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Indicators of scientific value: An under-recognised ecosystem service of coastal and marine habitats

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ABSTRACT

Coastal ecosystems provide a broad range of ecosystem services, which can be used to justify habitat conservation. The cultural ecosystem services of coastal ecosystems are generally underappreciated, and this is particularly the case when quantifying their scientific value. We created a tiered set of indicators to quantify scientific value spatially, and tested them using the case study of the island nation of Singapore. We conducted a systematic review of research papers, book chapters, conference reports and academic theses produced across 10 coastal ecosystems in Singapore, including mangroves, seagrasses, coral reefs, beaches and artificial coastal structures. At least 656 articles have been produced on Singapore's coastal zone, with 2201 unique observations, showing that scientific value is spatially variable along Singapore's coastline. Novel indicators such as the Site Impact Factor are able to differentiate scientific value between sites. This method has shed light on an under-recognised, but important cultural ecosystem service, and is applicable to other spatially-bounded coastal, marine and terrestrial landscapes.

1. Introduction

More than 625 million people live in the coastal zone (Neumann et al., 2015), and a large proportion of them rely directly or indirectly on the benefits, or ecosystem services that coastal habitats provide. The scope of coastal ecosystem services is broad and includes provisioning services such as food production, construction materials and pharmaceutical products (Albert et al., 2015), regulating services such as carbon sequestration (Mcleod et al., 2011) and coastal protection (Möller et al., 2014; Spalding et al., 2014; Horchard et al., 2019), and various cultural ecosystem services, such as recreation, tourism, aesthetic, spiritual and scientific value (James et al., 2013; Spalding et al., 2017).

Cultural ecosystem services are generally understudied because of their often intangible nature, and they have received little attention in coastal ecosystems in particular (Quieroz et al., 2017). Cultural ecosystem services are commonly not included in ecosystem service assessments and valuations, which can severely hamper coastal management and decision-making (Hernández-Morcillo et al., 2013; Martin et al., 2016). We are beginning to understand the value and spatial distribution of selected coastal cultural ecosystem services, such as tourism (Spalding et al., 2017; Spalding and Parrett, 2019) and recreation (Zhang et al., 2015). These cultural ecosystem services are generally the most tangible and quantifiable, and can thus be more readily included into coastal management planning (e.g., Ruia-Frau et al., 2013; Martin et al., 2016). However, there are a paucity of suitable indicators that allow the quantification of more intangible cultural ecosystem services, such as the scientific value of ecosystems to society.

Scientific value is defined as the characteristics of an ecosystem that contribute to opportunities for scientific investigation, discovery and knowledge (Tempera et al., 2016; Haines-Young and Potschin, 2018). It is important to robustly quantify cultural ecosystem services for decision making, and scientific value is no exception. This understudied ecosystem service has been used to justify the importance of coastal habitats as diverse as the coral reefs of Aldabra atoll (Gaymer, 1966) and Hawaii (Cesar and van Beukering, 2004), wetlands in China (Li and Gao, 2016) and open water ecosystems (Armstrong et al., 2012; Tempera et al., 2016), despite not being quantified. Some potential metrics have been suggested to measure scientific value, including the presence of study sites or species of particular interest, statistics of scientific publications, or willingness to pay for research programmes (de Groot et al., 2010; Tempera et al., 2016). However, few of these potential metrics have been tested, and studies that have attempted to

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use them (e.g., Kibria et al., 2017) have done so in a cursory manner, where scientific value cannot be mapped spatially. Perhaps the strongest attempt to quantify scientific value has been conducted in terrestrial ecosystems for the Amazon rainforest (Correia et al., 2016), but even here scientific value was not put within an ecosystem service framing. Only one rudimentary indicator (number of published papers) was used and the study was unable to quantify scientific value spatially. We currently lack comprehensive indicators that spatially quantify multiple aspects of scientific value in a repeatable and comparative manner.

The relative difficulty in appropriately quantifying intangible cultural services such as scientific value has resulted in a lack of empirical evidence to support how much they can contribute to ecosystem valuations (Schaich et al., 2010). The result is that the value of cultural service provision is widely considered as under-estimated in many settings (Quieroz et al., 2017). This may have significant implications for holistic management strategies, which are attempting to follow the ecosystem services framework, wherein the management objectives may be prioritised based on inaccurate or inadequate information (Chan et al., 2012). An incomplete understanding of cultural ecosystem services can affect how an area is managed, its perceived value, and eventually, the level of ecosystem service that can be provided by that area (Chan et al., 2012).

The aim of this study was to quantify the scientific value of coastal ecosystems through the creation of a tiered set of indicators, that include novel spatial indicators of scientific value, such as Ecosystem Impact Factor and Site Impact Factor. While we intend for these indicators to be broadly applicable to all ecosystems (including terrestrial), we tested these indicators using the case study of tropical coastal and marine ecosystems in Singapore, an island nation in Southeast Asia.

2. Conceptual framework

2.1. Definitions of scientific value

In an ecosystem services framing, scientific value is defined as the presence of features in an ecosystem with special scientific interest (de Groot et al., 2010), or the characteristics of an ecosystem that contribute to opportunities for scientific investigation, discovery and knowledge (Tempera et al., 2016; Haines-Young and Potschin, 2018). Scientific value is sometimes combined with, or used interchangeably with educational value (e.g., de Groot et al., 2010; Mocior and Kruse, 2016; Zandersen et al., 2017). For the indicators presented in this current study, we focus on scientific value only, as an ecosystem service that is distinct from educational value. Although education as a cultural service has the potential to provide value on a broad scale collectively, its value can be viewed as largely intrapersonal, that is most important to the person experiencing that ecosystem service. Scientific value differs as an ecosystem service, because it is one that contributes to a broader field of knowledge, and incorporates many more facets beyond education. The key distinction we draw here is that educational value requires many individuals to engage with it collectively before it would be considered as a valuable service on more than a localised scale. Whereas the information that scientific value can provide has the potential to be valuable on a broad scale as soon as the information is disseminated.

Key to the definition of scientific value is that the ecosystem provides *opportunities* for value. Scientific value cannot be realised until it is extracted, or those opportunities taken through the use of complementary (human or man-made) capital. Thus, scientific value is not immediately inherent in all ecosystems, similar to other intangible cultural ecosystem services. One way of realising the contribution an intangible ecosystem service makes to society, is to quantify it. However, attempts to quantify intangible services have notably different success rates due to the tendency of assessors to rely on economic valuation methods (Farber et al., 2002). Frequently used, direct monetary assessments such as contingent valuation and cost-benefit analyses, have the potential to yield important information on the provision of certain cultural ecosystem services (Farber et al., 2002). However, the economic focus of these techniques can lead to inaccuracies, as many intangible services, such as scientific value, have non-market values (Spangenberg and Settele, 2010). For this reason, it would be inappropriate to use a direct monetary assessment to define and quantify scientific value, and the creation of a suite of alternative quantifiable indicators could provide a much-needed increase in cultural ecosystem assessment accuracy, and subsequently their inclusion into decision making.

2.2. Tiering of scientific value indicators

There is no single indicator that can adequately capture all facets of scientific value. This study proposes a tiered approach that incorporates multiple indicators that capture the many facets of scientific value (Table 1). Similar to other ecosystem services (such as carbon; IPCC, 2006), tiering allows flexibility based on capacity, information

Table 1
The indicators of scientific value developed for this study.

Indicator	Description
Tier 1 – ecosystem level indicators	
1.1 Number of articles per ecosystem	Quantity of publicly-accessible articles published in journals, books, conference proceedings and student theses
1.2 Ecosystem impact factor	The number of citations per ecosystem divided by the number of articles published from that ecosystem, as an indicator of the influence of each ecosystem within the scientific literature
1.3 New species and genera per ecosystem	The number of species and genera described from an ecosystem that are new to science
1.4 Author reach	Number of authors and co-authors who contributed to the research, as an indicator of academic reach and the size of the research community utilizing opportunities for scientific value from ecosystems
Tier 2 – location level indicators	
2.1 Number of articles per site	The number of articles published on a particular site. This is an indicator of the relative contribution of a particular site to scientific value
2.2 Site impact factor	The number of citations per site divided by the number of articles published from that site. This is an indicator of the influence of each site within the scientific literature, and its contribution to scientific value
2.3 Number of articles per ecosystem per site	The number of articles published on different ecosystems per site. This is an indicator of the relative influence of particular ecosystems on the scientific value of a site
Tier 3 – context-specific indicators	
3.1 Non-published opportunities to extract scientific value	This may include information on opportunities for citizen science, student reports, commercial studies, data derived from Environmental Impact Assessments, and government surveys and reports
3.2 Approved research permits	The number of research permits approved for an ecosystem or site is an indicator of research opportunity and effort
3.3 Allocated research funding	A direct indicator of economic value and priority placed on research conducted in a particular ecosystem
3.4 Others	Other indicators specific to the case study, including the incorporation of other forms of knowledge, as determined by the assessor

availability and study purpose. Each tier is comprised of multiple indicators, and indicators can be added or removed, depending on the assessor's requirements or unique aspects of their study system.

In this study, Tier 1 quantifies scientific value at the ecosystem level (Table 1). This is the broadest tier, because fundamentally an ecosystem service has to be described for, and attributed to a specific ecosystem. By attributing scientific value at the ecosystem level, this tier is aspatial and allows the quantification of the relative importance of different ecosystems for a particular case study. Tier 1 includes two indicators that define scientific value through publicly accessible scientific contributions to the literature. These include the number of articles published per ecosystem (1.1), and the ecosystem impact factor (1.2); a novel metric that calculates the number of citations accrued by all articles published in that ecosystem divided by the total number of articles published in that ecosystem.

Citation metrics are only one way to measure impact, and for this reason there are two Tier 1 indicators that do not rely on citation or article numbers. One specific metric of scientific value is the number of species or genera described from an ecosystem that are new to science (1.3), as one particular and easily quantifiable contribution an ecosystem can make to broader scientific knowledge. Additionally, author reach (1.4) links strongly to the definition of scientific value above, as it explicitly represents the number of opportunities for the extraction of scientific value (Kibria et al., 2017). Author reach is calculated as the number of authors contributing to published articles for a particular ecosystem. Author reach does not represent unique authors (as often an author will contribute to more than one paper), but rather the number of total opportunities for authors to participate in research in a particular ecosystem. This indicator also does not include other participants in research that are not acknowledged in the authorship list, though authorship, if assigned appropriately, should highlight opportunities for scientific value based on a substantial contribution to the intellectual conception or completion or the research (e.g., Berg, 2018).

Tier 2 quantifies scientific value across space by incorporating location-specific information on where scientific value is extracted. Ecosystem services are rarely uniform across a landscape, but vary due to numerous physical and socioeconomic factors. It is important in environmental management to understand spatial variation in ecosystem service provision, in order to inform ecosystem service-development trade-off analyses across a landscape (Bagstad et al., 2013; Sun et al., 2015).

Spatial information is most easily extracted from study site descriptions contained in scientific articles. This information is used in three indicators (Table 1), including the number of articles per site (2.1) and a site impact factor (2.2) that is calculated as the number of citations accrued per site divided by the number of articles produced from that site. While locations themselves cannot be ascribed an ecosystem service value, it is still important for decision makers to know which locations have made a particular contribution to scientific knowledge. To link more specifically to the ecosystems of study, a third indicator, *Indicator 2.3,* calculates the number of articles per ecosystem per site. Using Tier 2 indicators in conjunction with Tier 1 also links them specifically to an ecosystem services framing.

Tier 3 incorporates context-specific information that may be available to particular ecosystem service assessors. While Tiers 1 and 2 can be quantified for any case study through a comprehensive literature review, Tier 3 makes use of additional information that may only be available for a specific case study. This gives an assessor the flexibility to incorporate their own indicators that have specific meaning for their context. Examples of potential Tier 3 indicators include the number of non-published data sources such as internal government reports or Environmental Impact Assessments (3.1). Approved research permits (3.2) can be used as a measure of official opportunities that have applied to extract scientific value. Allocated research funding (3.3) does not link directly to opportunities for scientific value, but is required to support creators of scientific value and provide opportunities to undertake research, and gives an indication of the monetary value that decision makers and society put on the scientific value of a particular ecosystem (Table 1).

2.3. Limitations of the proposed scientific value indicator framework

Indicators 1.2 and 2.2 represent scientific value as an impact factor, similar to how scientific journals are ranked. As academics and applied researchers, we are well aware of the issues around measuring academic impact using this metric. The impact factor of a journal does not always correlate with the quality and impact of the individual article (Simons, 2008; Chorus and Waltman, 2016), and the same may hold true when calculating Ecosystem and Site Impact Factors. It is for this reason that Tier 1 is composed of indicators that do not all rely solely on citation metrics.

A number of indicators rely on the published literature (journal articles, book chapters, conference proceedings and theses) as their core dataset because they are publicly accessible and searchable by any assessor. However, this precludes other forms of scientific knowledge outputs, such as internal government reports or unpublished citizen science records. These all represent opportunities for the extraction of scientific value, but cannot be easily searched or collated during an assessment. If assessors know that such sources are available for their study location, then these should be included in a Tier 3 assessment.

A focus on formal scientific literature as an indicator of scientific value may also miss other forms of knowledge, such as traditional ecological knowledge. For this reason, the most recent version of the Common International Classification of Ecosystem Services (CICES) Framework has broadened the definition of scientific knowledge to include these other forms of knowledge (Haines-Young and Potschin, 2018). While this was not expected to be an issue in the Singapore context, it may be a limitation when applying the indicators suggested in this study to other contexts where the coastal zone has a stronger connection with local communities. Other forms of knowledge should be included within a Tier 3 assessment.

3. Materials and methods

3.1. Study site description

Indicators of scientific value were tested to the Tier 2 level in Singapore; a country located in a region that is fundamentally underrepresented in cultural ecosystem service assessments (Martin et al., 2016). Singapore is also a suitable case study because it represents a complex and spatially heterogeneous coastal landscape, comprised of multiple tropical coastal ecosystems. The assessment of Singapore's coastal scientific value was conducted up to Tier 2 in order to show the broader utility of the indicator framework, since it is Tiers 1 and 2 that are most transferrable to other locations.

Singapore is home to a range of coastal ecosystems, including mangrove forests, seagrass meadows, tidal flats, coral reefs, rocky shores and natural and artificial beaches. Singapore is a tropical coastal biodiversity hotspot, home to at least 255 hard coral species (Huang et al., 2009), 36 mangrove vegetation species (Saenger et al., 2019), and 12 seagrass species (Yaakub et al., 2013). However, Singapore's coastal ecosystems have undergone rapid transformation due to land reclamation for urban and industrial development, particularly over the last 60 years. Singapore has lost more than 70% of its coral reefs since 1922 due to land reclamation (Heery et al., 2018), and more than 90% of its mangrove forests since the 1800s (Lai et al., 2015) due to land reclamation, reservoir construction and aquaculture (Friess et al., 2012). Singapore's coastal ecosystems continue to be impacted by stressors such as pollution and sedimentation from land use change and dredging (Lai et al., 2015; Sin et al., 2016; Heery et al., 2018).

Today, many of Singapore's remaining coastal ecosystems have been legally protected. Two of Singapore's four Nature Reserves incorporate coastal ecosystems within their management boundaries, including mangroves and rocky shore. Singapore opened its first Marine Park in 2015, covering 40 ha and encompassing ecosystems such as coral reefs, seagrass meadows and sandy shores. Singapore's remaining coastal ecosystems have and continue to provide important ecosystem services such as food provision from local fisheries and global climate mitigation through carbon sequestration (Friess, 2017). Singapore's coastal ecosystems also contribute important cultural ecosystem services, and a number of intertidal and subtidal locations are accessible to the public for recreational and tourism use.

3.2. Systematic review

A systematic review was conducted to comprehensively assess the research papers and reports conducted on Singapore's coastal ecosystems up to the year 2018. A number of sources and bibliometric databases were analysed. Google Scholar was used as the primary search database because it is the most expansive, and able to better search for conference proceedings, book chapters and other grey literature sources. The systematic review was also conducted on the databases Web of Science and Scholarbank@NUS, the latter a local academic database that includes unpublished sources such as undergraduate and graduate theses.

Two iterations of search terms were used (Table 2). To capture a broad sweep of the literature, the broad search string “Singapore” AND “Coast” was first used. The search string “Singapore” AND “beach” OR “mangrove” OR “mud flat” OR “open water” OR “reef” OR “rocky shore” OR “seagrass” OR “seawall” OR ”tidal flat“ was subsequently used, to pick up articles related to each focal ecosystem that may have been missed in the initial search.

Several exclusion criteria were applied to the initial search results. Duplicates produced by the multiple searches were removed. All titles and abstracts were screened for relevance, specifically: 1) whether that the article referred to a coastal ecosystem; and 2) whether primary data were collected in Singapore. If such information was not immediately available from the article title or abstract, the articles were read in their entirety. Only studies relating to new data collected in Singapore, or discussion specific to Singapore were included, and literature reviews were omitted.

For each article summary information was collected, such as: the surname of the first author; number of coauthors; article title; year of publication; type of article (journal article, conference or book chapter, graduate thesis, undergraduate thesis, report, or other); name of the journal, conference proceedings or book that it was published in; and number of citations received on Google Scholar. The study ecosystem(s) for each article (beach, coral reef, mangrove, open water, rocky shore, seagrass, seawall, tidal flat, or other) were also recorded. “Open water” is a broad category of ecosystems found in open sea areas, because a more specific typology of water and/or marine benthic ecosystems does not exist in Singapore. If a study was conducted across multiple ecosystems, then the individual ecosystems studied were listed.

The individual locations where each study was conducted were extracted from the article text, Tables or Figures. Geographic coordinates were used if they were reported in the text, but most often a location was ascribed to a site name described in the text. The location of each site was calculated in GIS, with coordinates referring to the centre of the site. Since studies were overwhelmingly site-based, the resulting data were represented in a point layer, not a continuous layer. Studies that were conducted at the national scale (n = 91) were not included in the Tier 2 analysis, as they were not ascribed to a specific location. These studies mostly related to national-scale oceanographic studies.

3.3. Calculation and statistical analysis of indicators

Tier 1 and 2 indicators were calculated from the database as described in Table 1. For Tier 1, ecosystems were ranked for each indicator, these rankings were scored from 1 to 10 (the relative position of one ecosystem against all the others), and the composite score across all indicators determined the ecosystems' final ranked position. Tier 1 indicators were further analyzed in a Principal Components Analysis (PCA) using the package “stats” in R (Version 3.5.1) (R Core Team 2018) and R Studio (Team RStudio, 2019). PCA is a suitable tool to statistically analyse differences in scientific value between ecosystems, as it is able to utilize information from multiple indicators within the scientific value framework.

4. Results

4.1. Ecosystem level indicators of scientific value (Tier 1)

Mangroves had the highest scientific value assessed at Tier 1, with the highest average ranking across all indicators, and the highest values for *Indicators 1.1* and *1.3* (Table 3). Open water ecosystems and coral reefs also have high scientific value at this Tier, with open water having the highest Ecosystem Impact Factor and coral reefs having the highest Author Reach. Seagrasses had the lowest scientific value of all quantified ecosystems, with few published studies and the lowest Ecosystem Impact Factor.

For *Indicator 1.1,* mangroves were the most published coastal and marine ecosystem in Singapore, with 173 publications found in the review, accounting for 21% of all publications analysed. Coral reefs were also a popular ecosystem of study, accounting for 20% of all publications. 158 studies (19.5%) were conducted on open water ecosystems, and were primarily concerned with oceanography, particularly the modelling of tidal currents and anomalies in the waters around Singapore. Of the identified ecosystems, seagrasses are currently the most poorly studied in Singapore, with only 30 publications specific to this ecosystem.

The calculation of *Indicator 1.2* showed that open water ecosystems

Table 2

Databases and search terms used in the systematic review.

Database	Search string	Pre-screening search results	Post screening search results	% grey literature
Google Scholar	“Singapore” AND “coast”	1000	337	24.9
Web of Science	“Singapore” AND “coast	131	29	18.2
Scholarbank@NUS	“Singapore” AND “coast”	718	22	81.8
Google Scholar	“Singapore” AND “beach” OR “mangrove” OR “mud flat” OR “open water” OR “reef” OR “rocky shore” OR “seagrass” OR “seawall” OR ”tidal flat”	1000	61	29.5
Web of Science	“Singapore” AND “beach” OR “mangrove” OR “mud flat” OR “open water” OR “reef” OR “rocky shore” OR “seagrass” OR “seawall” OR ”tidal flat”	335	199	6.0
Scholarbank@NUS	“Singapore” AND “beach” OR “mangrove” OR “mud flat” OR “open water” OR “reef” OR “rocky shore” OR “seagrass” OR “seawall” OR ”tidal flat”	180	8	100
Total	3364		656	22.1

Table 3
Ecosystem-level indicators of scientific value (Tier 1), ranked by total score across all indicators. For method of calculation see Section 3.3.

Ecosystem	Indicator					
	1.1 # of articles	1.2 Ecosystem Impact Factor	1.3 # new species	1.3 # new genera	1.4 Author reach	Overall ranking/ 10
Mangrove	173	25.54	67	4	485	1.4
Reef	162	22.44	10	1	574	2.8
Open water	158	26.46	7	0	472	3.2
Beach	76	22.16	12	2	189	4
Tidal flat	80	16.14	14	0	198	4.6
Rocky shore	40	23.08	6	0	93	5.6
Seawall	42	16.50	0	0	145	6.6
Other	33	20.88	0	0	80	7.2
Seagrass	30	11.67	3	0	103	7.6
Unknown	11	20.36	4	0	24	7.6

have the highest Ecosystem Impact Factor, defined as the average number of citations per publication per ecosystem (26.46). Papers published on open water ecosystems were primarily oceanographic or pollution studies. Papers published on topics relating to mangroves, rocky shores and coral reefs were also well cited, with average Ecosystem Impact Factors of 25.54, 23.08 and 22.44 respectively. Papers describing research in seagrass ecosystems received the fewest citations relative to the number of papers published.

Indicator 1.3 calculated that 7 genera new to science have been described from Singapore's coastal and marine ecosystems. Four of the new genera from Singapore were described from mangroves. New genera described from Singapore's coastal ecosystems included protzoans such as *Suturothrix* spp. (Enchelyidae; Foissner, 2008), insects such as *Mangalcoris* spp. (Miridae; Murphy and Polhemus, 2012) and *Ngirhaphium* spp. (Dolichopodidae; Evenhuis and Grootaert, 2002) and sea anemones such as *Synpeachia* spp. (Haloclavidae; Yap et al., 2014). This indicator also showed that at least 123 new species have been described from Singapore's coastal and marine ecosystems. 54.5% of the new species described were found in mangroves, and mostly referred to invertebrates. One paper alone, from research conducted at a mangrove site on the west coast of Singapore, was responsible for the description of 14 new species of fly (Grootaert, 2018). Other notable studies that described multiple new species were linked to large-scale research initiatives such as Singapore's Comprehensive Marine Biodiversity Survey, that took place between 2010 and 2015 (Tan et al., 2016).

Regarding *Indicator 1.4,* Singapore's coastal and marine ecosystems have provided at least 2363 individual opportunities for authors to participate in the extraction of scientific value. Opportunities for scientific value were highest for coral reefs (574 opportunities), mangrove (485) and open water (472) ecosystems. These three ecosystems alone accounted for 65% of all research opportunities, clearly showing the relative popularity of these three ecosystems for research in Singapore compared to understudied ecosystems such as seagrasses (103) and rocky shores (93).

When all Tier 1 indicators were taken together, it was clear that mangroves, open water and coral reefs provided a level of scientific value that was distinct from Singapore's other coastal ecosystems (Fig. 1). PCA analysis explains > 70% of the overall variation in Tier 1 indicators, with mangroves further removed from open water and coral reefs, due to the influence of *Indicator 1.3*, as a large number of new species and genera have been discovered in Singapore's mangroves.

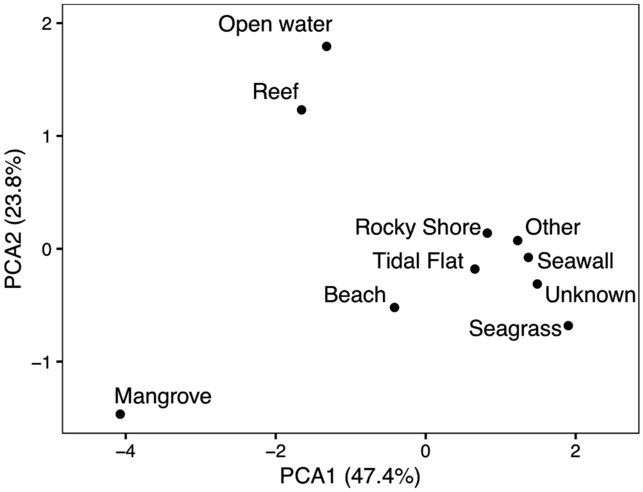

Fig. 1. Principal component analysis of the Tier 1 indicators of scientific value.

4.2. *Location level indicators of scientific value (Tier 2)*

The systematic review generated 2201 individual, spatially explicit observations of scientific value in Singapore's coastal and marine environment across 656 studies. *Indicator 2.1* showed that while scientific value is distributed across Singapore's mainland and offshore islands (Fig. 2), the most popular sites for research were Pulau Semakau and Pulau Hantu (106 and 98 unique observations), followed by Raffles Lighthouse (94), St. John's Island (90), Sungei Buloh Wetland Reserve (83), Pasir Ris Park (69), Changi Beach (65), Mandai Mangrove and Mudflat (63), Sister's Island and East Coast Park (62). Five of these locations are dominated by coral reefs, and their high representation is reflected in the fact that most coral reef studies were conducted on multiple reefs (an average of 3.79 sites per study), increasing the number of total observations for locations where this ecosystem is present.

Site Impact Factor (*Indicator 2.2*) showed substantial variation across Singapore's coastal landscape. Harbourfront, along the south coast of Singapore, had the highest site impact factor of 149.00, followed by NW Sentosa (50.33), Tuas 2 (49.82), Sembawang (49.73), Bedok (47.20), Punggol West (45.57), Keppel Bay (43.67), Pedra Branca (43.00), Sarimbun (41.27) and West Coast Park (41.00). However, impact factor can be influenced by a small number of highly cited papers; for example, the Harbourfront location has the highest Site Impact Factor, but only 1 (highly cited) research study was conducted at this site. When the Site Impact Factor is calculated only for sites with > 10 observations, a number of new sites appear: Tuas 2 (49.82, n = 11), Sembawang (49.73, n = 26), Punggol West (45.57, n = 14), West Coast Park (41.00, n = 19), Kranji mudflats (38.97, n = 38), Sarimbun (38.83, n = 12), Tanah Merah (38.48, n = 23), Jurong Island (37.00, n = 15), Lim Chu Kang (35.90, n = 51) and Pasir Ris (33.88, n = 68). Only 5 sites are found on both rankings, showing that the Site Impact Factor metric is particularly sensitive to the influence of specific highly cited papers when the number of observations or studies used to calculate the metric are low.

Indicator 2.3 shows the strong linkages between Tiers 1 and 2. Sites that produced the largest quantity of published research outputs (*Indicator 2.1*) were often home to ecosystems that were ranked as having high scientific value according to the suite of Tier 1 indicators used (Fig. 3). Most sites incorporated multiple ecosystems, but they were often dominated by the production of papers relating to a specific ecosystem of high Tier 1 scientific value, such as coral reefs (Pulau Semakau n = 106, Pulau Hantu n = 98, Raffles Lighthouse n = 94, St John's Island n = 90, Sisters Island n = 62) or mangroves (Sungei Buloh n = 83, Pasir Ris n = 69 and Mandai n = 63).

5. Discussion

5.1. *The scientific value of Singapore's coastal and marine ecosystems*

All coastal and marine ecosystems in Singapore provide scientific

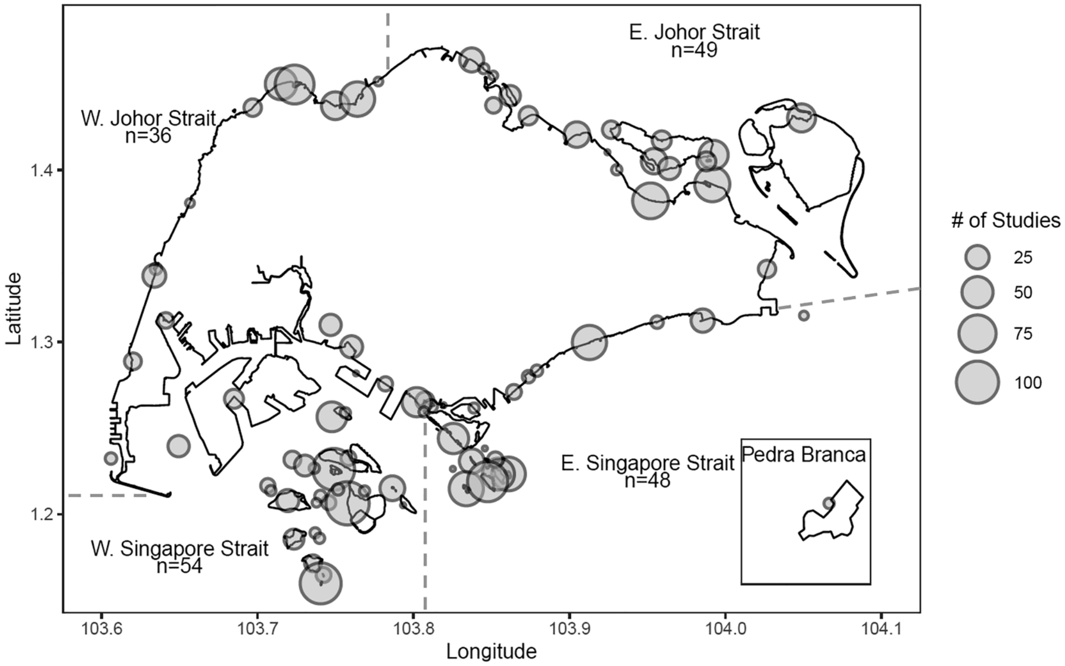

Fig. 2. Spatial distribution of published articles per site in Singapore. Quadrants represent the number of studies conducted in open water, where a specific location was not defined.

value, though the level of ecosystem service provision differs between them. The Tier 1 indicators were successfully able to distinguish levels of scientific value between different ecosystems across four different metrics that encompass different aspects of scientific value. The Tier 1 indicators showed that three ecosystems – mangroves, open water and coral reefs – had been ascribed a much higher scientific value in Singapore, compared to other coastal ecosystems. Mangroves produced the highest levels of scientific value according to Tier 1, with more publications produced on this ecosystem than any other. A disproportionately large number of species and genera new to science were also described from Singapore's mangroves, compared to other coastal and marine ecosystems in Singapore. Many of these were described from Mandai Mangrove and Mudflat, which has been well known as the site of discovery of a number of new Coleoptera and Hemiptera species for decades (Briffett, 1991; Friess et al., 2012). The high number of taxa discovered in Singapore's mangroves is in large part due to the existence of research centers focused on biodiversity and taxonomy (the Raffles Library and Museum, established in 1877; re-established as the Raffles Museum for Biodiversity Research in 1998 and the Lee Kong Chian Natural History Museum in 2014). The presence of several key researchers focused on mangrove crab taxonomy (Tan, 2017) has furthered this trend.

Open water and coral reef ecosystems were also ranked as having high scientific value. Open water had the highest Ecosystem Impact Factor. Research studies on this ecosystem were mostly concerned with oceanography and coastal/ocean engineering disciplines. This scientific discipline has a strong influence on overall citation rates (Radicchi et al., 2008; Slyder et al., 2011), upon which the impact factor metric is based. The database collected for Singapore suggests that oceanographic journal papers (in open water ecosystems) had higher citation rates than papers with research questions of taxonomy or basic ecology (found in many of the other ecosystems). Oceanographic studies are popular in Singapore due to the establishment of key oceanographic research laboratories such as the Tropical Marine Science Institute at the National University of Singapore (Chou, 2017; Taylor 2017) and the Singapore-Delft Water Alliance, and the development of a number of hydrodynamic models for Singapore's waters (e.g., Kurniawan et al., 2011).

Coral reef studies were ranked highest in terms of opportunities for author reach, with almost 100 more opportunities for scientific value being exploited for coral reefs compared to the next ranked ecosystem. Publications relating to coral reefs had an average of 3.5 authors per paper, though this was highly variable, with some reef papers having 13 authors (Chou et al., 2016). This may reflect the complex nature of logistics, field assistance, and multidisciplinary analysis required when studying reef environments. The number of authors participating in coral reef research also reflects the long legacy of study on this ecosystem since at least the 1960s, including the establishment of an offshore coastal and marine research station in the southern islands of Singapore, where Singapore's reefs are located (Chou, 2017).

Seagrass meadows received a low score for scientific value, as assessed using these indicators. This supports other studies that have attempted to assess the broader societal value of seagrass. For example, Duarte et al. (2008), showed that up to the mid 2000s, seagrasses were substantially under-researched globally compared to other coastal ecosystems such as coral reefs. The same study also highlighted how seagrasses were fundamentally underrepresented in the media, accounting for only 1.6% of new stories on coastal ecosystems. The low scientific value of seagrass doesn't indicate that it is less important, rather that this ecosystem is not as well studied, and thus there have been fewer previous opportunities to extract scientific value from its latent potential. Communication of the importance of seagrasses to science and communities has been highlighted as a key direction for future seagrass research (Nordlund et al., 2018). The recommendations of Duarte et al. (2008) to increase the representation of seagrass in coastal research – including an increase in formal and informal educational activities for seagrasses, and better partnerships between researchers and public communicators – will go some way to increasing the scientific and public value of this important, but currently under-recognised ecosystem.

5.2. Spatial variation in scientific value

The Tier 2 indicators presented here have allowed investigation into how the provision of scientific value differs spatially. Scientific value shows clear variation in ecosystem service provision along Singapore's

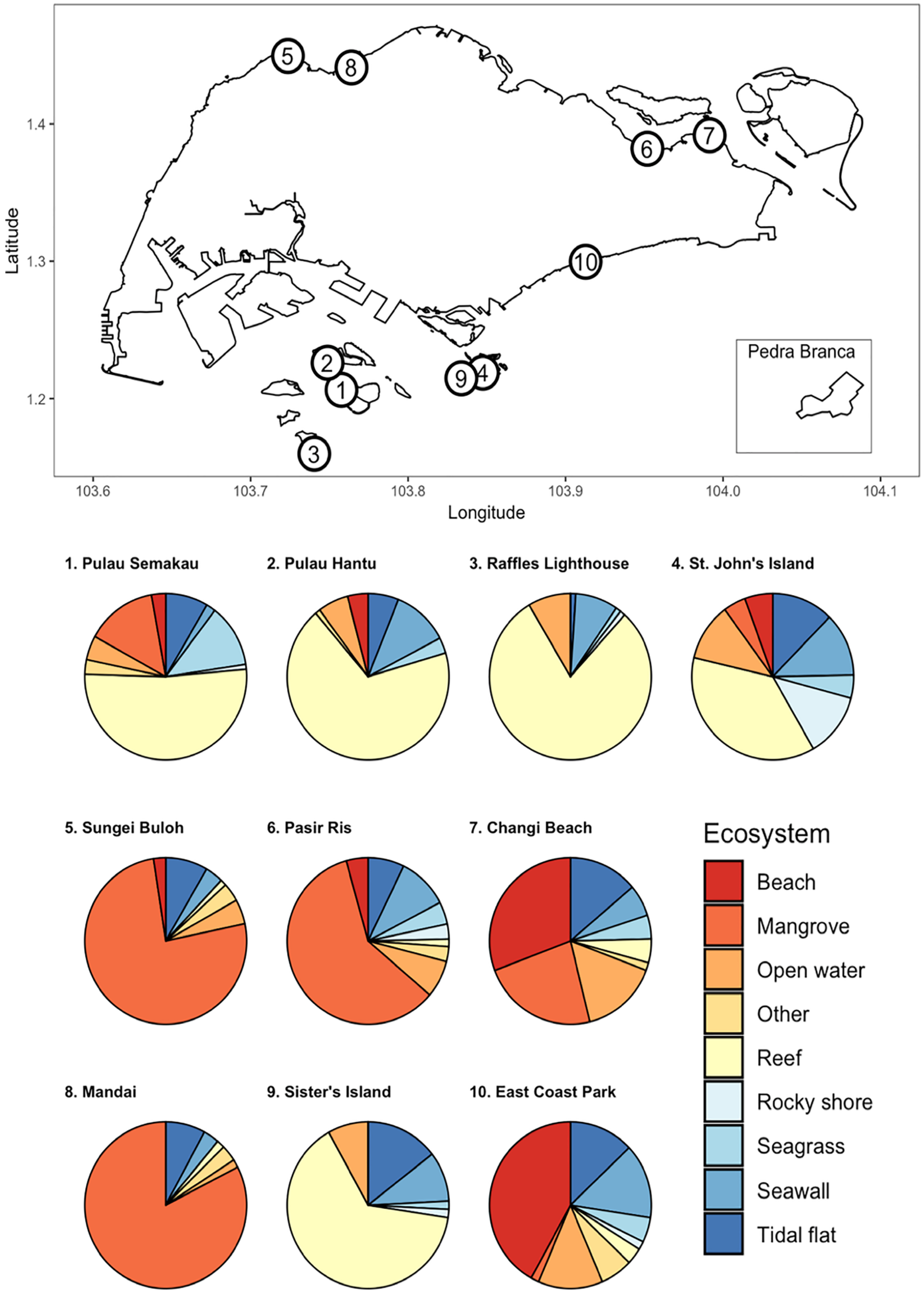

Fig. 3. Distribution of ecosystems per site, for 10 sites with the largest number of studies. See also Table S1.

coastline. As an ecosystem service, the distribution of scientific value is strongly determined by the distribution of underlying coastal ecosystems. Thus, sites that are home to large areas of ecosystems that ranked highly in Tier 1 are strongly represented at Tier 2. For example, coral reefs were one of the highest ranked ecosystems as per the Tier 1 indicators, particularly *Indicator 1.1*, the number of scientific articles produced (162 articles; ranked 2nd overall). In Tier 2, this translates to sites with a high number of published articles (*Indicator 2.1*) also being strongly represented. Since Singapore's reefs have high scientific value according to the Tier 1 assessment, this would influence the overall spatial distribution of scientific value at Tier 2. Thus, the southern offshore islands of Singapore become a hotspot of scientific value; these islands are where the majority of Singapore's coral reefs are located due to lower levels of turbidity compared to the north coast of Singapore, where large fluvial sediment sources such as the Johor estuary are present (Heery et al., 2018). *Indicator 2.3* (articles per ecosystem per site) strengthens this link between the Tiers further, as it shows that 8 of the top 10 sites for scientific value according to Tier 2 are sites where the dominant ecosystems were ranked 1st (mangroves) and 2nd (coral reefs) for Tier 1.

Spatial variation can also be explained in part by site accessibility, such as whether the site is open to the public, or infrastructure such as boardwalks and site managers are present. Six of the ten sites with the highest scientific value are sites managed by the National Parks Board, and are open to the public. However, accessibility cannot entirely explain spatial variation, as some sites are currently state land with no public access allowed (Mandai), or are physically inaccessible and require expensive boat charters to access (for example, many of the coral reef sites to the south of Singapore). These sites continue to be popular for research despite their limited accessibility, either because they represent good examples of a particular ecosystem, or they have a long history of research. For example, the now publicly inaccessible Mandai Mangrove and Mudflat has been a site of extensive scientific research effort since at least the 1980s, primarily for sample collection for invertebrate taxonomy studies (Friess, et al., 2012). It is harder to ascribe earlier studies to this site due to lack of study site maps in publications, extensive coastline changes and difference in site nomenclature, though scientific research at sites close to, or at Mandai, has been described from at least the turn of the 20th century (Ridley, 1901, 1907). Ecosystems and sites with a legacy of research effort have increased familiarity and long-term data, encouraging researchers to return and build upon previous research endeavours.

5.3. *Comparison of scientific value indicators with other approaches*

Comparisons of the presented framework of indicators with other approaches is difficult because scientific value has rarely been quantified before, though suggestions have been made as to how this could potentially be done. A small number of researchers have conceptualized scientific value in terms of the number of scientific studies conducted in an ecosystem, assessed in terms of the number of scientific articles produced (de Groot et al., 2010; Sun et al., 2018). The present framework incorporates this as an indicator (*Indicator 1.1*), so it's results can be easily compared to these existing conceptualizations of scientific value. However, Tier 1 in the present study goes much further than these previous basic conceptualizations of scientific value, by also providing information on citation metrics to better assess the impact of each article, rather than relying solely on the number of articles produced.

It is also important to note that using the number of scientific articles as the sole metric of scientific value does not adequately match with the full definition of scientific value, which requires the assessment of the *opportunities* for scientific investigation, discovery and knowledge (Tempera et al., 2016; Haines-Young and Potschin, 2018). The scientific value framework presented here moves beyond the single, basic metric of article volume, to include a greater diversity of metrics that help capture the multi-faceted nature of scientific value, such as the number of authors who have had the opportunity to extract scientific information (*Indicator 1.4*). As such, the framework presented here provides indicators that more strongly match the definition of scientific value than those suggested previously.

5.4. *Management implications of scientific value indicators*

The quantification of scientific value is not purely an academic exercise, but can have real applied impact, if sufficient information on this ecosystem service is available. Scientific value as an ecosystem service may have already influenced land use planning and conservation in Singapore's coastal environment. For example, the scientific value of Mandai Mangrove and Mudflat has been recognized by environmental stakeholders for a number of decades (Briffett, 1991), and rudimentary attempts had been made to characterise it through metrics such as species discovery (*Indicator 1.3*) (Friess et al., 2012). Local environmental stakeholders and academic researchers have led calls for its conservation (Chua, 2013), and when the formal conservation of this site was announced in 2018, media reporting highlighted previous scientific data collected at Mandai, and opportunities for future research at the site (Choo, 2018; Tay, 2018). This example shows that scientific value has the potential to be an influential ecosystem service in decision making, and one that a range of government and non-governmental stakeholders can understand and value.

There is evidence to suggest that successful identification of cultural ecosystem services can be a significant motivator for managing and conserving areas for amenity-related purposes (Chan et al., 2012). Beyond individual examples such as Mandai, a transparent set of indicators can help formalize scientific value as a consideration in future management and conservation decisions. Environmental data is most likely to be used by decision makers when it is accessible, easy to interpret and straightforward to integrate into the decision-making process (Cvitanovic et al., 2015). The tiered set of scientific value indicators presented here have been constructed with these key points in mind, with the view of being useable by, and accessible to the various stakeholders that may contribute data or viewpoints into conservation and management decision-making. In particular, the indicators have been designed to be quick to create, using information that where possible is available from publicly accessible literature databases such as Google Scholar. The indicators are also designed to be straightforward to calculate, interpret and comprehend, without the need for specialized software. The indicators of scientific value are also flexible; the framework presented here should be modified to suit the characteristics of the study location and the ecosystems present, either by removing or adding to the Tier 1 and Tier 2 indicators, or by incorporating case study-specific information in Tier 3.

The Tier 2 indicators presented here are designed to be simple to visualize, as this is a particularly important factor in the effective communication of environmental data to decision makers (Grainger et al., 2016). When managing changes to ecosystem status that can occur over large spatial scales, it is important to develop quantifiable indicators for cultural service assessments that are spatially explicit and easily mapped. The ability to visualise 'hotspots' and changes in cultural service provision over space and time provides environmental managers with the information required to support local scale decision making (Turner and Daily, 2008) and trade-off analyses at different spatial scales across a landscape (Rodríguez et al., 2006; Syrbe and Walz, 2012). The Tier 2 indicators of the presented framework create a spatial axis with which to understand the distribution of scientific value across the landscape, driven by various natural and human factors (*sensu* Syrbe and Walz, 2012) such as ecosystem presence, protected area status, access, and historical precedence for scientific research. *Indicators 2.1* and *2.2* provide straightforward indicators of research effort and opportunities assigned to specific sites of interest for management, and *Indicator 2.3,* in conjunction with the aspatial indicators of Tier 1, put this in an explicit ecosystem services framing.

A focus on scientific value supports a broader desire from academics and policy makers to move beyond the prioritisation of a select few tangible or easily quantifiable services, and a stronger emphasis on cultural ecosystem services within management decisions (Plieninger et al., 2015). Cultural ecosystem services present some of the most compelling reasons for ecosystem conservation, and are considered an integral component in the growing number of ecosystem service framework-based management options (Chan et al., 2011). The creation of a standardized, transparent and simple set of indicators allows us to include scientific value as an additional ecosystem service in these discussions.

6. Conclusions

Cultural ecosystem services are omitted from or fundamentally undervalued in many existing ecosystem service assessments. This is particularly the case for tropical coastal ecosystems, and intangible cultural ecosystem services such as scientific value. While limited to formal scientific knowledge (as opposed to other knowledges such as indigenous knowledge), the indicators presented here represent the most indepth attempt to define, frame, quantify and spatialise the ecosystem service of scientific value to date. When tested using a case study, these indicators have shown that coastal ecosystems can contribute substantial scientific value, even along urbanised coastlines that have experienced rapid habitat loss. The tiered indicators developed in this study are able to clearly differentiate scientific value between ecosystems, and importantly they are also able capture the spatial variation in scientific value both within sites and across a landscape of different ecosystems. Creating indicators that can quantify scientific value in a spatially-explicit manner, alongside the quantification of other cultural ecosystem services, can create the evidence that decision-makers need in order to make informed coastal management interventions. The indicators created here are suitable to quantify the scientific value of a range of coastal, marine and terrestrial ecosystems in different settings across the globe. This study provides a quantitative framework for scientific value, upon which individual assessors should modify and improve with supplementary indicators most relevant to their location, including the incorporation of other forms of scientific knowledge.

CRediT authorship contribution statement

Daniel A. Friess: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Project administration, Funding acquisition. **Erik S. Yando:** Methodology, Investigation, Formal analysis, Writing - review & editing. **Lynn-Wei Wong:** Methodology, Investigation, Data curation, Writing - review & editing. **Natasha Bhatia:** Methodology, Writing - original draft, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106255.

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