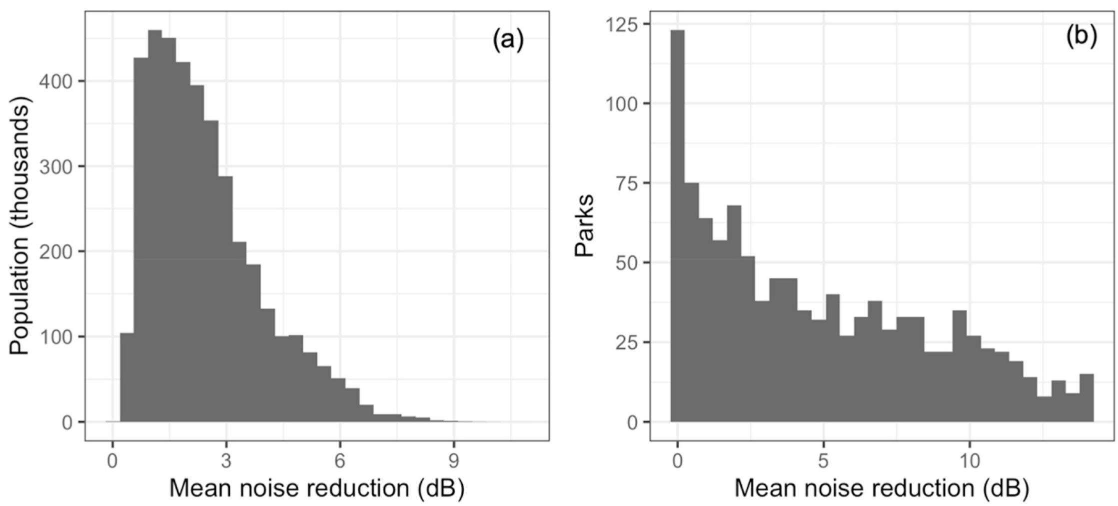

Fig. 2. Variation in the mean reduction in noise level due to the presence of vegetation in (a) the area within a 10-minute walk of people's homes and (b) public parks and open spaces.

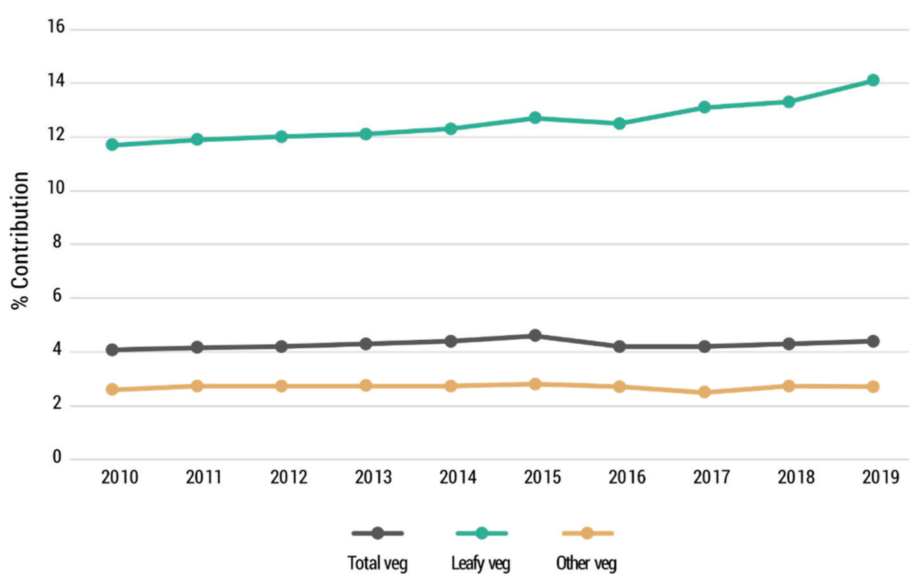

Fig. 3. Annual percentage contribution of local production of vegetables for local consumption.

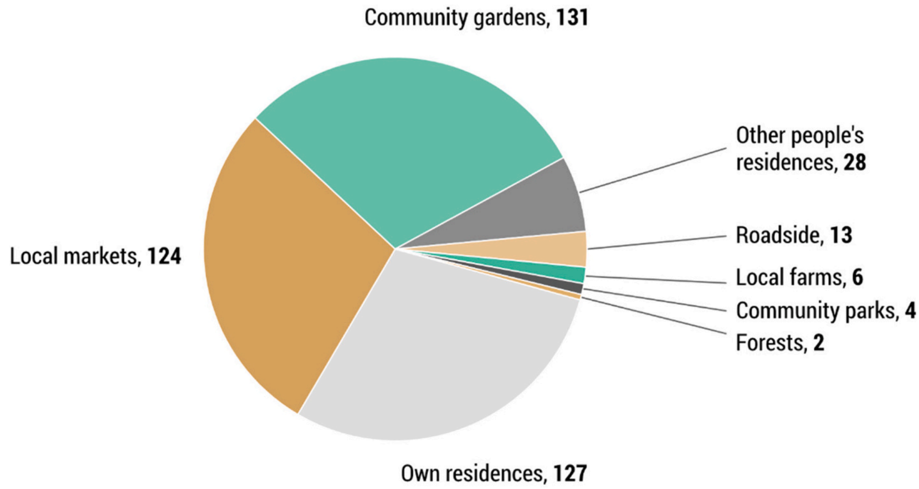

Fig. 4. Frequency of supply of fresh medicinal plants by local sources.

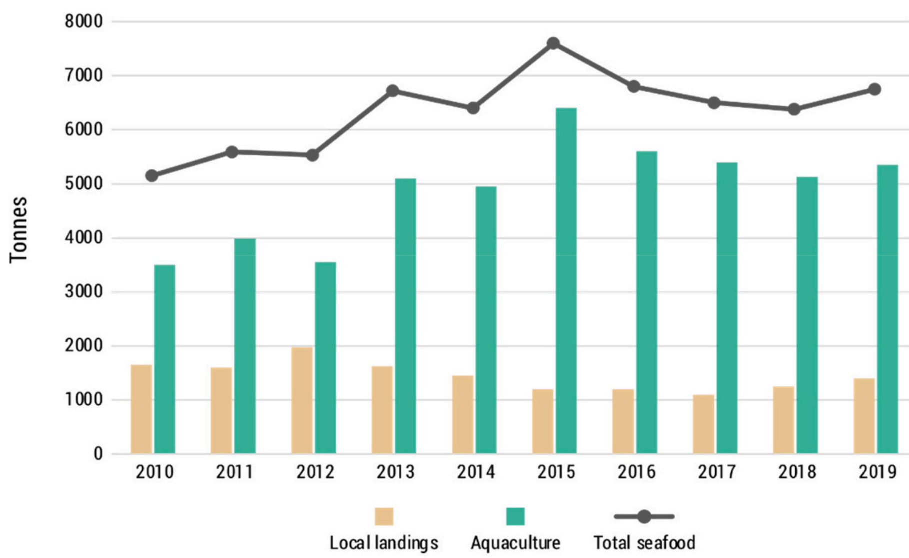

Fig. 5. Contribution of aquaculture and local landings to total local production of seafood (2010–2019).

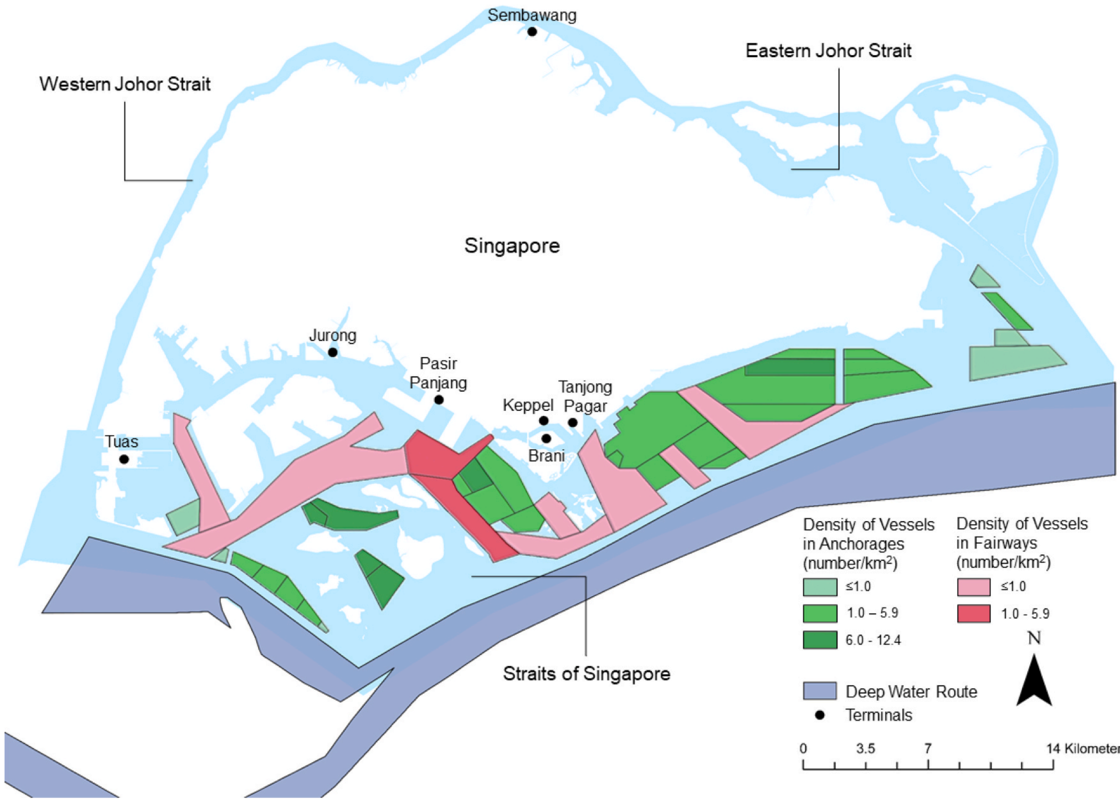

Fig. 6. Map of anchorages, navigation lanes including fairways and the deep-water route within Singapore's seaspace, and terminals.

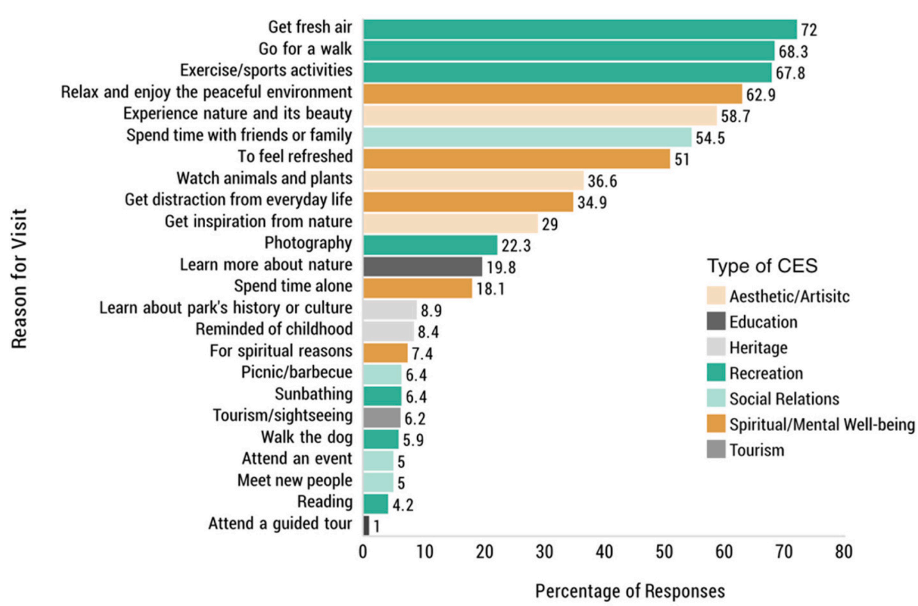

Fig. 7. Main reason(s) for visits to nature spaces, across all the study sites. Respondents were allowed to choose as many options as were applicable to them.

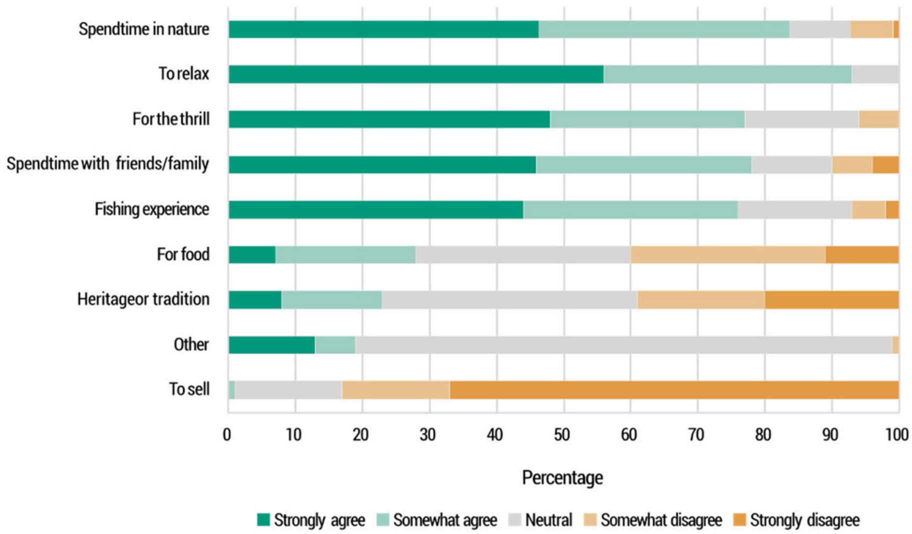

Fig. 8. The motivations of anglers in Singapore to fish

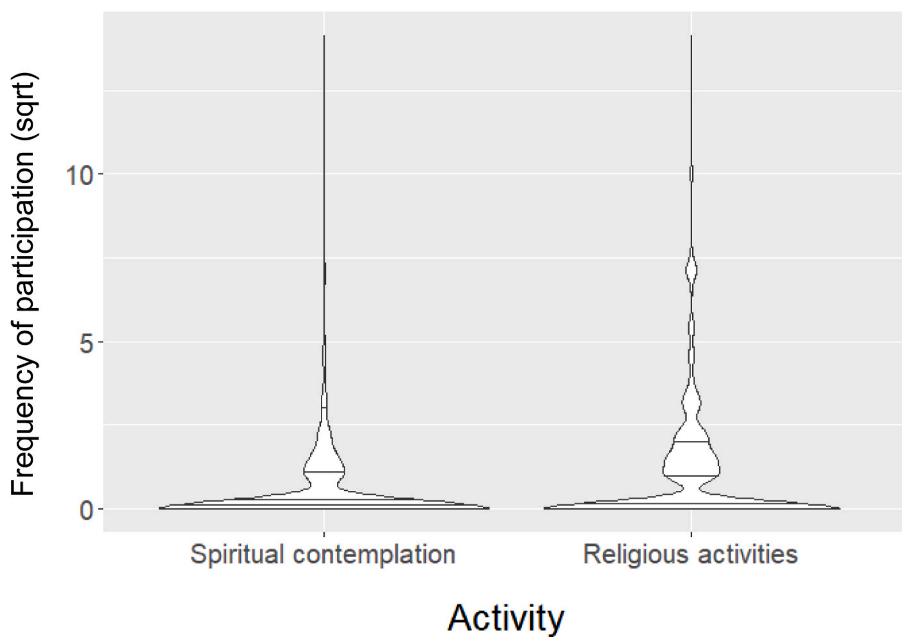

Fig. 9. Violin plots for the square root frequency of participating in spiritual contemplation and religious activities in Singapore for the past one year by 1500 Singapore citizens and permanent residents. Violin plots show the overall distribution of participation in each activity – the wider the sections of the plot show there are more observations for a value of frequency.

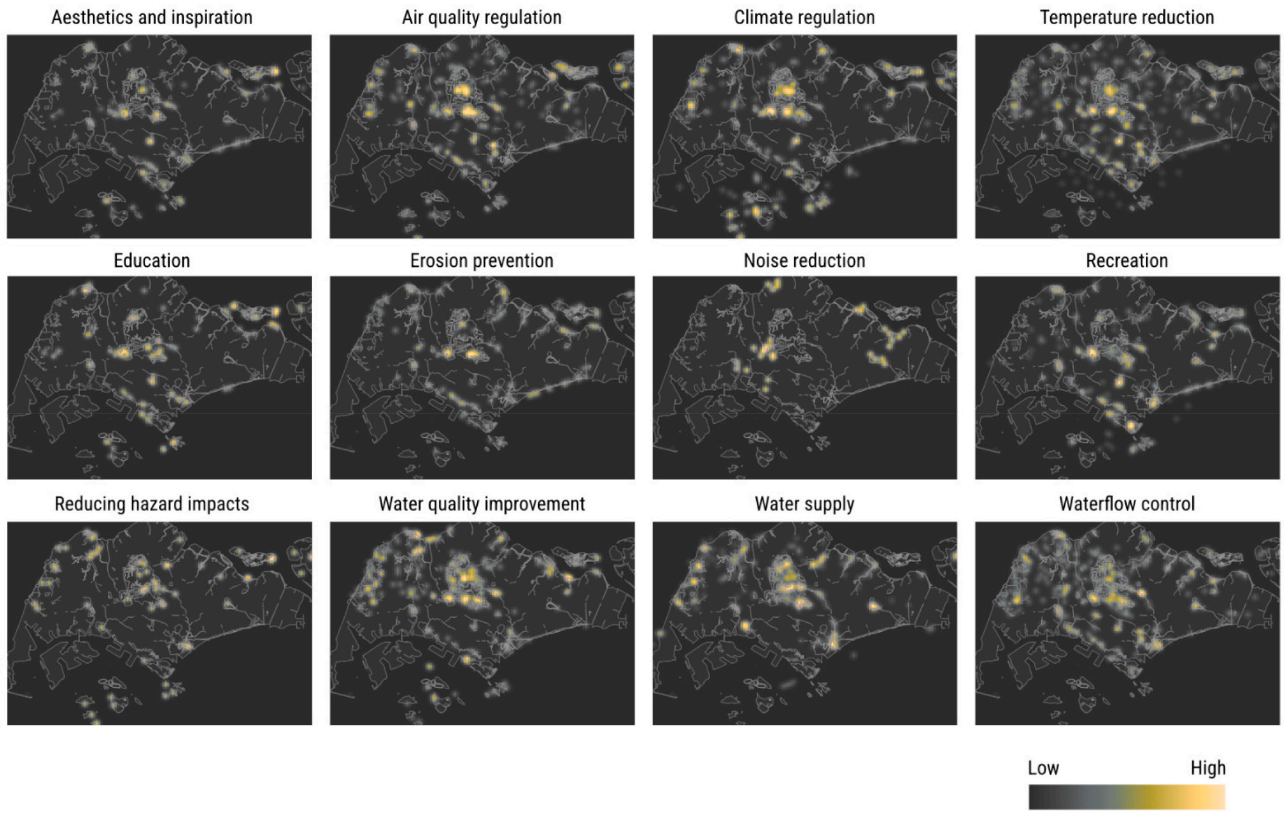

Fig. 10. Participatory mapping outcome for ecosystem services. The warmer the color, the greater the importance the location is in providing the ecosystem service in Singapore's nature space.

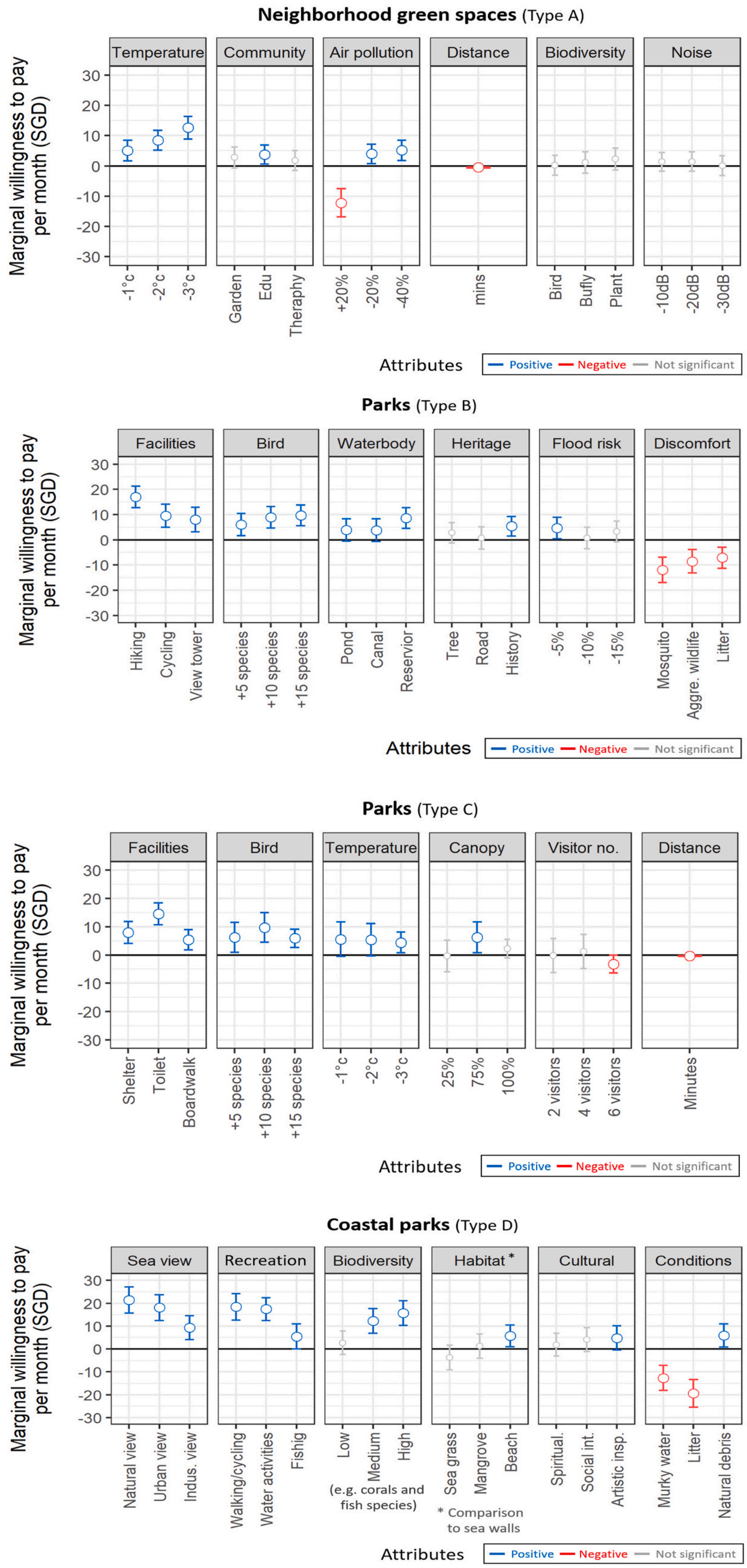

Fig. 11. Choice experiment results from the analysis of neighborhood green spaces and parks based on Yan et al. (2022). Confidence intervals overlapping with zero were not statistically significant and are greyed out.

Table 1
Ecosystem area, sequestration per ha per year, and total sequestration per year for carbon in all ecosystems (median values shown for all ecosystems, except mangrove, seagrass, and mudflats) based on Friess et al. (2023), Friess et al. (2016), Donato et al. (2011), Fourqurean et al. (2012), Chen and Lee (2022).

Ecosystem Class	Ecosystem Area (sqkm)	Ecosystem Area (ha)	Carbon Sequestration (MgC/ha/yr)	Total Sequestration Per Ecosystem per year (Mg C)
Artificial impervious surfaces	287	28′735	−4.75	−136′349
Unvegetated pervious surfaces	55	5′468	0.07	402
Freshwater marsh/swamp	3	258	1.40	362
Managed trees	81	8′104	4.29	34′768
Managed shrub turf	108	10′812	1.22	13′191
Unmanaged trees	140	13′987	3.30	46′159
Unmanaged grass	13	1′344	0.72	968
Mangroves	8	826	1.65	1′360
Seagrass	1	108	0.49	52
Mudflats	2	203	−1.82	−370
Inland water	48	4779	1.24	5′927

Table 2
Regressions of the relative importance of different landscape elements on cooling effect. AIC of this model was 44465.

Variable	Coefficient	p-value
Constant	−3.88	< 0.001
Percentage of landscape of managed trees	0.0117	< 0.001
Patch density of managed trees	−0.000338	< 0.001
Area-weighted mean shape index of managed trees	−0.0765	< 0.001
Percentage of landscape of managed shrub/turf	0.0306	< 0.001
Patch density of managed shrub/turf	0.000290	< 0.002
Area-weighted Euclidean nearest neighbor distance of managed shrub/turf	−0.00132	< 0.017
Patch density of young secondary forest	0.000806	< 0.011
Area-weighted Euclidean nearest neighbor distance of young secondary forest	−0.00146	< 0.003
Percentage of landscape of buildings	0.0579	< 0.001
Area-weighted mean shape index of buildings	0.0910	< 0.001
Percentage of landscape of impervious surface	0.0279	< 0.001
Area-weighted mean shape index of impervious surface	−0.0285	< 0.002

Table 3
Mean, minimum, and maximum removal of PM_{10} per day ($g/m^2/day$) across ecotopes.

Type	Mean	Min	Max
Freshwater swamp and marsh	0.011	0.001	0.018
Mangrove	0.011	< 0.001	0.018
Vegetation with structure dominated by human management (w Tree Canopy)	0.007	< 0.001	0.020
Vegetation with limited human management (w Tree Canopy)	0.013	< 0.001	0.036

Table 4
Estimated mean annual nutrient export per hectare across ecotopes.

Type	Mean Nitrogen Export ∓ s.d. (kg/ha/yr)	Mean Phosphorus Export ∓ s.d. (kg/ha/yr)
Buildings and artificial surfaces	18.6 (7.2)	5.4 (1.9)
Non-vegetated impervious surfaces	10.1 (4.8)	2.8 (1.3)
Freshwater marsh and herbaceous swamp	2.9 (1.2)	0.1 (0)
Mangrove	3.9 (3.7)	0.8 (0.9)
Managed vegetation (tree)	11.1 (4.7)	6.3 (2.5)
Managed vegetation (grass)	6.3 (4.5)	3.5 (1.4)
Unmanaged vegetation (tree)	2.6 (1.2)	0.9 (0.4)
Unmanaged vegetation (grass)	2.4 (2.4)	1.1 (0.7)

Table 5
Associations of urban green space provision indicators within 5-minute walking distance of residence (400 m circular buffer) with mental and general health, based on Zhang, Tan et al. (2021).

	Variables	Adjusted models for mental health			
		Odds Ratio	p value	95 % C.I. for Odds Ratio	
				Lower	Upper
Quantity	Vegetation (tree, shrubs and grasses) cover	1.017	0.107	0.997	1.039
	Tree cover	1.035**	0.004	1.012	1.060

(continued on next page)

Table 5 (*continued*)

	Variables	Adjusted models for mental health			
		Odds Ratio	p value	95 % C.I. for Odds Ratio	
				Lower	Upper
	Green open spaces for recreational activities including built structures	1.041	0.072	1.000	1.093
	Perceived quantity	1.037	0.709	0.855	1.254
	Sum of greenery pixels from Google Stree View	1.005	0.220	0.997	1.013
	Average of greenery pixels from Google Stree View	4.054	0.372	0.187	87.813
Quality	Perceived usage quality based on household survey	1.366**	0.006	1.094	1.706

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2025.101774.

Data availability

All the data produced in this study is available in this document.

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