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Characterizing Coastal Ecosystem Service Trade-offs with Future Urban Development in a Tropical City

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Abstract With rapid urbanization in the coastal zone and increasing habitat losses, it is imperative to understand how urban development affects coastal biodiversity and ecosystem service provision. Furthermore, it is important to understand how habitat fragments can best be incorporated into broader land use planning and coastal management, in order to maximize the environmental benefits they provide. In this study, we characterized the trade-offs between (a) urban development and individual mangrove environmental indicators (habitat quality and ecosystem services), and (b) between different environmental indicators in the tropical nation of Singapore. A range of biological, biophysical, and cultural indicators, including carbon, charcoal production, support for offshore fisheries, recreation, and habitat quality for a threatened species were quantified using field-based, remote sensing, and expert survey methods. The shape of the trade-off Pareto frontiers was analyzed to assess the sensitivity of environmental indicators for development. When traded off individually with urban development, four out of five environmental indicators were insensitive to development, meaning that relatively minor degradation of the indicator occurred while development was below a certain threshold, although indicator loss accelerated once this threshold was reached. Most of the pairwise relationships between the five environmental indicators were synergistic; only carbon storage and charcoal production, and charcoal production and recreational accessibility showed trade-offs. Trade-off analysis and land use optimization using Pareto frontiers could be a useful decision-support tool for understanding how changes in land use and coastal management will impact the ability of ecosystems to provide environmental benefits.

Keywords Blue carbon · Deforestation · Mangrove · Shoreline development · Urbanization · Singapore

Introduction

The coastal zone experiences disproportionately high human population densities and rates of migration (Small and Nicholls 2003; Neumann et al. 2015), with concomitant increases in coastal development and declines in coastal habitat extent (*sensu* Gittman et al. 2015). This is especially the case for tropical coastal mangrove forests, which are experiencing rapid rates of decline due to land cover conversion for urban development, agriculture, and aquaculture (Richards and Friess 2016; Thomas et al. 2017). Such land cover changes are expected to continue as pressure grows in coastal regions in the future, with up to 83% of the world's population expected to live in urban areas by 2100 (Grübler et al. 2007). Thus, coastal ecosystems have experienced, and will continue to experience, rapid declines in the extent and quality, with many coastal ecosystems now existing in urban and peri-urban settings.

Despite large losses, patches of vegetated habitats that remain in urban areas can still provide a range of ecosystem services that benefit the surrounding urban populations

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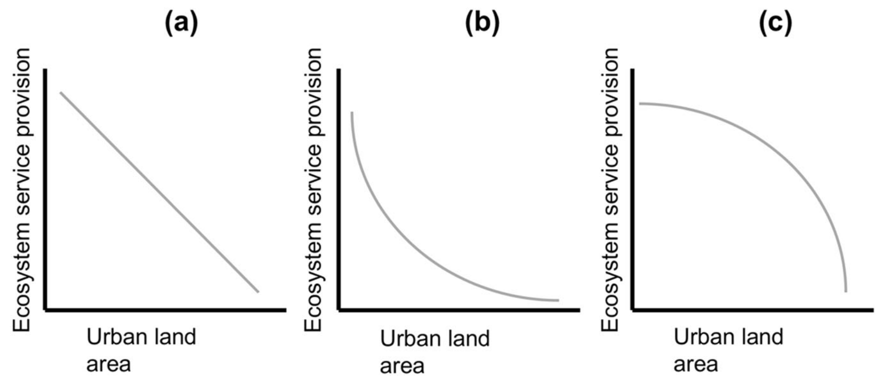

Fig. 1 Three hypothetical Pareto frontiers indicating **a** linear, **b** sensitive, and **c** less-sensitive trade-offs between ecosystem service provision and urban land development

(Bolund and Hunhammar 1999). Urban ecosystems play a particularly important role in providing cultural ecosystem services to urban populations, from the tangible (e.g., recreation and education) to the abstract (e.g., esthetic, spiritual, and religious values) (e.g., Gobster and Westphal 2004). Urban ecosystems can also store substantial volumes of carbon (e.g., Davies et al. 2011; Dobbs et al. 2014; Zhao and Sander 2015), mitigate urban heat island effects (Onishi et al. 2010; Roth and Chow 2012), and provide a source of food to local populations (Wills et al. 2009). Understanding urban biodiversity and ecosystem services is now an important research priority (Kremer et al. 2016; McDonnell 2015; Ziter 2016).

The importance of ecosystem services in urban contexts means that there are likely to be trade-offs between continued service provision and future urban development. Future urbanization will often remove the existing habitat patches and reduce the total value of ecosystem service provision across a cityscape, although with careful land use planning, it may be possible to find objectively optimal solutions that balance ecosystem service provision and urban development.

The trade-offs between urbanization and the provision of an ecosystem service can vary from very sensitive to insensitive. The sensitivity of the trade-off can be defined in terms of the extent to which increasing the value of one factor results in a decrease in the value of another, and these relationships can be characterized as the shape of the optimal or Pareto frontier (Fig. 1) (Emmerich and Deutz 2007). In some cases, increasing urbanization will result in a linear decrease in ecosystem service provision (Fig. 1a). For more sensitive trade-offs, the value of service provision decreases rapidly with increasing urbanization (Fig. 1b), and in these cases, it may be hard to find compromises between urban development and ecosystem service provision (Emmerich and Deutz 2007). Conversely, less-sensitive trade-offs show Pareto frontiers that curve outward (Fig. 1c), indicating that it is possible to increase the area of land under urban usage while experiencing proportionally small losses in ecosystem service provision. It is these less-sensitive trade-offs that are generally preferable in ecosystem management, because they allow relatively high values of conflicting benefits to be simultaneously provided, which may make it easier to find acceptable compromises (Emmerich and Deutz 2007). Understanding the shape of Pareto frontiers is thus important as the sensitivity of a trade-off must be considered when trying to integrate ecosystem services into land use planning, which is a crucial challenge in landscape management (de Groot et al. 2010).

This study aims to facilitate mangrove conservation and sustainable urban development in the tropical nation of Singapore by characterizing a range of trade-offs that exist between (a) land use development and the provision of various mangrove environmental indicators (including habitat quality and mangrove ecosystem service indicators), and (b) between different mangrove environmental indicators. The city–state of Singapore has experienced rapid urban development over the last 50 years since becoming independent, and such development is expected to continue in the future. Singapore also has a robust and far-sighted land use-planning framework, providing an opportunity for the inclusion of ecosystem services and mangrove conservation into future development. Additionally, tropical urban ecosystem services are substantially under-researched compared to temperate urban areas (Ziter 2016); Singapore provides a case study that broadens our knowledge of development-environment trade-offs in the tropics.

Methods

Study-Site Description

Overview of land use planning in Singapore

Singapore is a small island city-state in Southeast Asia, with a land area of 775.5 km^2 (De Koninck et al. 2008). The city has grown rapidly over the past 50 years to a current population of 5.5 million, resulting in a high-population density of 7615 people per km^2 (Department of Statistics

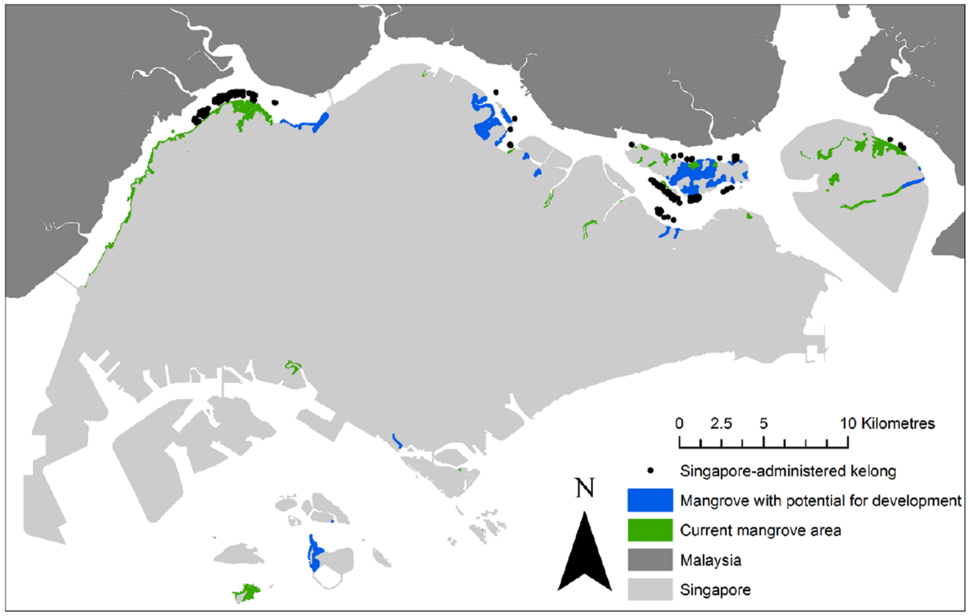

Fig. 2 National mangrove cover in Singapore, including areas that will potentially be developed according to either the 2013 Land Use Plan or the 2014 URA Master Plan. The distribution of current kelongs (floating offshore aquaculture) in Singapore's waters is also indicated.

2014). Singapore follows an urban development strategy of a "City in a Garden" with green spaces covering 61.2% of the land area, although the majority of these green spaces are either managed terrestrial vegetation or secondary rainforest (Yee et al. 2010).

Due to land constraints, urban development and land reclamation in Singapore is guided by an extensive land use planning framework of long-term concept plans (reviewed every 10 years), which are enacted through medium-term master plans (reviewed every 5 years). This planning framework is developed by the governmental Urban Redevelopment Authority (URA). In this study, the potential for future mangrove loss due to urban development was assessed using two recently published planning documents; the 2013 Land Use Plan (similar to a Concept Plan) with a time horizon to 2030 (MND 2013), and the 2014 URA Master Plan, with a time horizon of approximately 2024–2028 (URA 2014). These plans indicate the areas where land reclamation and urban development is expected to take place along Singapore's coastline. We identified 17 mangrove patches where land use change was indicated in at least one of the two plans (Fig. 2).

Singapore's mangrove forests

Singapore is located in a global hotspot for mangrove floral biodiversity (Spalding et al. 2010), and mangrove forests historically covered much of the coastline before the pre-colonial period (before 1819). However, Singapore's mangrove forests have long been affected by land cover change. Freshwater reservoir construction in former estuaries (Ziegler et al. 2014), land reclamation for urban and industrial use (Lai et al. 2015, and other indirect stressors such as pollution and insect pest infestations (Murphy 1990; Friess et al. 2012; Nor and Obbard 2014) have destroyed much of Singapore's mangrove resource, with an acceleration in deforestation after Singapore gained independence in 1965. Mangrove forests now cover less than 1% of Singapore's land area (Yee et al. 2010), with further losses expected in the future (up to 33% of the remaining mangroves lost by 2030) according to the land use plans described above (Lai et al. 2015).

Despite their small current extent, recent research has highlighted how Singapore's mangroves still provide a range of ecosystem services that are important in the local urban context (Friess 2017). Historically, Singapore's mangroves were managed by the colonial government for charcoal production to provide fuel for the rapidly expanding urban population (O'Dempsey 2014). Mangroves can disproportionately store more carbon than terrestrial forested ecosystems (Donato et al. 2011), and Singapore's present-day mangroves store the equivalent amount of the annual carbon emissions of 621,000 people (Friess et al. 2016). Singapore's mangroves also provide important cultural ecosystem services to the local population. The access to mangroves is now tightly managed through the park system, and mangrove parks and nature reserves provide important recreational, educational, and aesthetic value to visitors (Richards and Friess 2015; Thiagarajah et al. 2015). Mangroves provide ecosystem services related to fisheries (Jaffar et al. 2004), and the habitat also provides high invertebrate biodiversity, including the mangrove horseshoe crab (*Carcinoscorpius*

Table 1 Habitat quality and ecosystem-service indicators that are or could be provided by Singapore's mangroves

Indicator	Type	Quantification	Units
Vegetation of carbon storage	Regulating ecosystem service	Mass of carbon stored in mangrove tree biomass	Megagrams of carbon
Rhizophora spp. mangrove charcoal production	Provisioning ecosystem service	Mass of carbon stored in aboveground *Rhizophora* spp. biomass	Megagrams of carbon
Recreational accessibility	Cultural ecosystem service	Total length of mangrove boardwalks	km
Fish production (supporting offshore aquaculture)	Regulating ecosystem service	Total number of kelongs within 1 km of a mangrove forest, assumed to be supported in part by nutrient production from the mangrove	Number of kelongs
Habitat quality for mangrove horseshoe crabs	Biodiversity	Habitat quality score by a panel of experts	Sum of scores for all 17 sites (1–5-point scale)

rotundicauda), which is a species of high conservation concern (Cartwright-Taylor et al. 2011).

Quantification of Environmental Indicators

For each of the 17 mangrove patches at the risk of conversion, we estimated the provision of five environmental indicators (Table 1), with four relating to ecosystem service provision and one relating to faunal biodiversity. We also estimated the impacts that urban development would have on each environmental indicator, at each of the 17 mangrove locations with a potential for development listed above. The effectiveness of using trade-off analyzes strongly depends on the suite of indicators that are chosen for analysis. To ensure that a broad range of indicators were used, we consulted the literature on mangrove ecosystem services, particularly from Singapore (O'Dempsey 2014; Friess et al. 2016; Richards and Friess 2015; Thiagarajah et al. 2015), to identify five indicators that represent habitat quality for a key species of conservation interest, for regulating, provisioning, and cultural benefits of mangroves (Table 1).

Vegetated carbon storage

Mangrove-vegetated biomass carbon was previously quantified for the whole of Singapore by Friess et al. (2016). This published data set was produced by combining field measurements (*sensu* Kauffman and Donato 2012) taken at 49 sampling plots that were spatially distributed throughout Singapore's mangrove extent with high-resolution Pleiades satellite imagery and topographic data. Regression models were used to predict tree biomass carbon across the whole landscape, while soil carbon was upscaled from previous site assessments. The study by Friess et al. (2016) provided a spatial layer of carbon stock for the modeling process in this current study.

Charcoal production

The high calorific value of *Rhizophora* spp. makes charcoal production a key provisioning ecosystem service of mangroves in Southeast Asia (Bandaranayake 1998), and was historically an important use of mangroves in Singapore. The potential for *Rhizophora* spp. extraction for charcoal production was calculated in a similar manner to vegetated carbon, using the same remotely-sensed imagery and a data set of field records. However, only the field data for *Rhizophora* spp., and only the *Rhizophora* allometric equations, were used when building regression models, and only estimates of aboveground *Rhizophora* biomass carbon were made as belowground biomass is not typically harvested.

Recreational accessibility

Mangroves in Singapore are generally inaccessible to the average visitor due to their fragile and muddy environment, so are only legally accessed via boardwalks or raised tracks. The length of such walkways within each mangrove site was used as a proxy for recreational value (due to the resulting accessibility and potential for recreation). A previous study established the spatially-variable link between recreational value and accessibility in a mangrove patch in Singapore (Richards and Friess 2015), primarily due to walkways and facilities. Walkway lengths were digitized from freely available OpenStreetMap data that were updated between 2012 and 2014 (OpenStreetMap 2015).

Support for offshore aquaculture

Increasing food security is a key concern for Singapore, and government targets to increase locally-grown fish to deliver 15% of fish consumed (up from 4% in 2011) have led to the promotion of offshore aquaculture in Singapore's waters (AVA 2011). Mangroves can export nutrients to the surrounding marine areas, supporting offshore fishery production, although these relationships are complex and often context specific (Lee 1995). This environmental benefit was quantified using a binary indicator, by assuming that aquaculture activities are improved if the offshore aquaculture facility is located within 1 km of a patch of mangrove. Kelongs (offshore-floating aquaculture platforms) were digitized using Bing Maps imagery (dated between 2001 and 2004) that is available to stream through ArcGIS (Bing Maps 2015; Fig. 1).

Importance for mangrove horseshoe crab populations (habitat quality indicator)

Singapore's mangroves are a shelter to internationally-important populations of the mangrove horseshoe crab (*Carcinoscorpius rotundicauda*). We chose to focus on habitat quality for horseshoe crabs as an indicator because they are a particularly-threatened species in Singapore (Cartwright-Taylor et al. 2011), and the International Union for the Conservation of Nature (IUCN) has explicitly encouraged signatory governments to consider sustainable coastal development around the areas of the horseshoe crab habitat (IUCN 2012). Mangrove horseshoe crabs are a flagship species that have garnered significant national attention through the work of local conservation NGOs and their conservation may act as an umbrella for the conservation of other benthic invertebrate species that utilize the same habitat.

The relative quality of each of the 17 mangrove patches for mangrove horseshoe crabs was evaluated by consultation with an expert review group from the Nature Society Singapore (NSS), which has led much of the horseshoe crab research in Singapore, and which conducts regular monitoring of horseshoe crab population size and fecundity. The expert review group was asked to score each mangrove site using a 5-point scale, with a score of 5 indicating that the location was highly important for the mangrove horseshoe crab population in Singapore, and a score of 1 indicating that it was highly unlikely that any horseshoe crab would be present at the location. The sum of the scores for each of the mangrove patches was used as the index of the relative habitat quality for horseshoe crabs across the country.

Trade-off Simulations

To explore the possible decision space and identify optimal Pareto frontiers, we first generated a subset of all possible combinations of scenarios for the 17 patches identified as potentially at risk from development in the two Land Use Plans. All patches had at least three alternative management states; they could either be protected as a mangrove forest, sustainably managed for charcoal production, or developed. There are a very large number of possible combinations of these alternative management states (more than 400 million); so, it was not possible to consider all of them when identifying the boundary of the optimal frontier. Instead, we used an iterative procedure to gradually optimize the frontier over repeated runs until it stabilized. A series of 50,000 scenarios were first generated by randomly assigning plausible states to each of the 17 mangrove patches. The optimal frontier from the 50,000 scenarios was then calculated. A new generation of 50,000 scenarios was then generated from the optimal scenarios, by randomly modifying approximately 10% of the mangrove patches in each of the optimal scenarios. A new optimal frontier was then identified among the second generation of scenarios, and the process was repeated until there was no change in the scenarios which made up the optimal frontier. This analysis was conducted in R using an implementation of Pareto frontier quantification that was originally written in the Python language (Bull 2012).

To analyze the sensitivity of the trade-offs between environmental indicators and urban development, we estimated pairwise trade-offs between each indicator and urban development. To assess whether it would be possible to provide multiple benefits along with increasing urbanization, we also calculated pairwise trade-offs between each of the six indicators. In some cases, there was no trade-off between the pairs of indicators; it was possible to maximize both of them simultaneously. We define such relationships where no trade-offs were found as synergies.

The optimization approach used in this study identifies the Pareto optimal solutions for the universe of possible scenarios that can be generated, given the input data. The iterative optimization algorithm ensures that the generated Pareto frontiers can be considered as highly likely to represent the optimal solutions within the context of the simulation system. However, since they represent only the single optimal solution, it is not possible to evaluate confidence intervals/measures of error for the simulated Pareto frontiers.

Study Assumptions

The modeling approach used in this study makes certain assumptions relating to the indicators used and the relationships between indicators and development, and the results given below should be viewed with these caveats in mind. For example, we assume a relationship between the presence of mangroves in the vicinity and the support of offshore (floating) aquaculture. However, the degree to which mangroves export nutrients to benefit fish growth, and the distance to which the effect may extend, have been debated (Lee et al. 2014). There is some association between the distribution of mangroves and the placement of kelongs in Singapore; the majority of kelongs are found along the northern coast where a mangrove is found, and kelongs in the south of Singapore are also found close to the remaining mangrove fragments.

For our recreational indicator, we assume that public access is constrained to public infrastructure such as boardwalks only. This assumption is supported by a previous study that showed how mangrove cultural ecosystem service value is explicitly linked to proximity to such features (Richards and Friess 2015), and because public access to the mangrove floor is prohibited without a state permit.

We made a number of assumptions about the potential impacts of sustainable mangrove charcoal harvesting, as this is not currently practised in Singapore. We assume that sustainable harvesting of *Rhizophora* spp. for charcoal production would have a negative impact on the mass of carbon biomass stored, as *Rhizophora* spp. trees would necessarily be removed from the system. However, the impacts of *Rhizophora* spp. removal on carbon sequestration are more complex to predict, as removing trees may stimulate the growth and enhance carbon capture if they are replanted (Alongi 2011). We assumed that sustainable harvesting of *Rhizophora* spp. would also remove the value of the mangrove for boardwalk-based recreation, due to the periodic disturbance of mangrove areas. Charcoal harvesting was assumed to not have a negative impact on the other environmental indicators, including the habitat quality for horseshoe crabs. It is conceivable that removing the tree biomass could have either a positive or a negative impact on the species, but no information was available to assess the likely direction and magnitude of this effect.

For the urban development scenarios, we assumed that (a) the entire mangrove patch would be lost, and (b) there is a direct and linear relationship between the mangrove area and the environmental indicator value of each patch. While we acknowledge that this relationship may often be non-linear or may be affected by sudden state changes (*sensu* Folke et al. 2004), we lack sufficient information on the direction or magnitude of change, so that we can only assume a direct and linear relationship. We also assumed that (c) the replacement land use does not produce equivalent environmental benefits. However, while they may not produce equivalent environmental services, urbanized areas may still be able to produce some level of non-mangrove environmental indicators; for example, linear and fragmented street tree patches in urban areas are still an important biomass carbon store (Tan et al. 2009), and microclimate regulators in the Singapore context (Richards and Edwards 2017).

Results

Characterizing Urban Development–Ecosystem Service Trade-offs

All five environmental indicators showed trade-offs against urban development, but the shape of the trade-offs varied (Fig. 3). The indicators of carbon storage, *Rhizophora* spp. charcoal, recreation, and mangrove horseshoe crab conservation showed outward-curving trade-off relationships, indicating relatively less-sensitive trade-offs (Fig. 3a–d). These less-sensitive trade-offs indicate that relatively high levels of habitat quality and ecosystem service benefits can be maintained while simultaneously allowing urban development. For example, the development of half of the potential new land area identified in this study (1478 ha) could result in a loss of only 8% of the total carbon stored in vegetation (4747 mg lost), if the locations for this development were selected carefully (Fig. 3a). Similarly, expanding the urban area by 2282 ha, to more than 75% of the potential area identified in this study, could be achieved with only a resulting decrease of 20% in the overall suitability of the habitat for horseshoe crabs (from a score of 37 to 30) (Fig. 3d). The number of offshore aquaculture facilities serviced by mangroves showed a trade-off relationship that was approximately linear, indicating a trade-off which is closer to neutral (Fig. 3e). None of the ecosystem service indicators modeled showed an inward-curving, highly-sensitive trade-off relationship, which would signify a disproportionate loss of ecosystem services compared to the corresponding level of land development.

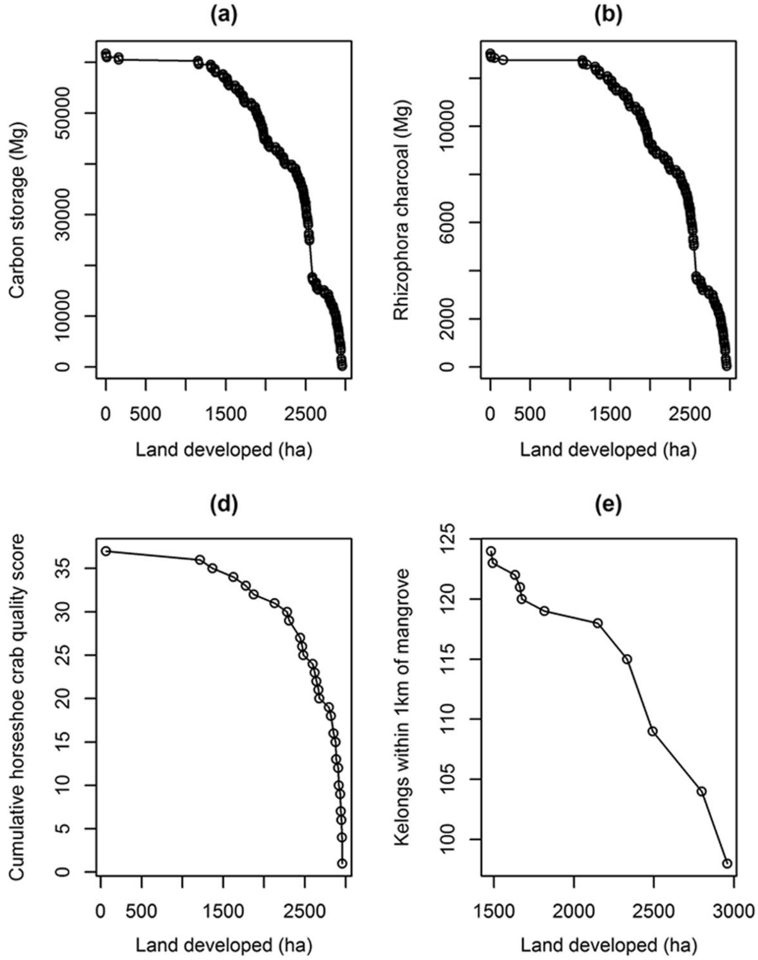

Fig. 3 Trade-off relationships between environmental indicators and urban development

Characterizing Trade-offs between Environmental Indicators

Many of the ecosystem service and conservation indicators were synergistic with each other. The servicing of offshore aquaculture by nearby mangroves could be maximized simultaneously with any of the other indicators (Fig. 4). Similarly, the simulated scenarios that provided the highest-quality habitat for mangrove horseshoe crabs also provided the highest levels of carbon storage, they could provide the largest supply of *Rhizophora* spp. charcoal, and provided the longest length of mangrove boardwalk (Fig. 4). Biomass carbon storage and boardwalk length (as a proxy of recreation accessibility) also showed a synergistic relationship. Conversely, biomass carbon storage and harvesting of *Rhizophora* spp. carbon for charcoal production showed a linear trade-off (Fig. 4). *Rhizophora* spp. charcoal production and boardwalk length showed an outward-curving, less-sensitive trade-off relationship (Fig. 4).

Discussion

Trade-Offs between Urban Development and Environmental Indicators

Across the urban landscape of Singapore, coastal environmental indicators were not projected to decline linearly with increasing coastal development. Four of the five indicators that were modeled in this study showed insensitive trade-offs with urban development (Fig. 3); in effect, they can be expected to decline nonlinearly with increased development. Trade-offs were not particularly sensitive in cases where some mangrove sites provide high levels of an environmental indicator value compared to the area of land that could be gained by development there. Conversely, other patches provided less indicator values per square meter of land that could be developed, so that the loss of these patches would have a lesser impact on large-scale indicator provision. An example of an indicator that is insensitive to urban development is recreational

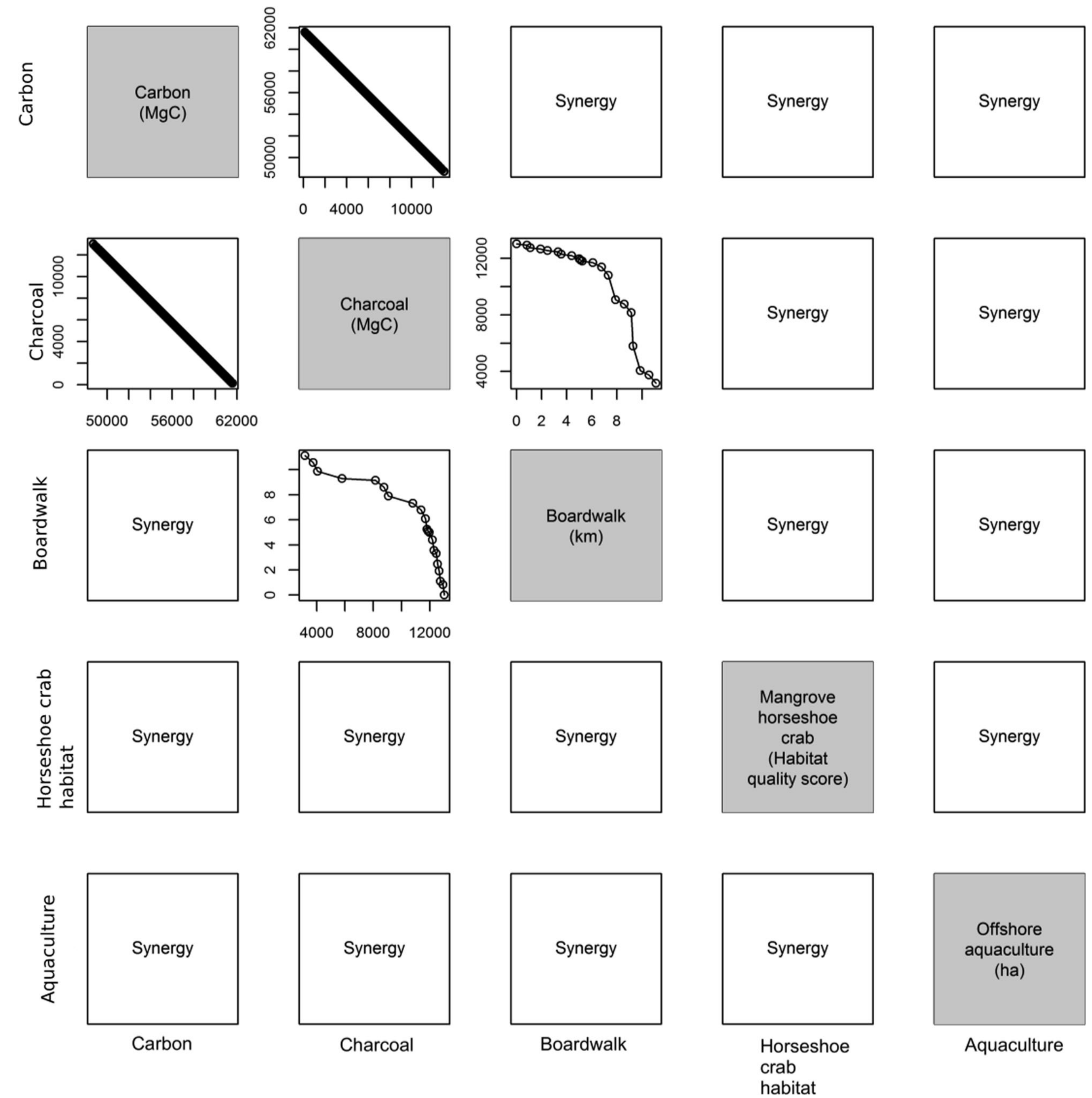

Fig. 4 Pairwise trade-off or synergistic relationships between different environmental indicators. Trade-off relationships between pairs of indicators are plotted against each other. Trade-off relationships are indicated with Pareto frontier diagrams, while relationships that were found to show no trade-off (synergies) are indicated by the term "Synergy."

accessibility, an important cultural ecosystem service that mangroves provide to Singapore's wholly urban population (Thiagarajah et al. 2015). A substantial proportion of Singapore's mangroves is on state or military land, so they are inaccessible to the public for recreational purposes. These patches include many mangroves that are projected to be converted into urban development under the 2013 URA Land Use Plan and 2015 URA Master Plan. The inaccessibility of these mangroves means that their loss would not have a huge impact on ecosystem services related to recreational accessibility. However, the loss of a few habitat patches with high recreational accessibility would cause a rapid decline in recreational ecosystem service provision. For example, Berlayer Creek in the south of Singapore is a small patch of remnant mangrove that has been transformed into a recreational resource through the addition of a footpath, boardwalks, and viewing platforms. Under the plans outlined in both the 2013 URA Land Use Plan and the 2014

URA Master Plan, the area in and around Berlayer Creek is likely to be converted into residential use within the next 35 years, potentially resulting in the loss of the mangrove recreational resource. However, the urban land area that would be gained by replacing the Berlayer Creek mangrove would be small because the patch covers a small area, and further land reclamation is not proposed. Protecting the Berlayer Creek mangrove and the associated recreational infrastructure in the future could thus provide a way to maintain the provision of mangrove recreational services for neighboring residential communities, while developments in less publicly accessible mangroves around Singapore could yield a greater area of urban land for development.

Carbon storage also showed an insensitive trade-off with coastal development, in part due to the substantial spatial variation in mangrove carbon stocks at the national scale (Friess et al. 2016). Thus, careful spatial planning of development could maximize the carbon storage ecosystem service that Singapore's mangroves provide. Maximizing vegetated carbon storage is important in the Singapore context because Singapore's annual per capita carbon emissions are more than double that are recorded for other Asian nations (Velasco and Roth 2012). The protection of mangrove patches could reduce emissions released due to development, and could also offset emissions from other sectors. The United Nations Framework Convention on Climate Change requires countries to undergo a full and regular accounting of carbon emissions and stocks, including those stored in vegetation biomass. Singapore has contributed to this by implementing a national-scale remote sensing and field analysis of vegetated carbon stocks (Straits Times 2013) as part of this accounting process.

No highly sensitive trade-offs were identified between urban development and any of the environmental indicators. Sensitive trade-offs can occur when the sum of the ecosystem service or conservation benefit that is provided by the complete mangrove network is greater than the sum of its parts, for example, in cases where the provision of a particular benefit strongly depends on connectivity between different mangrove patches, such that losing any one mangrove patch would have a substantial negative impact on provision. The importance of the connectivity between patches was not modeled explicitly for any of the environmental indicators used in this study, as it is unlikely to be important over the short term for maintaining biomass carbon stocks, *Rhizophora* trees, boardwalks, or offshore aquaculture. Connectivity could potentially be important for ecological indicators (Fitzgibbon et al. 2007), such as the horseshoe crab habitat quality indicator used in this study. However, it is unlikely that mangrove horseshoe crabs regularly travel for long distances between patches; a mark and recapture study of a related species found that less than 20% of the individuals moved from the release point during one breeding season (Rudloe 1980). Maintaining the connectivity between the patches may be important for the long-term conservation of mangrove species that were not the focus of this study, as well as other ecosystem services not included in this study, such as pollination and the regulation of pests (Kremen 2005; Mitchell et al. 2013).

The lack of highly sensitive trade-offs, and the dominance of insensitive trade-offs between urban development and environmental indicators is potentially encouraging for the future of urban mangrove ecosystem service provision in Singapore. The shape of the observed trade-offs indicates that it should be relatively easy for compromises to be made between urban development and each of our indicators individually (Emmerich and Deutz 2007). However, this does not necessarily mean that it will be possible to provide multiple services and conservation benefits alongside urban development in the future (Sanon et al. 2012), as there may be trade-offs between providing different ecosystem services (Bennett et al. 2009; Rodríguez et al. 2006).

Trade-offs between Environmental Indicators

Our analysis of pairwise trade-offs between the various environmental indicators used in this study identified that the majority of relationships were either synergistic or showed insensitive trade-offs (Fig. 4), suggesting that it should be possible to provide relatively high levels of biomass carbon storage, recreational value, offshore aquaculture, and good-quality habitat for mangrove horseshoe crabs simultaneously. This is perhaps not surprising, as the provision of many environmental indicators is influenced by habitat quality (*sensu* Power 2010), and the cultural ecosystem services provided by temperate woodlands are associated with the perceived habitat quality (e.g., Agbenyega et al. 2009).

However, there is a linear trade-off between protecting Singapore's mangrove biomass carbon stock, and developing a sustainable mangrove charcoal industry, as charcoal production requires the removal of carbon from the ecosystem. This is an example of a case in which management of one ecosystem service impinges on another (Bennett et al. 2009). When considering which conservation benefits and ecosystem services to prioritize in the future, Singapore therefore faces a choice that is common in mangrove management; natural ecosystems can either be utilized for the extraction of provisioning ecosystem services, or protected for their biodiversity and the regulatory and cultural services that they provide (Grasso 1998; Nickerson 1999).

Generally, environmental trade-off studies focus on single indicators that are assumed to act in isolation. However, ecosystem services and ecosystem functions interact in myriad ways, and a poor understanding of these interactions may mean that managing for one ecosystem service may have unintended and unforeseen consequences on others (Rodríguez et al. 2006). Bennett et al. (2009) highlight that studies looking at correlations and relationships between environmental indicators are important. Such studies can help us understand overall ecosystem resilience and avoid unintended and large-scale shifts in the provision of environmental indicators. Furthermore, they can help us to identify "ecological leverage points" where relatively small management interventions can yield disproportionately large benefits for multiple environmental indicators.

Implications for Land Use and Marine Spatial Planning (MSP) in Singapore

Singapore's remaining mangroves will come under pressure from urban development in the near- to medium-term future (MND 2013; URA 2014). This research highlights the importance of managing future mangrove development carefully, to protect some level of provision of a range of environmental benefits. Thus, the modeling framework presented here is of direct relevance to local decision makers and stakeholders in the following ways:

An aid to land use planning

The Pareto frontier approach highlights the objective trade-offs between environmental benefits and development, but development is further constrained by prevailing urbanization and environmental policies (Seppelt et al. 2013). The role of the simulation conducted in this study is therefore to provide baseline information for development and conservation authorities such as the URA and the National Parks Board, to test the impacts of existing public plans for development (e.g., MND 2013; URA 2014) alongside alternative scenarios and outcomes. Indeed, the benefit of the Pareto approach for Singapore's decision makers is the ability it gives them to identify optimal solutions from the large diversity of potential options available to them (Cao et al. 2012). Importantly, for development and conservation decision makers, we show that there are broad possibilities to achieve multiple benefits across the urban landscape of Singapore; none of the mangrove indicators showed sensitive trade-offs with development, or each other, and the majority of the environmental indicators were synergistic (Figs. 3, 4).

An aid to marine spatial planning

Managing optima for multiple coastal environmental indicators requires a holistic, landscape approach to managing coastal resources and trade-offs. This necessitates a broad integrated coastal zone management (ICZM) and MSP strategy. MSP strategies are more common in temperate nations (Douvere 2008) compared to countries in tropical Southeast Asia, although they are gaining traction in the Asian tropics through organizations such as the Partnership in Environmental Management for the Seas of East Asia. Singapore has reacted to these initiatives by recently producing its first Integrated Urban Coastal Management (IUCM) plan (TCCME 2013). This document is aligned more toward the tenets of ICZM (such as coordination, governance, and policies) rather than being an explicit MSP document. However, it does outline guiding principles relating to *Proactive Planning and Management* that require optimized and forward-looking planning that aims to "make the best use of Singapore's limited natural resources" (TCCME 2013). Another guiding principle in Singapore's IUCM relates to *Science-Based Management*, in which planning and management is holistic, comprehensive, and evidence-based (TCCME 2013). The approach used here demonstrates how such a comprehensive assessment using evidence on a broad range of indicators can help to identify a limited subset of management options that are objectively optimal, thus narrowing the options for decision makers to subsequently consider subjectively.

A tool to encourage stakeholder engagement in planning

The modeling approach as presented here provides an objective analysis of the trade-offs, with the various indicators and development scenarios that are all equally weighted. This provides an objective baseline for decision making, although the next step will be to tailor and weight the assumptions and decisions in the model to the needs of specific stakeholders (White et al. 2012). If Singapore is to develop an MSP to guide future development in mangroves, the objective trade-offs identified in the present study should be evaluated and prioritized subjectively by a broad stakeholder group, including participation from key stakeholders such as the URA, National Parks Board, Agri-Food and Veterinary Authority, and Port of Singapore Authority. With a number of coastal land uses present in a small area, Singapore's coastal management regime is complex, with a wide variety of stakeholders that may have views on development and conservation, including several government agencies, industries, local residents, and NGOs. These stakeholders must weigh the relative importance of the environmental indicators used here, and identify indicators of other benefits that may be of interest, in order to determine the priority mangrove patches for conservation, and the required area of mangroves to protect them. Ecosystem service tools that allow stakeholders to utilize their own knowledge have previously been shown to be an important contributor to successful and inclusive coastal spatial planning in a variety of contexts (McKenzie et al. 2014; Arkema et al. 2015).

Tools that encourage greater stakeholder engagement fit within broader efforts in Singapore toward greater public participation in decision making in the twenty-first century (Soh and Yuen 2006). Stronger stakeholder engagement in coastal management has long been advocated by NGOs in Singapore (NSS 2009) and is a key part of the *Active Partnerships* principle in Singapore's IUCM plan (TCCME 2013). The Pareto frontiers approach provides scenario outputs that provide the basis for tangible, focused, and evidence-based discussions between stakeholders.

Pareto Frontiers—A Framework to Assess Trade-offs for Coastal Management

Under development scenarios such as ones outlined here for Singapore, environmental indicators such as ecosystem services and habitat quality for organisms of high conservation interest may be key tools with which we can communicate the importance of ecosystems to policy makers and managers tasked with land development (*sensu* Granek et al. 2010). Future coastal management will require the optimal allocation of both human (development) and natural resources (ecosystem services), although current planning mechanisms often fail to incorporate environmental indicators sufficiently into planning and decision-making processes (de Groot et al. 2010). Environmental indicators may be missing from current planning mechanisms due to an incomplete knowledge of the relationships between environmental indicators and/or development, and because the nonmonetary nature of many indicators excludes them from traditional decision-making frameworks (Grêt-Regamey et al. 2013). The present study shows that Pareto frontiers can be a tool to visualize the trade-offs between a range of biological, biophysical, and human coastal environmental indicators in land development scenarios for urbanizing areas. However, the effectiveness of using Pareto frontiers, as with all trade-off analyzes, strongly depends on the suite of indicators that are chosen for analysis. The relevance of such analyzes can be enhanced by consulting the literature or stakeholder groups to identify indicators that are of interest, as well as by ensuring that a range of the types of indicators, such as those relevant to biodiversity, provisioning services, regulating services, and cultural services, are included.

Pareto frontiers have been used previously to analyze the trade-offs between a single environmental indicator and a single development strategy, for example, fish biomass vs. fishing intensity (Lester et al. 2013). Pareto frontiers are a useful concept for communicating to decision makers the potential impacts of development plans on single environmental indicators, as the frontier is easily defined and visualized. However, trade-off analysis should also consider the impact of development on bundles of ecosystem services, and interactions within bundles of environmental indicators, as most landscapes are multifunctional in terms of ecosystem service provision (Bennett et al. 2009; de Groot et al. 2010). Isolated studies have also investigated the trade-off between a development strategy and a small number of environmental indicators, such as the impact of renewable wind energy on both lobster fisheries and recreational activities (White et al. 2012). However, it becomes more difficult to interpret the trade-offs between multiple environmental indicators and/or development scenarios, due to the difficulties in visualizing such trade-offs, and the inherent difficulty in managing the optima for multiple purposes.

Conclusions

The coastal zones of many tropical nations continue to develop rapidly, leading to the loss of coastal habitats, their associated biodiversity, and the ecosystem services that support coastal populations (e.g., Lai et al. 2015; Richards and Friess 2016). To ensure the best possible provision of ecosystem services under increasing urbanization, it is important to understand how to best incorporate coastal ecosystems and their benefits into long-term and large-scale urban planning. This study has shown that many mangrove environmental indicators are synergistic with each other, meaning that urban development scenarios can be designed to provide multiple benefits from coastal areas. Furthermore, even in a dense city such as Singapore, some level of coastal environmental indicators can be protected alongside development, if development is focused within lower-value coastal areas. Characterizing the shape of the trade-offs between environmental indicators and urban development can help urban planners to better understand the sensitivity of biodiversity and ecosystem service provision to new developments. This information could be used to shape decisions about where and how to expand cities, to allow future urban developments to provide much-needed space while still protecting biodiversity and the important ecosystem services that help to make cities more pleasant to live in.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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