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Green port structures and their ecosystem services in highly urbanized Japanese bays

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ABSTRACT

Green port structures (i.e. green infrastructure in ports and harbors) featuring habitats for marine organisms have been promoted in Japan as part of a comprehensive policy to reduce the environmental impact of ports and carry out habitat conservation, restoration, and creation. In this study, we evaluated the ecosystem services provided by green port structures in two highly urbanized bays (Tokyo Bay and Osaka Bay) in Japan. Our results show that the provision of some ecosystem services can be limited by circumstances particular to ports and other areas with restricted access. In the case of green port structures that have strong usage restrictions, for example, cultural services can only be provided if relevant authorities are prepared to conduct public events while ensuring participant safety. On the other hand, green port structures with weak usage restrictions are often equipped with incidental facilities such as parking lots and restrooms; these facilities can enhance the provision of cultural services (e.g. recreation and environmental education). Green port structures in highly urbanized bays often have usage restrictions, but their proximity to large populations means that they can potentially provide numerous ecosystem services. However, our study shows that appropriate management goals, such as protecting species and ensuring healthy habitats, are needed to maintain the value of these services in highly urbanized and eutrophic bays.

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Green infrastructure; port structure; tidal flat; restoration; ecosystem services

1. Introduction

Coastal areas provide places for people to relax, as exemplified by the waterfronts of Boston (David and Gordon 1999; Bowen et al. 2019) and Baltimore (Timur 2013). In Japan, areas around harbors, which were once treated as industrial areas with limited public access, have been transformed by land-use changes into valuable urban areas that provide widespread public access to the sea (Yabe 1991). At the same time, the public has come to demand a greater abundance of nature, culture, and tradition in these places. These traits are integral to the provision of ecosystem services (Costanza et al. 1997, 2017), also known as nature's contributions to people (Pascual et al. 2017; Ellis, Pascual, and Mertz 2019). Improving the provision of ecosystem services requires maintaining a rich ecosystem, which often entails the restoration of marine habitats.

This is an issue of global concern. In 1992, the Convention on Biological Diversity (https://www.cbd.int/) was adopted as a comprehensive international framework for preserving biodiversity and promoting the sustainable use of biological resources. Efforts are underway in coastal regions around the world to restore and create artificial wetlands, tidal flats, seaweed beds, and coral reefs with the ultimate goal of restoring and preserving coastal habitats. In Chesapeake Bay in the United States, for example, these efforts have included reducing nutrient inputs into the bay and restoring three major bay habitats (seagrass beds, oyster reefs, and tidal marshes) (Kemp et al. 2005). In recent years, ecosystems in the bay have been greatly affected by rising human populations and extensive agricultural activities, which increase nutrient input into the bay and cause severe eutrophication. As a consequence, many plant species (seagrasses

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and other submersed vascular plants) have declined. In San Francisco Bay, large-scale tidal wetland restoration projects have been implemented to counteract an approximately 80% reduction in tidal wetland area over the last 150 years (Marcus 2000; Brown 2003; Callaway et al. 2011). In the U.K., wetlands are being restored in areas that formerly existed as drained and farmed arable land to prevent biodiversity loss and increase the provision of ecosystem services (Kelvin et al. 2014). Mangroves have also been the focus of restoration efforts worldwide. As populations expand in coastal zones, mangroves are increasingly being cleared for coastal development, aquaculture, or resource use. Globally, about 20–35% of mangrove area has been lost since 1980 (Polidoro et al. 2010). In response, rehabilitation and restoration projects are becoming more prevalent, with some countries even achieving increases in mangrove area (Alongi 2002; Andradi-Brown et al. 2013). Similar efforts are underway for coral reefs, which have declined over the past several decades owing to disease and other stressors such as storms and temperature anomalies (Jaap 2000; Precht 2006; Lirman and Schopmeyer 2016). Seaweed-bed and mangrove restoration projects have also attracted attention in recent years as a means of enhancing blue carbon (i.e. coastal carbon stocks) for climate change mitigation (Pendleton. et al. 2012; Greiner et al. 2013; Alongi 2018; Kuwae and Hori 2019).

In Japan, the country's rapid economic development since the 1960s has coincided with a rapid increase in industrial and domestic wastewater and excessive nutrient and organic effluxes into the sea, causing serious eutrophication, algal blooms, and oxygen depletion in many coastal areas (Furukawa and Okada 2006). Therefore, a total maximum daily loads program was implemented in 1979 to reduce total loading of industrial and domestic wastewater (Okada and Peterson 2000). In addition, sewage systems were improved, with the sewered population in Japan reaching 79.3% in 2018 (Japan Sewage Works Association: https://www.jswa.jp/sewage/qa/rate/). As a result, coastal water quality has improved considerably since the 1970s. However, the abundance and diversity of marine organisms have not fully recovered (Hibino et al. 2013). One reason for this is thought to be a reduction in spawning habitat (Sato 2010; Furukawa, Atsumi, and Okada 2019). For example, Tokyo Bay, which is one of the most urbanized bays in Japan, contained 136 km^2 of tidal flats in 1920, but as coastal development and land reclamation progressed during and after the 1960s, tidal flat area declined to only 10 km^2 in 2002 (i.e. 7% of the 1920 area) (Furukawa and Okada 2006). Some 97% of fish species in Tokyo Bay use tidal flats as nursery habitats (Akiyama, Iseri, and Okada 2014); consequently, this reduction in tidal flat area is thought to have had a serious impact on fish populations in the bay. Osaka Bay is an example of another highly urbanized bay; currently, only 1% of its natural shoreline remains due to widespread coastal reclamation (International EMECS Center 2007). To improve this situation and restore lost habitats, several tidal flats and marine forests (i.e. seagrass meadows and macroalgal beds) have been created in both bays (Working Group for Marine Natural Reclamation 2003).

In these coastal environmental conservation and improvement projects, a growing awareness of declines in ecosystem services and the need to improve existing management has led to a shift toward ecosystem-based approaches to coastal and marine management and conservation (Leslie and McLeod 2007; Barbier et al. 2008; Levin and Lubchenco 2008). The goal of marine ecosystem-based management is to protect, maintain, and restore ecosystem functions to achieve long-term sustainability of marine ecosystems and the human communities that depend on them (Levin and Lubchenco 2008).

Another concept that is gaining traction is the "Building with Nature" approach to infrastructure construction (Borsje et al. 2017). Under this approach, engineers start from the existing natural system and make use of ecosystem services to meet society's needs for infrastructure functionality while also creating room for natural development (De Vriend et al. 2015). In addition, the "Working with Nature" approach has been proposed to more succinctly capture the concept as it applies to navigation infrastructure (PIANC 2008).

In Japan, a related policy of port "greenization" was established to encourage environmentally friendly port design and to implement a comprehensive program of habitat conservation, restoration, and creation (MLIT Ports and Harbours Bureau 2005). Under this policy, environmentally friendly hard port structures with habitats for marine organisms were built across the country. Hard port structures with habitats are a hybrid of gray (hard) and green infrastructure. The gray (hard) components fulfil the essential functions of a port structure (e.g. wave resistance and dissipation), and the green components fulfil the multifunctional functions of the ecosystem (e.g. biological habitat functioning and water quality improvement) (Kuwae and Crooks 2020). Technical development of hard port structures with habitats began in the 2000s, and in 2014, guidelines were established for their maintenance and management (MLIT Ports and Harbours Bureau 2014).

In this paper, restored and created port habitats and hard port structures with habitats are referred to as green port structures (i.e. green port infrastructure). First, we quantify the ecosystem services provided by four green port structures and four natural tidal flats in Tokyo Bay and Osaka Bay, which are highly urbanized bays that currently feature several green port structures. Then, we discuss the characteristics of the ecosystem services provided by the green port structures in comparison with those provided by natural tidal flats.

2. Methods

2.1. Evaluation of green port structures

We evaluated ecosystem services provided by green port structures in Tokyo Bay and Osaka Bay (Figure 1, Table 1). The two bays have nearly the same surface area. As many as 30 million people live in the watershed of Tokyo Bay. In addition, 17 million people live in the watershed of Osaka Bay (MLIT Kinki Regional Development Bureau 2014). As mentioned in the introduction, both bays have experienced considerable urbanization, and most of the coastline has been reclaimed.

Despite the large numbers of people that live near each bay, the provision of some ecosystem services has been limited by circumstances particular to ports with restricted access. In this study, we refer to green port structures with strong usage restrictions as limited-use green port structures and those with weak usage restrictions as less-limited-use green port structures. In other words, limited-use green port structures are those that the public cannot normally access and use, and less-limited-use green port structures are those that the public can normally access and use.

In Tokyo Bay, we evaluated two green port structures (Figure 1): Shiosai Nagisa (Figure 2) is in the MLIT Kanto Regional Development Bureau, Yokohama Research and Engineering Office for Port and Airport and is a limited-use green port structure, and Umi Koen is a restored and created tidal flat and a less-limited-use green port structure (Table 2). The natural Tama River and the Obitsu River tidal flats were used as reference sites. In Osaka Bay, we evaluated two green port structures (Figure 1): Sakai 2-ku (Figure 3) is in a port area and is a limited-use green port structure, and Nanko Wetland is a wild bird sanctuary containing restored and created wetlands and is a less-limited-use green port structure. The natural Omaehama and Yodo River tidal flats were used as reference sites.

Table 1. Basic dimensions of Tokyo Bay and Osaka Bay. Adapted from the Osaka Bay environmental database (MLIT Kinki Regional Development Bureau, 2014).

	Tokyo Bay	Osaka Bay
Total surface area (km^2)	1380	1447
Area with depth ≤ 10 m	360	140
Area with depth ≤ 20 m	730	740
Mean water depth (m)	45	30
Area of reclaimed land (km^2), 1945–1991	157	85
Population of watershed (in millions), 2014	30	17

2.2. Evaluation of ecosystem services

Gray infrastructure is not evaluated here as it is typically examined during the design process. Instead, we focus on ecosystem services provided by green infrastructure. Okada et al. (2019) identified 12 services derived from tidal flats: food provision, coastal protection, recreation, environmental education, research, historical designation as a special site, everyday rest and relaxation, removal of suspended matter, organic matter decomposition, carbon storage, degree of diversity, and rare species. In this study, to avoid double counting of some services, the list of services was revised to the following: provisioning services (food provision), regulating services (water quality improvement and global warming mitigation), cultural services (recreation, environmental education, research, historical site, and everyday relaxation), and supporting services (species conservation) (Table 3). Moreover, indices for these services were

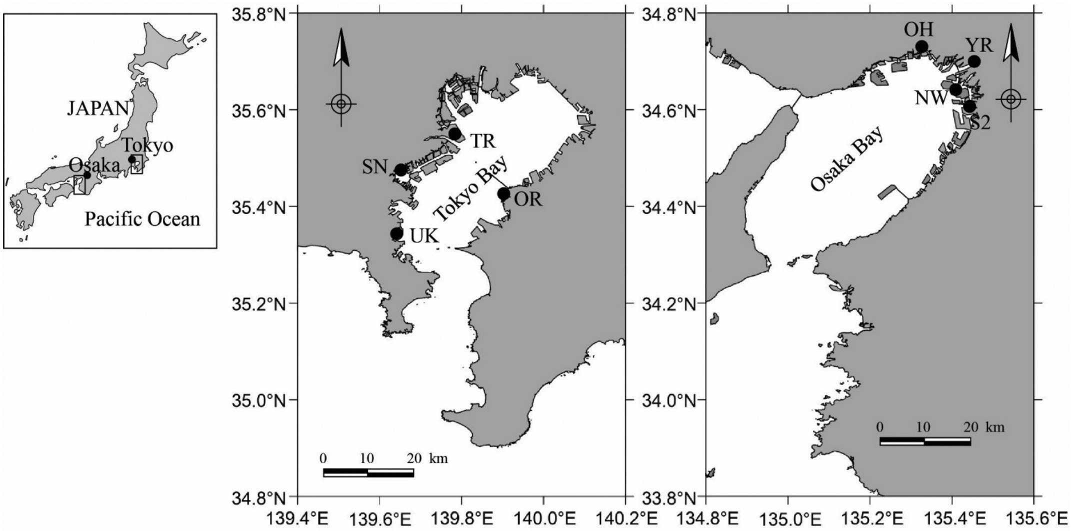


Figure 1. Locations of green port structures and tidal flats in Tokyo Bay and Osaka Bay. Abbreviations are as follows: UK, Umi Koen; SN, Shiosai Nagisa; TR, Tama River tidal flat; OR, Obitsu River tidal flat; S2, Sakai 2-ku; NW, Nanko Wetland; OH, Omaehama; YR, Yodo River tidal flat.

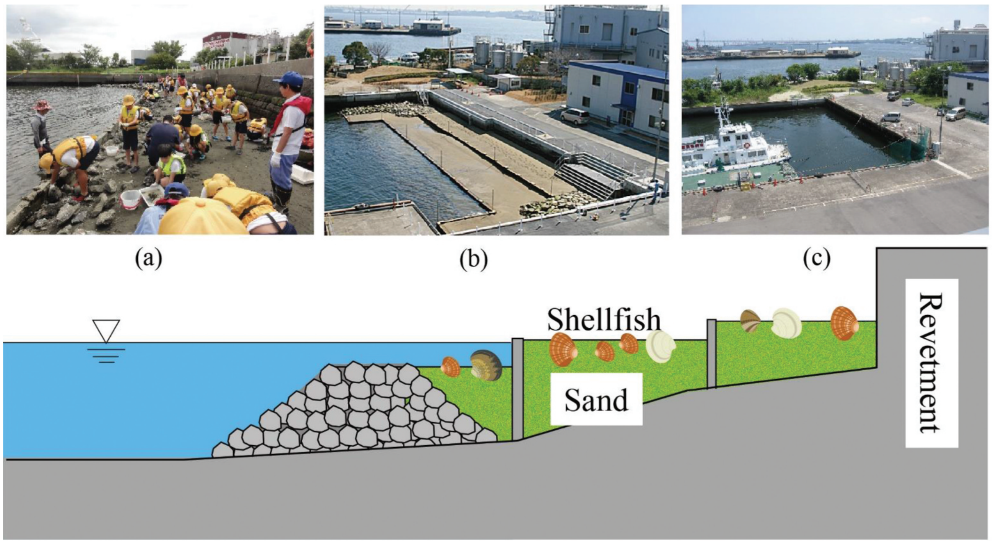


Figure 2. Hard port structure with habitats (Shiosai Nagisa). (a) Environmental education activities being held on the tidal flat. (b) View of the port after construction of the green port structure. (c) The port before the construction of the hard port structures with habitats. Photographs were provided by the MLIT Kanto Regional Development Bureau, Yokohama Research and Engineering Office for Port and Airport.

standardized by converting them to amounts per unit time (i.e. flow units), thus making it possible to sum individual economic values.

The index used for provisioning services was changed from biomass per unit area (t ha^{-1}; stock units) of commercially important species to catch quantity per unit area per year (t ha^{-1} yr^{-1}; flow units) by using the Schaefer production model (Schaefer 1957; Okada et al. 2020). Coastal protection services were excluded from the evaluation because we did not evaluate the effects of gray infrastructure and because the effect of wave reduction on the tidal flats examined in this study is very small (Okada et al. 2015). Removal of suspended matter and organic matter decomposition stem from related ecosystem processes and would likely be double-counted if assessed as two distinct services. Thus, the two services were combined into one water quality improvement service. The index for this service was defined as the magnitude of annual chemical oxygen demand (COD) removal (t-COD ha^{-1} yr^{-1}), and was estimated by multiplying the biomass of benthic organisms by an assumed production/biomass (P/B) ratio. Here, the P/B ratio was set to 2, which is the average value for coastal benthic organisms (Schwinghamer et al. 1986). The carbon storage service was renamed global warming mitigation for ease of understanding. Because the double-counting problem also applies to biodiversity and providing habitat for rare species, the two were combined into one species conservation service, which was defined as the maximum number of species observed during a year (species yr^{-1}).

The indicators used for cultural services (recreation, environmental education, research, historical site, and everyday relaxation) are the same as in Okada et al. (2019). The names of two of the services, historical site and everyday relaxation, have been slightly modified from those used in Okada et al. (2019) (where they were called "historical designation as a special site" and "everyday rest and relaxation," respectively) for clarity.

2.3. *Scoring ecosystem services*

Service scores I_i were calculated for each service i by following the methods described by Okada et al. (2019). The calculation process is similar to that used for the Ocean Health Index (Halpern et al. 2012). I_i was calculated from the normalized present status x_i and the likely near-term future status $x_{i,F}$ as follows:

$$I_i = (x_i + x_{i,F})/2, \tag{1}$$

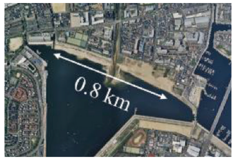
where x_i was obtained by normalizing the observed present status X_i by a reference value$X_{i,R}$:

$$x_i = X_i/X_{i,R} \, . \tag{2}$$

$X_{i,R}$ was defined as the maximum observed status of service i in the four tidal flats in each bay during the most recent 5-year period. Reference values can be regarded as the environmental capacity specific to each bay. Since the environmental capacity of each bay is different, different reference values were used for Tokyo Bay and Osaka Bay.

The likely near-term future status $x_{i,F}$ takes into account trends in the conditions of natural and social systems over the most recent 5-year period, such as dissolved oxygen, stability of ground (e.g. erosion, deposition, consolidation, subsidence), predatory or competitive species interactions, management of habitat conditions, incidental facilities, and accessibility (Okada et al. 2019).

Table 2. Basic information on study sites. See Figure 2 for details on Shiosai Nagisa, and Figure 3 for details on Sakai 2-ku. Aerial photographs were downloaded from the Geospatial Information Authority of Japan (https://mapps.gsi.go.jp/).

	Green port structures		Natural habitats	
	Limited-use	Less-limited-use		
	Shiosai-Nagisa	Umi Koen	Tama River tidal flat	Obitsu River tidal flat
Overview	 	 	 	
Year of establishment	2008	1980	-	-
Area (ha)	0.04	15	25	650
Length of coastline (km)	0.035	1	2	3.5
Sediment D50 (mm)	0.2–1.0*	0.3–0.5**	0.1–0.2***	0.2****
	Sakai 2-ku	Nanko Wetland	Omaehama	Yodo River tidal flat
Overview	 	 	 	
Year of establishment	2009	1983	-	-
Area (ha)	0.06	15	5	10
Length of coastline (km)	0.040	0.5	0.8	0.5
Sediment D50 (mm)	0.4^{+}	1.2–1.3^{++}	1.0^{+++}	0.2^{++++}

*Morohoshi et al. (2008), **Yamanaka, Murai, and Inoue (2007), ***Ariji et al. (2010), ****Sassa, Watabe, and Ishii (2007), $^{+}$MLIT, Kinki Regional Development Bureau, Kobe Research and Engineering Office for Port and Airport (2013), $^{++}$Nishio, Endo, and Yamochi (2016), $^{+++}$Ishigaki et al. (2004), $^{++++}$Natuhara et al. (1998)

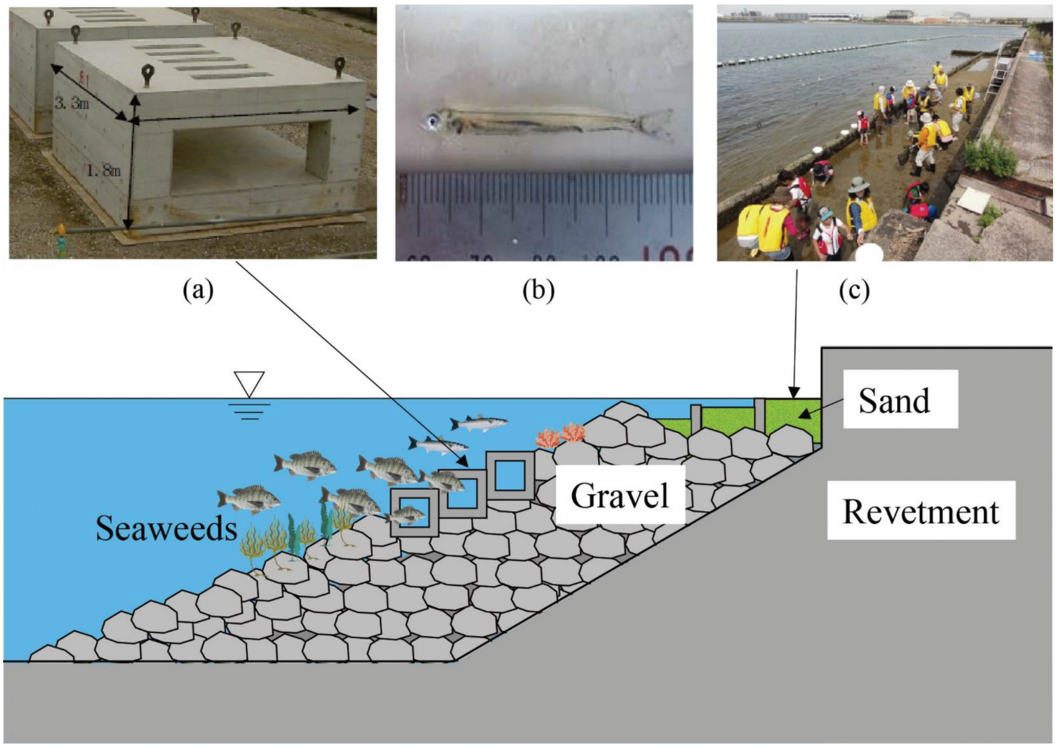


Figure 3. Hard port structure with habitats (Sakai 2-ku). (a) Artificial reef blocks placed below the intertidal zone. (b) Juvenile ayu (*Plecoglossus altivelis*) collected from the tidal flat. (c) Environmental education activities being held on the tidal flat. Photographs were provided by the MLIT Kinki Regional Development Bureau.

Table 3. List of ecosystem services provided by tidal flat ecosystems.

Service category	Service	Specific content of services provided	Proxy	Measurement units
Provisioning services	Food provision	Supplying seafood as food	Annual catch	t ha^{-1} yr^{-1}
Regulating services	Water quality improvement	Organic matter decomposition	Annual COD*-removal amount	t-COD ha^{-1} yr^{-1}
	Global warming mitigation	Carbon storage in organisms and sediment	Annual carbon storage	t-C ha^{-1} yr^{-1}
Cultural services	Recreation	Marine leisure	Annual visitors for recreation	Number of visitors ha^{-1} yr^{-1}
	Environmental education	Environmental education	Annual visitors for environmental education	Number of visitors yr^{-1}
	Research	Research	Number of annual reports and papers	Papers yr^{-1}
	Historical site	Festivals and rituals	Number of annual rituals and festivals	Number held yr^{-1}
	Everyday relaxation	Rest and relaxation	Annual visitors for rest and relaxation	Number of visitors ha^{-1} yr^{-1}
Supporting services	Species conservation	Existence of diverse species	Number of annual confirmed species	Species yr^{-1}

*COD: Chemical Oxygen Demand

Any difference between the normalized present status x_i and likely near-term future status $x_{i,F}$ indicates an increase or decrease in the value of the service over the next 5 years; this is defined as the sustainability score S_i:

$$S_i = (x_{i,F} - x_i)/x_i \tag{3}$$

A positive sustainability score means that the service will improve under present conditions, and a negative score means the service will decline.

2.4. Data collection

We used data collected during the 5 years prior to the evaluation year. For green port structures and natural tidal flats in Tokyo Bay, the data were from Okada et al. (2019) who set the evaluation year as 2013 and used data from 2009–2013. For Osaka Bay, we prioritized data availability rather than matching the evaluation year used in Tokyo Bay. Therefore, we selected a data collection period of 2012–2016, when data availability was relatively high, and an evaluation year of 2016. Data collection methods for Osaka Bay are described below.

For food provision service scores, as there was no data available on catch quantity per unit area per year (t ha^{-1} yr^{-1}) for commercially important species, we instead used the biomasses per unit area (t ha^{-1}) of these species. We used data from Endo and Otani (2019) for the Yodo River tidal flat and data from Otani et al. (2018) for Omaehama. Since there is no fishing at Sakai 2-ku and the Nanko Wetland, these sites were excluded from the evaluation.

To calculate water quality improvement service scores, we used the wet weight (g-wet m^{-2}) of benthic organisms. Global warming mitigation service scores were calculated from sediment total organic carbon (mg-C g-dry^{-1}) or ignition loss (%). Species conservation service scores were calculated from the number of benthic species. The data used for each wetland were as follows: Sakai 2-ku, MLIT Kinki Regional Development Bureau, Kobe Research and Engineering Office for Port and Airport (2013, 2014, 2015, 2016, 2017); Nanko Wetland, Kume (2016); Yodo River tidal flat, Endo and Otani (2019); and Omaehama, Otani et al. (2018).

To calculate recreation service scores, we needed the number of recreational visitors per year (people yr^{-1}), and to calculate everyday relaxation service scores, we needed the number of routine users per day (people d^{-1}). However, preexisting data were not available for the four sites. Instead, we conducted field surveys on November 18 2017 at three of the sites (surveys were not conducted at Sakai 2-ku because recreation and relaxation is not permitted at this site). The survey followed the method described by Okada et al. (2019).

Research service scores were calculated from the number of papers and reports published during the years 2012–2016. These were identified by searching Google Scholar, CiNi, J-Stage, and Agri-Knowledge (keywords: Sakai No.2 & seawall, Pro-Environmental & seawall or Osaka Bay & seawall for Sakai 2-ku, Osaka nanko bird sanctuary, Osaka & nanko & tidal flat or Osaka Bay & Artificial tidal flat for Nanko Wetland, Juso & tidal flat, Yodo River & tidal flat or Osaka Bay & tidal flat for Yodo River tidal flat, Omaehame, Nishinomiya & tidal flat or Osaka Bay & tidal flat for Omaehama. In addition, we conducted interviews with members of research institutions, administrators, and nonprofit organizations about research activities that relate to green port structures or natural tidal flats.

Environmental education service scores were calculated from the number of visitors for environmental education activities. Historical site service scores were calculated from the number of rites and festivals. To obtain these numbers, we conducted interviews with administrators and nonprofit organizations associated with the green port structures or natural tidal flats.

3. Results

Service scores for each of the green port structures and natural tidal flats are shown in Figure 4. Scores were calculated by assigning equal weight to each service.

3.1. Limited-use green port structures

Provisioning services. There are no food provision services provided by Shiosai Nagisa and Sakai 2-ku because commercial fishing is not permitted and public access is restricted.

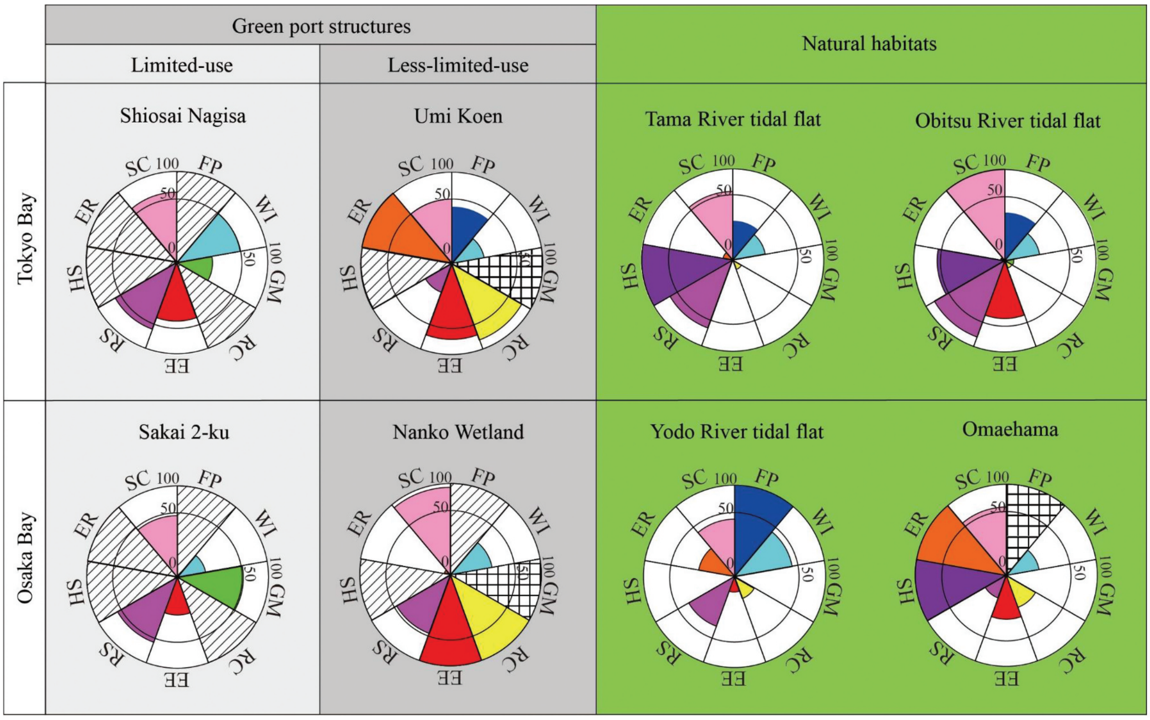


Figure 4. Ecosystem service scores for each green port structure or tidal flat. Diagonal stripes indicate restricted services, and cross hatches indicate services for which data were not available. Abbreviations are as follows: FP, Food provision; WI, Water quality improvement; GM, Global warming mitigation; RC, Recreation; EE, Environmental education; RS, Research; HS, Historical site; ER, Everyday relaxation; SC, Species conservation.

Regulating services. The value of the water quality improvement services provided by Shiosai Nagisa was higher than those provided by natural tidal flats (i.e. the Tama River and Obitsu River tidal flats in Tokyo Bay) because of the higher benthic organism biomass at Shiosai Nagisa than at the natural tidal flats. By contrast, the value of the water quality improvement services provided by Sakai 2-ku was not as high as those provided by natural tidal flats (i.e. the Yodo River tidal flat and Omaehama in Osaka Bay). The low score at Sakai 2-ku was caused by low benthic organism biomass. The global warming mitigation services provided by Shiosai Nagisa and Sakai 2-ku were higher than those provided by natural tidal flats in each bay. This is most likely because both green port structures are less than 10 years old and the carbon storage capacity of the bottom sediments at both sites is not yet saturated.

Cultural services. Public access is restricted at Shiosai Nagisa and Sakai 2-ku; consequently, the two sites provide no recreational, historical, or everyday relaxation services. On the other hand, environmental education services and research services can be provided with the cooperation of administrators so long as the safety of participants is taken into account. The environmental education service score for Shiosai Nagisa met or exceeded scores for the natural tidal flats (the Tama River and Obitsu River tidal flats in Tokyo Bay), as did the score for Sakai 2-ku (in comparison to the Yodo River tidal flat and Omaehama in Osaka Bay).

Supporting services. The species conservation service score for Shiosai Nagisa was almost the same as or smaller than those of natural tidal flats in Tokyo Bay. The score for Sakai 2-ku was comparable to those of natural tidal flats in Osaka Bay.

3.2. Less-limited-use green port structures

Provisioning services. Although commercial fishing is banned in Umi Koen, shellfish collection is allowed. The bivalve *Ruditapes philippinarum* is particularly abundant, and the food provisioning score at this green port structure was comparable to that of natural tidal flats in Tokyo Bay. By contrast, because the Nanko Wetland is a bird sanctuary, both commercial fishing and shellfish gathering are prohibited. Consequently, it does not provide any food provisioning services.

Regulating services. The water quality improvement service score for Umi Koen was nearly the same as that of natural tidal flats in Tokyo Bay. The score for Nanko Wetland was smaller than or almost the same as that of natural tidal flats in Osaka Bay. Global warming mitigation service scores were not evaluated at either tidal flat owing to a lack of data.

Cultural services. Both less-limited-use green port structures scored higher on recreation services and environmental education services than did natural tidal flats. Everyday relaxation service scores were high in Umi Koen, but were almost zero in Nanko Wetland. Although many people live in the area around Umi Koen, few residents live near Nanko Wetland. The research service score for Umi Koen was lower than those calculated for natural tidal flats, but the score for Nanko Wetland was higher than at natural tidal flats. Research services are difficult to interpret because they are affected not only by field conditions such as environmental status and the ease of field research, but also by external factors such as interest and the availability of research funding. Historical site services were not provided by Umi Koen and Nanko Wetland.

Supporting services. Although the species conservation service score for Umi Koen was not low, it was still less than that of natural tidal flats in Tokyo Bay. However, the species conservation service score of Nanko Wetland, which is a protected bird sanctuary, was higher than that of natural tidal flats in Osaka Bay.

4. Discussion

4.1. Ecosystem services provided by green port structures

The species conservation service scores of limited-use green port structures were almost the same as or smaller than those of natural tidal flats (Figure 4). Limited-use green port structures function like protected areas by restricting human use, including by fisheries. However, as exemplified by Shiosai Nagisa and Sakai-2-ku, high species conservation service scores cannot be expected, because green port structures are often installed in areas where the natural environment has deteriorated. To achieve a level of biodiversity comparable to that of natural tidal flats, adaptive management practices (Thom 2000) should be adopted and appropriate monitoring and habitat management should be carried out.

The environmental education service scores of limited-use green port structures met or exceeded the scores for natural tidal flats (Figure 4). Ensuring the safety of on-site environmental education is important (Ernst 2012). Environmental education in limited-use green port structures is carried out in places where access is normally restricted, so further safety management by administrators and educators is required. With effective safety management, however, the provision of environmental education services can meet or exceed that of natural tidal flats.

Less-limited-use green port structures had higher recreation and environmental education service scores than did natural tidal flats (Figure 4). This is likely related to the ease of access provided by incidental facilities such as parking lots and restrooms. Umi Koen and Nanko Wetland are equipped with such facilities. With less-limited-use green port structures, these incidental facilities can be built during construction of the green port structures themselves, providing an advantage over natural tidal flats. In addition to these incidental facilities, education programs featuring on-site trained educators are important for boosting environmental education (Jhaveri and Smith 2019). The resulting ease of use helps attract not-for-profit organizations, which conduct many environmental education events. Therefore, less-limited-use green port structures with incidental facilities can provide cultural services more effectively than do natural tidal flats.

Historical site services were not provided by either of the less-limited-use green port structures (Figure 4). This may reflect a lack of widespread recognition of the historical value of coastal sites (Chaudhary et al. 2019); in fact, neither green port structure was initially designed to provide historical site services. This is an important aspect that should be improved upon in future green port structures.

The species conservation service score of Umi Koen was less than those of natural tidal flats in Tokyo Bay (Figure 4). This lower score may reflect the trade-offs that often exist between conservation and human use (Bennett, Peterson, and Gordon 2009; Ruijs et al. 2013; Deng, Li, and Gibson 2016). On the other hand, the species conservation service score of Nanko Wetland was higher than those of natural tidal flats in Osaka Bay (Figure 4). This high score may be thanks to the administrator’s conservation-minded management. In this wetland, people are not allowed to enter tidal flats in the bird sanctuary. Instead, visitors use telescopes to watch the birds from observation huts and learn about bird ecology. This ethos of enjoying cultural services provided by natural systems while minimizing adverse impacts mirrors the approach taken in marine protected areas and national parks (Gonson et al. 2017; Walden-Schreiner et al. 2017; Piñeiro-Corbeira et al. 2020). To improve ecosystem services, it is important to understand the trade-offs among on-site services and to implement appropriate management strategies (Weijerman et al. 2018; Chaudhary et al. 2019). The Nanko Wetland, as a less-limited-use green port structure and a bird sanctuary, is a unique place where conservation and human use, instead of being in conflict, can go hand in hand.

4.2. Sustainability and management

Note that we do not consider the sustainability of research services in the following discussion for the reasons outlined in Section 3.2 – research services are affected not only by field conditions but also by external factors.

Green port structures are often subjected to severe environmental conditions. In the absence of effective management, these conditions can also degrade the ecosystem services provided by the green port structures. Therefore, in the following text, we discuss the sustainability of ecosystem services provided by green port structures based on the sustainability scores defined in equation (3).

We found negative sustainability scores for a variety of ecosystem services provided by green port structures (Table 4). Shiosai Nagisa, for example, had negative sustainability scores for global warming mitigation and environmental education services. Similarly, Umi Koen had negative sustainability scores for food provision and recreation services. Finally, Sakai 2-ku had negative sustainability scores for water quality improvement, global warming mitigation, and environmental education services. Tokyo Bay and Osaka Bay are remarkably eutrophic, and negative sustainability scores were found for natural tidal flats as well as for the green port structures. However, sustainability scores were more negative for the green port structures than for the natural tidal flats. Therefore, green port structures may require more appropriate management than natural tidal flats. The conceptual model of Okada et al. (2019) can be used as a reference for increasing sustainability in green port structures. For example, a positive sustainability score for environmental education services in Shiosai Nagisa could be achieved by attracting more visitors, conducting publicity, improving accessibility, protecting species,

Table 4. Calculated sustainability scores for all services. Negative sustainability scores are indicated by gray shading.

	Green port structures							
	Limited-use		Less-limited-use		Natural habitats			
Service	Shiosai Nagisa	Sakai 2-ku	Umi Koen	Nanko Wetland	Tama River tidal flat	Obitsu River tidal flat	Yodo River tidal flat	Omaehama
Food provision	—	—	−25	—	5	17	36	—
Water quality improvement	51	−1	17	5	−15	13	0	−26
Global warming mitigation	−61	−29	—	—	0	−2	0	0
Recreation	—	—	−1	12	−7	16	12	17
Environmental education	−44	−3	10	7	0	17	4	7
Historical site	—	—	—	—	3	17	0	7
Everyday relaxation	—	—	10	17	−3	17	8	17
Species conservation	9	10	23	14	12	32	−13	15

ensuring healthy habitats, and improving stability of ground.

5. Conclusions

Some ecosystem services provided by green port structures in highly urbanized bays are limited by circumstances particular to ports and other areas with restricted access. For green port structures with strong usage restrictions (i.e. limited-use green port structures), the provision of cultural services depends on whether authorities are prepared to conduct public events while maintaining the safety of participants. On the other hand, green port structures with weak usage restrictions (i.e. less-limited-use green port structures) are often equipped with incidental facilities such as parking lots and restrooms; these green port structures can provide more people-related ecosystem services than natural tidal flats. Green port structures in highly urbanized bays often have usage restrictions, but their proximity to large populations means that they can potentially provide numerous ecosystem services. Therefore, green port structures should be managed in a way that balances usage restrictions against the provision of ecosystem services.

In addition, we also need effective management to maintain the value of these services. In this study, we were able to evaluate the services themselves and understand the environmental factors that could be used to effectively increase sustainability. When planning a green port structure, similar methods should be used to comprehensively assess the services provided by the structure and to develop a management plan to maintain this value after the structure is completed.

Our study only evaluated the ecosystem services provided by restored and created tidal flats, restored and created wetlands, and sand-covered green port structures. In the future, it will be important to assess and evaluate the ecosystem services of other types of green port structures, such as seaweed beds and artificial reefs constructed out of gravel and blocks, in highly urbanized bays.

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