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Priority areas for mixed-species mangrove restoration: the suitable species in the right sites

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Abstract

The rapid mangrove loss and fragmentation observed in the past decades have catalyzed numerous efforts to restore mangroves globally, but nearly half of these efforts fail or underperform. Planting the wrong mangrove species on the wrong site, and overrelying on mangrove monocultures are the main mistakes. Here, we develop a methodological approach that combines a Geographic Information System-based suitability analysis and landscape connectivity analysis to identify suitable areas for species-specific and mixed-species mangrove restoration, and priority areas in terms of patch importance. We apply this approach to the Large Xiamen Bay in southeast China. Results from the case study emphasize the critical need of considering species-specific characteristics in mangrove restoration planning and the spatial heterogeneity of priority areas for mixed-species restoration. We find that mangrove restoration could indeed increase landscape connectivity of mangrove habitats. Larger patches would have more significant effects on habitat connectivity, and several small patches could be considered as stepping stones to promote landscape-level connectivity. The proposed approach has various implications for mangrove restoration efforts both at the study site and in other parts of the world.

1. Introduction

Mangroves are among the most biodiverse ecosystems in the world (Lee *et al* 2014), providing multiple ecosystem services to local and global communities, including global climate regulation (Donato *et al* 2011), coastal protection (Hochard *et al* 2019), and recreational opportunities (Spalding and Parrett 2019). However, they are one of the most threatened ecosystems, and although deforestation rates have declined from 1%–2% to around 0.13% per year over the past three decades (Bryan-Brown *et al* 2020), remaining mangroves are fragmented and expected to decline further (Saintilan *et al* 2020). This will most likely impact the provision of the ecosystem services they provide, as many of these services such as erosion prevention, shoreline protection, and climate regulation depend on the size and arrangement of forest patches (Bryan-Brown *et al* 2020).

Mangrove restoration has been encouraged globally to compensate for mangrove loss. Despite widespread mangrove restoration, success rates remain disappointingly low (Balke and Friess 2016). Arguably one of the most common errors during mangrove restoration is the failure to select the most suitable species for the right site (Worthington and Spalding 2018), since mangrove species have different tolerance to environmental factors, such as temperature (Chen *et al* 2017), salinity (Barik *et al* 2018), and elevation (Leong *et al* 2018). Furthermore, restoration through monocultural models were not successful in some contexts (Bosire *et al* 2008). This is largely because plantations with single species have a more limited potential to host biodiversity (e.g. fish, crabs, birds), and are more likely to suffer from pests (Hai *et al* 2020). Conversely scholars have argued that a mix of suitable species is crucial for fulfilling the ecological and physical functions of restored mangroves (Juliet and Dorothée 2017).

Ecosystem restoration has been receiving significant policy attention in recent decades. With a growing number of studies pointing to the ecological and economic case for mangrove restoration (Su *et al* 2021), there have been calls to improve mangrove restoration knowledge and interventions (Lewis *et al* 2019). Some of the most pressing needs are solutions that can improve the spatial planning of mangrove restoration actions, especially given the limited resources often allocated for restoration (CBD 2012). It is critical to accurately identify priority mangrove restoration sites and offer more nuanced information about the most appropriate species and restoration models in these priority areas (Worthington and Spalding 2018). However, there are two major knowledge gaps when it comes to selecting the appropriate sites and species for mangrove restoration.

The first is that most studies fail to provide exact guidance on the appropriate mangrove species or areas suitable for mixed-species restoration. Most suitability studies of mangrove restoration using Geographic Information Systems (GIS) at the national (Syahid *et al* 2020) and local scale (Jumawan and Macandog 2021) have failed to specify species, while only one study to the best of our knowledge has considered species-specific environmental factors but did not identify the appropriate species or areas for mixed-species restoration (Suhardiman *et al* 2013).

On the other hand, mangrove restoration studies fail to consider landscape connectivity properly. In order to achieve efficient conservation and restoration planning, many scholars have emphasized the important role of landscape connectivity (Tambosi *et al* 2014) to identify the most critical fragments for restoration (d'Acampora *et al* 2018). In the context of mangrove restoration, higher connectivity could improve their potential to increase biodiversity, ecosystem functioning, and stability in meta-community networks (Thompson *et al* 2017) and enhance their resilience to potential climate change threats (Van der Stocken *et al* 2019). However, to the best of our knowledge there have not been any studies applying concepts and methodologies related to landscape connectivity for mangrove restoration.

Here, we develop a methodological approach that can inform in a nuanced manner the spatial planning of species-specific and mixed-species mangrove restoration, as well as the priority areas for mangrove restoration in terms of landscape connectivity. We use as a case study the Large Xiamen Bay (LXB) ecosystem in southeast of China, as it presents an ideal context considering the extensive mangrove degradation over the past decades (Lin *et al* 2007), the high fragmentation of the mangrove habitat (Zhang *et al* 2021), and the renewed interest for mangrove restoration by the local and national government (see section 4). Our approach combines (a) a high-resolution (30×30 m) GIS-based suitability analysis to identify suitable areas and appropriate species for restoration actions, (b) a landscape connectivity analysis using a graph theory framework (Minor and Urban 2008) to evaluate the effectiveness of restoration response to landscape connectivity, and (c) a patch importance analysis (Bodin and Saura 2010) to identify the priority patches for restoration and stepping stones to promote landscape-level connectivity. We present the results through a map of priority patches for mangrove restoration in the LXB, and their corresponding suitable mangrove species. We believe that the proposed approach has the potential to be adapted in other geographical contexts to inform regional-scale mangrove restoration planning and assist decision-makers in the efficient allocation of limited resources.

2. Data and methods

2.1. Study area

The LXB ecosystem is a semi-closed subtropical bay on the west bank of the Taiwan Strait, located in the mouth of Jiulong River on the southeast coast of China (24°29′09″N, 118°14′12″E). The extent of natural mangroves shrank dramatically from 320 ha in the 1960s to merely 21 ha due to rapid urbanization and the expansion of aquaculture ponds (Lin *et al* 2005). Although artificially cultivated mangroves expanded total area, mangrove habitats are still very fragmentated (Zhang *et al* 2021). Overall the existing mangrove habitats in the LXB are approximately 480 ha based on a satellite image in Google Earth on 26 July 2019. Here we divide the study area into nine subregions based on the natural characteristics and the administrative management of coastal and marine areas in the LXB (figure S1 and table S1 in supplementary information available online at stacks.iop.org/ERL/17/065001/mmedia).

2.2. Environmental parameters and data

Non-biological factors such as the elevation, velocity of tidal flow, salinity, temperature, and substrate, are recognized as limiting factors in the distribution of mangrove communities (Alongi 2008). Based on previous studies (Lewis *et al* 2019), we use six environmental parameters for the suitability analysis, namely salinity, elevation, tidal inundation time, slope, wind speed and flow speed. Although the zonal distribution of mangroves is primarily regulated by temperature (Osland *et al* 2016), we do not use temperature as an environmental parameter in our suitability analysis considering the relatively small scale of the study site.

The salinity data is collected from a numerical study of ecological variables in Xiamen Bay (Huang 2018). The mean salinity is determined by averaging the salinity values obtained at the high and low tidal periods, while the salinity of the open sea area is supplemented with global seawater salinity data from HYCOM+NCODA Global 1/12° (www.hycom.org/dataserver/gofs-3pt0/analysis). The bathymetry and tidal data (tide elevation and time) consist of 8699 predicted points in the tidal flat area collected from the State Key Laboratory of Marine Environmental Science (Xiamen University). The slope map is generated through bathymetry data using the Slope tool in ArcGIS 10.3. See supplemental methods for more information about the calculation of tidal inundation time. Data on the velocity of tidal flow is obtained from the State Key Laboratory of Marine Environmental Science (Xiamen University). Wind speed observations are obtained from the NOAA (www.ncdc.noaa.gov/isd) supported by the National Centers for Environmental Information (NCEI). The classification of flow and wind speed is based on natural breaks.

The intertidal zone in the LXB covers approximately 30 600 ha and is characterized by six types of natural intertidal land use cover, i.e. mudflat, sand, rock, saltmarsh, mangrove, and gravel areas (Su and Peng 2021), based on the classification of intertidal sediment types, grain size and coverages from remote sensing data. In general, mangroves thrive in coastal areas that are constantly inundated and have a mud and sand substrate (Kathiresan and Bingham 2001). Considering that the sandy beaches in the LXB are mostly used for recreation and tourism, we use the map of mudflat areas as the substrate map. The layer of intertidal covers of the LXB was obtained from Fujian Ocean and Fishery Bureau in 2015 and the extracted mudflat map from the intertidal covers layer is further calibrated using a satellite image captured on 26 July 2019, in Google Earth. Seawalls and other shoreline protection structures or port areas at the landward mangrove margin would hinder natural landward migration and induce sediment erosion in the mangrove area, and adjacent regions (Gilman and United Nations Environment Programme 2006). As a result, we create 5 m and 10 m buffer zones for seawalls and port areas (Hu 2016b), respectively, to exclude the mudflat zone close to seawalls and port areas.

2.3. Suitability analysis and mixed-species restoration scenario

The land suitability for mangrove restoration is evaluated using GIS analytical techniques, including interpolation and weighted sum overlay based on multi-criteria analysis. The Universal Kriging approach is used for the interpolation of the six parameters outlined above considering its advantages in generating Digital Models of Depth based on bathymetric surveys compared to Inverse Distance Weighted (IDW) approaches (Ferreira *et al* 2017). Considering the sampling units for tree density is often set as 30 × 30 m (Lechner and Rhodes 2016) and the layer of intertidal covers was derived from Landsat 30 m resolution satellite image, we resampled all maps of environmental parameters (i.e. salinity, elevation, tidal inundation time, slope, wind speed and flow speed) into 30 × 30 m pixels based on the bilinear interpolation, georeferenced with the projection system for WGS 1984 Transverse Mercator.

Given the fact that different mangrove tree species are sensitive to different levels of salinity, elevation, and tidal inundation time (Friess 2017, Barik *et al* 2018, Leong *et al* 2018), we collect the relevant information from literature about the effects of these three environmental factors on individual mangrove species. We identify seven mangrove species found in the LXB as good candidate species for mangrove restoration, namely: *Kandelia obovata, Aegiceras corniculatum, Avicennia marina, Bruguiera gymnorrhiza, Acanthus ilicifolius, Rhizophora stylosa*, and *Sonneratia apetala*. We propose a species index table containing five suitability classifications: unsuitable, poor, fair, suitable, and perfectly suitable (table 1). Figure S2 in the supplementary information depicts the spatial distribution of the six environmental parameters used in this study.

Following the reclassification of each parameter for a given mangrove species, we create a suitability map using the weighted overlay analysis. We assume that all environmental parameters are equally important, and thus assign them equal weights for the analysis. The weighted overlay analysis is conducted when the sub-parameter scores (see table 1) are assigned to the relevant layers in the ArcGIS 10.3 setting. A post mixed species restoration scenario was then generated by merging the results of 'perfectly suitable' and 'suitable' of each mangrove species and combining with the map of existing mangroves.

2.4. Landscape connectivity analysis and identification of priority areas for restoration

A series of techniques have been proposed for calculating connectivity within the remaining habitat and for prioritizing conservation actions (Volk *et al* 2018). In this study, we used Graph Theory models to evaluate landscape connectivity, allowing for assessing the importance of individual landscape elements and guide conservation or restoration efforts (Estrada and Bodin 2008). Essentially Graph Theory models utilize a set of patches (nodes) and links. The patches represent the habitat fragments, while the links indicate the potential of mangrove propagule to disperse between the patches (Galpern *et al* 2011). Here we define the dispersal distance for all mangrove

Table 1. Classification of indicators for mangrove restoration.

	Unsuitable	Poor	Fair	Suitable	Perfectly suitable	Citation
General						
Slope (%)	>4%	3%–4%	2%–3%	1.5%–2%	0%–1.5%	(Syahid *et al* 2020)
Velocity of flow [a]	High	Moderately high	Moderate	Moderately low	Low	(Abd-El Monsef *et al* 2017)
Wind speed [a]	High	Moderately high	Moderate	Moderately low	Low	(Krauss and Osland 2019)
Aegiceras corniculatum						
Elevation (m) [b]	<0, > 4	0–0.5, 3–4	0.5–1, 2.5–3	1–1.65, 1.75–2.5	1.65–1.75	(Luo 2015)
Tidal inundation time (h) [c]	<0.5, > 6	0.5–1, 5–6	1–1.5, 4.5–5	1.5–2, 3–4.5	2–3	(Luo 2015)
Sea surface salinity (‰)	>15	10–15	7–10	5–7	0–5	(Tang 2014)
Avicennia marina						
Elevation (m) [b]	<(−1),> 3	(−1.0)–(−0.5),2–3	(−0.5)–0,1.5–2	0–0.46, 0.56–1.5	0.46–0.56	(Hu and Ye 2009)
Tidal inundation time (h) [c]	<1, > 10	1–2, 9–10	2–3, 8–9	3–4, 6–8	4–6	(Liao 2010)
Sea surface salinity (‰)	<5, > 45	5–10, 40–45	10–15, 35–40	15–20, 30–35	20–30	(Huang *et al* 2014)
Acanthus ilicifolius						
Elevation (m) [b]	<0, > 4	0–0.5, 3–4	0.5–1, 2.5–3	1–1.7, 1.9–2.5	1.7–1.9	(Zhang *et al* 2011)
Tidal inundation time (h) [c]	>8	6–8	4–6	0–1, 3–4	1–3	(Zhang *et al* 2011)
Sea surface salinity (‰)	>15	10–15	7–10	5–7	0–5	(Zhu *et al* 2008)
Bruguiera gymnorrhiza						
Elevation (m) [b]	<(−1), > 3	(−1.0)–(−0.5), 2–3	(−0.5)–0, 1.5–2	0–0.46, 0.56–1.5	0.46–0.56	(He 2009)
Tidal inundation time (h) [c]	<1, > 10	1–2, 9–10	2–3,8–9	3–4.5, 6–8	4.5–6	(Jiang *et al* 2018)
Sea surface salinity (‰)	>40	<5, 35–40	5–10, 30–35	10–15, 25–30	15–25	(Mo *et al* 2001)
Kandelia obovata						
Elevation (m) [b]	<0, > 4	0–0.5,3–4	0.5–1, 2.5–3	1–1.57, 1.67–2.5	1.57–1.67	(Chen *et al* 2006)
Tidal inundation time (h) [c]	<2, > 10	2–3, 9–10	3–3.5, 8–9	3.5–4.6, 5.6–8	4.6–5.6	(Chen *et al* 2006)
Sea surface salinity (‰)	<3, > 30	3–5, 25–30	5–7, 20–25	7–10, 16.5–20	10–16.5	(Huang *et al* 2009)
Rhizophora stylosa						
Elevation (m) [b]	<(−1), > 3	(−1.0)–(−0.5), 2–3	(−0.5)–(−0.1), 1–2	(−0.1)–0, 0.5–1	0–0.5	(He 2009)
Tidal inundation time (h) [c]	<1, > 10	1–2, 9–10	2–3,8–9	3–5,6–8	5–6	(He and Lai 2009)
Sea surface salinity (‰)	>40	<5, 35–40	5–10, 30–35	10–15, 25–30	15–25	(Mo *et al* 2001)

(Continued.)

Table 1. (Continued.)

	Unsuitable	Poor	Fair	Suitable	Perfectly suitable	Citation
Sonneratia apetala						
Elevation (m) [b]	<(−1.5),> 4	(−1.5)–(−1),3–4	(−1)–(−0.5), 1.8–3	(−0.5)–0.1, 0.35–1.8	0.1–0.35	(Chen *et al* 2006)
Tidal inundation time (h) [c]	>12	10–12	0–1,9–10	1–4,6–9	4–6	(Peng 2017)
Sea surface salinity (‰)	>40	<5, 30–40	5–10, 25–30	10–15, 20–25	15–20	(Tang 2014)
Mangrove[d]						
Elevation (m) [b]	<(−1.5), > 4	(−1.5)–(−1), 3–4	(−1)–(−0.5), 2.5–3	(−0.5)–0, 1.75–2.5	0–1.75	
Tidal inundation time (h) [c]	>12	10–12	0–1, 9–10	1–2, 6–9	2–6	
Sea surface salinity (‰)	>45	40–45	35–40	30–35	0–30	

Note: [a] The classification of velocity of flow and wind speed is based on natural breaks due to the lack of quantitative report of classification.
[b] The elevation data has been converted based on the zero point of the Yellow Sea.
[c] The tidal inundation time is the time during a principal solar semidiurnal tidal cycle (12 h).
[d] Indexes for mangrove are summarized from the above species.

species as 5 km based on conservative estimates (Van der Stocken *et al* 2019).

The Probability of Connectivity (*PC*) index and Integral Index of Connectivity (*IIC*) (Saura and Pascual-Hortal 2007) are the most widely used indices to measure functional connectivity in conservation studies (Tambosi *et al* 2014). Both metrics are built on graph structures and use species dispersal capability, which presents a consistent behavior for analyzing landscape changes, and are considered robust for connectivity assessment (Pascual-Hortal and Saura 2006, Saura and Pascual-Hortal 2007). The *PC* can be expressed following equation (1):

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \times a_j \times p_{ij}^{*}}{A_{\mathrm{L}}^{2}} \tag{1}$$

where n is the number of patches in the study area, each with an area a_i or a_j, A_{L} denotes the total landscape area (including habitats and non-habitat), and p_{ij} is the probability of *a* species moving directly from patches i to j (without passing through any intermediate patch).

The *IIC* metric is similar to the *PC* metric but is based on networks with unweighted links. *IIC* differs from *PC* in that it considers the topological distance (d_{ij}) between patches i and j (i.e. minimum number of links that have to be passed to move from i to j). *IIC* is defined by equation (2):

$$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left(\frac{a_i \times a_j}{1+nl_{ij}}\right)}{A_{\mathrm{L}}^{2}} \tag{2}$$

where nl_{ij} indicates the number of links in the shortest path (topological distance) between patches i and j. *IIC* ranges from 0 to 1 and increases with improved connectivity.

Computing the metric before and after the removal of patch k allows for the evaluation of the importance of each patch (Bodin and Saura 2010) (see equations (3) and (4)). The *dIIC* and *dPC* quantify the loss of connectivity if patch k is removed from the habitat network. The higher the *dIIC* and *dPC* values, the more important the patch for connectivity. We investigate the patches with higher contributions (i.e. those ranked in the top 5%, 10% and 50% in terms of the estimated value of *dIIC* and *dPC*) to identify the suitable priority areas (i.e. ranked in the top 5%) for mangrove restoration.

$$dIIC_k\,(\%) = \frac{IIC - IIC_{\mathrm{remove}}}{IIC} \times 100 \tag{3}$$

$$dPC_k\,(\%) = \frac{PC - PC_{\mathrm{remove}}}{PC} \times 100. \tag{4}$$

Conefor Sensinode (version 2.6) (Saura and Torné 2009) was used to compute the above indices.

The final result of the priority suitable lands for mixed-species mangrove restoration is generated by combining maps of the *dIIC* and *dPC* values. Priority patches are identified when both the *dIIC* and *dPC* values are ranked among the top 5%. Suitable species in each patch are further determined by measuring the proportion of species-specific suitable lands in the patch. The technical framework of GIS-based suitability analysis and connectivity analysis outlined above is summarized in figure S3 in the supplementary information.

Table 2. Identified species in three validation sites.

Validation site	Area	Identified species
Jiulong River Estuary	320 ha	*K. obovata*, *A. corniculatum*, *A. marina*, *B. gymnorrhiza*, *A. ilicifolius*, *R. stylosa*, and *S. apetala*.
Xiatanwei	40 ha	*K. obovata*, *S. apetala*, *A. corniculatum*, *B. gymnorrhiza*, *R. stylosa*, *A. marina* and *Laguncularia racemose*
Fenglin Bay	15 ha	*K. obovata*, *R. stylosa* and *L. racemose*

2.5. Validation

In order to identify whether the variables and GIS-based suitability analysis are consistent with the reality on the ground, we reconducted the suitability analysis by replacing the mudflat map with the existing mangrove habitat map to validate variables and methods (Validation analysis I). The two largest mangrove habitats in the LXB (i.e. Jiulong River Estuary and Xiatanwei) and one on-going mangrove restoration project located at the Fenglin Bay in the west of Tong'an Bay, are selected for this validation exercise. Through ecological fieldwork conducted in July 2021, we identified the mangrove species growing in the three validation areas using visual identification. The suitable areas for mangroves and specific mangrove species predicted from our analyses (Validation analysis I) are cross-checked with the information from the field to determine the consistency of our analysis and validity of our study. Table 2 describes the identified species in three validation sites.

Here we need to point that the landfill activities for planting mangroves may have changed the elevation, slope and corresponding tidal inundation time during the restoration projects, especially in Xiatanwei and Fenglin Bay, which would affect the results of our validation analysis to some extent. To account for this, we re-ran the analysis by excluding the above three parameters (Validation analysis II).

2.6. Sensitivity analysis and uncertainties

We conducted two parallel sensitivity analyses. The first sensitivity analysis accounts for the possible effect of different propagule dispersal distances on identifying important patches. For this we conducted two analyses with dispersal distances of 1 km and 10 km. The second sensitivity analysis explores whether the buffer distances for seawall and port areas affect the total area of suitable lands. For this we increased the buffer distances of seawall and port areas to account for the impact of shrinkage extent on the patch importance. We considered the buffer distances of seawall at 25 m and port areas at 50 m, and further increase the buffers to 100 m for seawalls and 200 m for port areas. The results of the sensitivity analyses are reported in section 3.6.

It is worth noting that spatial data such as the ones used in this study unavoidably have inherent uncertainties (Lechner *et al* 2012). Furthermore, coastal hydrology and oceanography entail complex processes and are characterized by temporal variation. Although our data presented here reflect well an average phenomenon of coastal environment in the LXB that could be used in landscape planning, they admittedly cannot precisely capture the dynamic situation, such as stochastic events of typhoon and flooding. However, due to the type of analysis and underlying data it is not possible to quantify uncertainties properly. This is a limitation of this study that should be taken into consideration when using the outcomes of the analysis or adapting the methodology in other contexts. To account for this uncertainty, we rounded the results to 10 s of ha.

3. Results

3.1. Suitable areas for mangrove restoration

Our results show that a suitability analysis that does not specify species could overestimate the suitable areas for mangrove restoration actions. Also, the significant variation of suitable areas and the distribution between species highlights the critical need to specify species in mangrove restoration planning.

In more detail, when not considering species-specificity, the suitability analysis identified that approximately 60 ha of mudflat areas are perfectly suitable and 8240 ha are suitable for mangrove restoration (tables S2 and 2 for the information of classification of suitable areas). However, the suitable area decreased dramatically when factoring in the actual mangrove species for restoration, with a total area of 5990 ha classified as suitable for restoration.

Furthermore, the suitable areas varied between species and regions. For instance, the area suitable for *A. marina* (4360 ha) is almost 36 times larger than the area suitable for planting *A. corniculatum* (120 ha) (table S2 in supplementary information). Conversely, only <1% of the available mudflat area can be restored with the mangrove species *A. corniculatum* and *A. ilicifolius*. According to the distribution map of each mangrove species most of the suitable land for mangrove restoration is found in the Jiulong River Estuary, followed by the Dadeng sea area and the Tong'an Bay (figures 1(a) and (c)).

3.2. Suitable areas for mixed-species restoration

There is substantial potential for mixed-species mangrove restoration. Most suitable areas for mixed-species restoration can be planted with two or three species, while only small parts of areas are suitable to six or seven species. Spatial heterogeneity is also reflected in the suitable areas for mixed-species restoration.

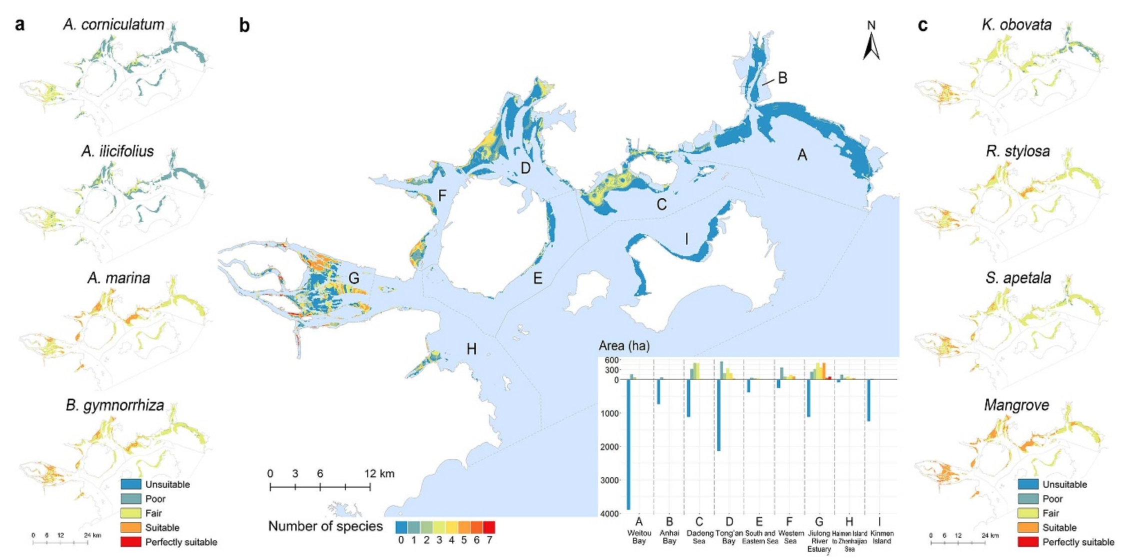

Figure 1. Suitable areas for mangrove restoration. Panels (a) and (c) present the results of the suitability analysis for each species. The map of mangrove in panel (c) shows the area suitable for mangrove restoration when not considering species. Panel (b) shows the area suitable for mixed-species mangrove restoration. The bar chart denotes the unsuitable (in blue) and suitable amounts of land for mangrove restoration and the corresponding number of species that could be planted in the same site in each subregion. See table S1 in supplementary information for more information on the LXB subregions.

We estimate that 4190 ha of the mudflat area could be planted with mixed mangrove species ($\geqslant$2 species), accounting for 70% of the total suitable areas and 14% of the total intertidal zone (figure 1(b); table S3 in supplementary information). Only a small portion of the mudflat could be planted with six or seven species (120 ha) in one unit (30 $\times$ 30 m).

Similarly, the actually suitable land for mixed-species restoration differed substantially between subregions (figure 1(b); table S3 in supplementary information). For example, in the Jiulong River Estuary, more than one-third of the intertidal zone (1770 ha) is suitable for mixed-species mangrove restoration, and only 20% is deemed unsuitable. On the other hand, in Kinmen Bay only 0.1% of the intertidal zone (4 ha) is suitable for mixed-species mangrove restoration, with the percentage of unsuitable land being 33%.

3.3. Landscape connectivity analysis of post-restoration scenario

Mangrove restoration could increase landscape connectivity undoubtedly when comparing the estimated values of landscape connectivity indexes (i.e. *IIC* and *PC*) prior and post-restoration. However this increase in landscape connectivity is heterogeneous across the study subregions.

In more detail, the values of *IIC* and *PC* are considerably higher in the Jiulong River Estuary (table 3), which is expected due to the fact that a provincial mangrove nature reserve is located in the Jiulong River Estuary. Across the entire LXB the values of *IIC* and *PC* are expected to increase dramatically from 8.00×10^{-6} to 4.00×10^{-4} and from 2.00×10^{-5} to 1.40×10^{-3} following mangrove restoration. Similar improvements are expected for the Tong'an Bay and Jiulong River Estuary. It is also worth noting that the disparity of *IIC* and *PC* values is expected to increase following restoration. This difference is mainly due to the growing number of mangrove patches that could be connected. However, while the estimated *IIC* and *PC* values in Jiulong River Estuary and Tong'an Bay are higher than other subregions, the results of connectivity analysis after restoration are expected to still be low in Anhai Bay and Kinmen Island (table 3).

3.4. Priority of restoration patches

Patch importance analysis enables us to estimate the importance of specific patches to the landscape connectivity for the whole study area. The results suggest that large patches (>10 ha) have more significant effects on habitat connectivity (figure 2), and several small patches (<1 ha) could be considered as stepping stones promote landscape-level connectivity.

In the existing mangrove habitat in the LXB, around 62% of the mangrove habitat is small patches (<1 ha) with lower *dIIC* or *dPC* value (i.e. not ranked in the top 10%), while almost all of the current patches with an area >10 ha are rated at the top 5% of *dIIC* and *dPC* values (table S4 in supplementary information). Similarly, in the post-restoration scenario small patches are expected to account for 73% of all patches, with nine patches expected to be >100 ha. It is worth noting that four small patches (<1 ha) have a high *dIIC* value (i.e. ranked in the top 10%) (table S4 in supplementary information). The total area of patches ranking in the top 5% of the *dIIC* value and *dPC* is expected to be 3800 ha and 3810 ha respectively, accounting for approximately 12% of the entire intertidal zone of the LXB.

Table 3. Estimated landscape connectivity index in LXB and its subregions.

		Existing mangrove habitat			Restoration scenario		
Region	Area (ha)	*N**	*IIC*	*PC*	N	*IIC*	*PC*
Large Xiamen Bay	126 050	172	8.00×10^{-6}	2.10×10^{-5}	856	3.52×10^{-4}	1.37×10^{-3}
Weitou Bay	16 620	—	—	—	38	6.00×10^{-6}	1.30×10^{-5}
Anhai Bay	2270	—	—	—	40	1.50×10^{-5}	2.80×10^{-5}
Dadeng Sea	10 480	2	—	—	87	7.03×10^{-3}	8.94×10^{-3}
Tong'an Bay	9520	18	1.80×10^{-5}	3.50×10^{-5}	119	3.49×10^{-3}	6.64×10^{-3}
South and Eastern Sea	9070	—	—	—	63	2.10×10^{-5}	4.90×10^{-5}
Western Sea	4540	2	—	—	85	3.36×10^{-3}	6.75×10^{-3}
Jiulong River Estuary	8830	130	1.61×10^{-3}	3.30×10^{-3}	334	2.94×10^{-2}	6.12×10^{-2}
Haimen Island to Zhenhaijiao Sea	13 550	—	—	—	68	9.70×10^{-5}	2.11×10^{-4}
Kinmen Bay	51 180	17	2.76×10^{-11}	4.82×10^{-11}	24	2.39×10^{-9}	6.86×10^{-9}

Note: The area estimates are rounded up to the closest 10 ha to reflect inherent uncertainties (see section 2.6). $^*N$ = Number of patches; **The number of patches in the restoration scenario is 856 for entire LXB while the sum-up number of sub-regions is 858. This is due to the statistical overlap in the junction of Jiulong River Estuary and Haimen Island to Zhenhaijiao Sea.

In terms of geographical distribution, the most important patches (i.e. ranked in 5% of *dIIC* and *dPC* values) are expected to be in Jiulong River Estuary and Dadeng Bay (figures 3(a) and (b)), at 1840 and 910 ha respectively for the top 5% of *dPC* values (figure 3(d)). However, no patch is expected to be both on the top 5% of *dIIC* and *dPC* in three subregions, namely Anhai Bay, the South and Eastern sea, and Kinmen Island (figure 3).

Finally, we identify a total of 41 priority patches with an area of 3420 ha that are expected to have top 5% *dIIC* and top 5% *dPC* results (figure 4). These patches are distributed across all LXB subregions except for the Anhai Bay, South and Eastern Sea and Kinmen Island. Most of these priority patches are found in Jiulong River Estuary (21 patches) and Tong'an Bay (8 patches), followed by Western Sea (4 patches) and Dadeng Sea (4 patches), with only one patch identified in Weitou Bay. Figure 4 presents the top five patches with suitable species in each subregion according to the *dIIC* and *dPC* value. The most suitable species in most priority patches are *A. marina, R. stylosa, B. gymnorrhiza* and *S. apetala* (figure 4). *K. obovata* is also a preferred species in Jiulong River Estuary and the Western Sea, while *A. corniculatum* and *A. ilicifolius* can only be considered in a small number of patches in Jiulong River Estuary.

3.5. Validation of results

From the validation analyses, we find that the estimated suitable areas for mangrove restoration account for 83% of the existing mangrove habitat in the validation sites (validation analysis I) and 94% when accounting for possible variation from ecological engineering before the plantation (validation analysis II) (table S5 in supplementary information).

In terms of mangrove species, the validation analysis (I) suggests that all of the seven species predicted to be suitable in different degrees in both Xiatanwei and Jiulong River Estuary, are also found in the validation sites (figures 5(a), (d) and table 2), which is consistent with the on-the-ground reality to a certain extent. Besides, an on-going coastal restoration project located at the Fenglin Bay, west side of Tong'an Bay (patch no. 9 in our result), adds credibility to our results (figure 5(b)). The satellite images captured from Google Earth show the land cover change from bare flat in September 2020 (figure 5(b)) to mangrove habitat in January 2021 (figure 5(c)) through plantation. Although *K. obovata* is only suitable in a limited area, suitable species from our analysis are consistent with the species used for restoration (i.e. *K. obovata* and *R. stylosa*). Overall, the validation analysis and the on-going coastal restoration project suggests that our results for species-specific mangrove restoration planning are robust.

3.6. Sensitivity analysis

Results from the sensitivity analysis of the dispersal distance show that when using *dIIC* as an indicator, the total area of priority patches in the LXB declined by almost 290 ha for 1 km dispersal distances, when compared to 5 km, while for 10 km dispersal distances only 6 ha of areas changed (table S6 in supplementary information). However, we observe that priority areas remain the same when using *dPC* as the indicator for identifying the priority areas (table S6 in supplementary information). This result suggests that the results of *dIIC* were more sensitive than those of *dPC*

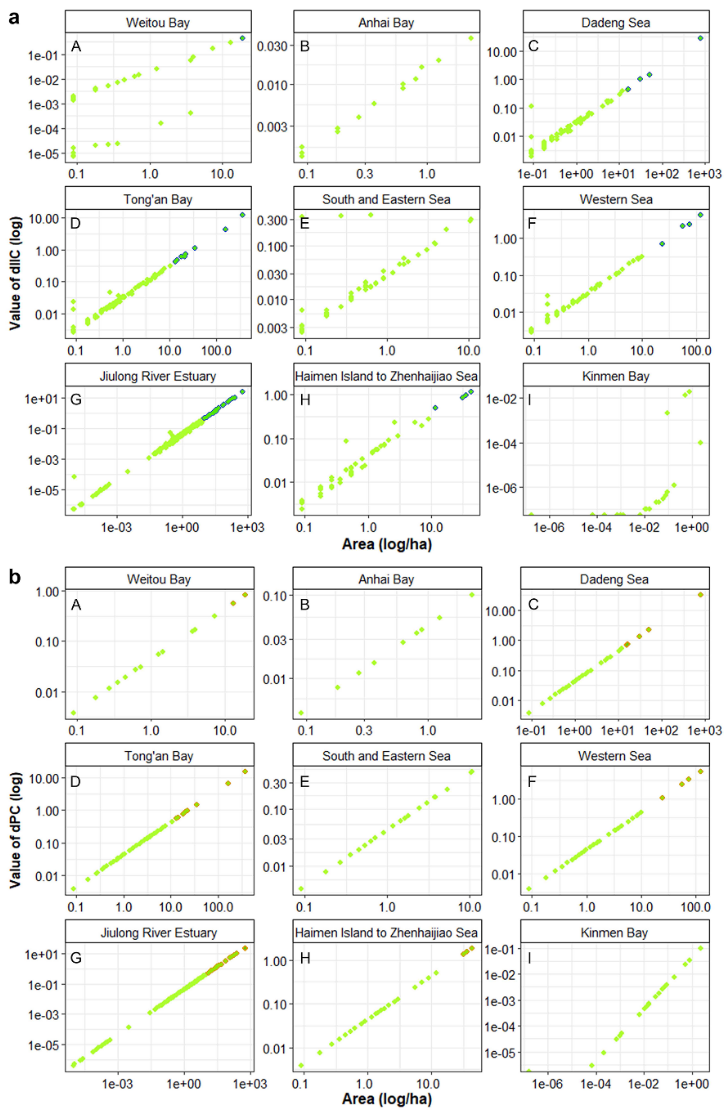

Figure 2. Scatter charts for patches sizes and their *dIIC* (panel (a)) or *dPC* values (panel (b)). The dots in the colored outlines suggest the *dIIC* or *dPC* value that are ranked in the top 5% in terms of the magnitude, essentially indicating the importance of these patches for mangrove restoration. See figure 3 for the location of each subregion (code).

to the changes of dispersal distance. In addition, we do not observe changes in the location of priority areas with changes in dispersal distance (figures S4 and S5 in supplementary information).

Similar results are also found through the sensitivity analysis of buffer distances. It is expected that by increasing the buffer distances of seawalls and port areas, it would reduce the suitable areas for species specific mangrove restoration (table S7 in supplementary information) and the total priority areas (table S8 in supplementary information) since the total mudflat area was reduced with larger buffers. However, we do not observe changes in the distribution of priority areas, indicating that the changes of buffer distance had little effect on identifying the priority areas for mangrove restoration (figures S6 and S7 in supplementary information).

Overall, when considering the above both the sensitivity analysis of buffer distance and dispersal distance suggest that our results are robust.

4. Discussion

4.1. Priority areas for mixed-species mangrove restoration

Overall this study identified the suitable and priority areas for mixed-species mangrove restoration in the LXB ecosystem, a highly degraded and fragmented coastal ecosystem. We developed a generic approach that combines a GIS-based suitability analysis with landscape connectivity analysis. We investigated seven mangrove species found in the study area, estimating the potential restoration area for each of them. The overall analysis helped us understand

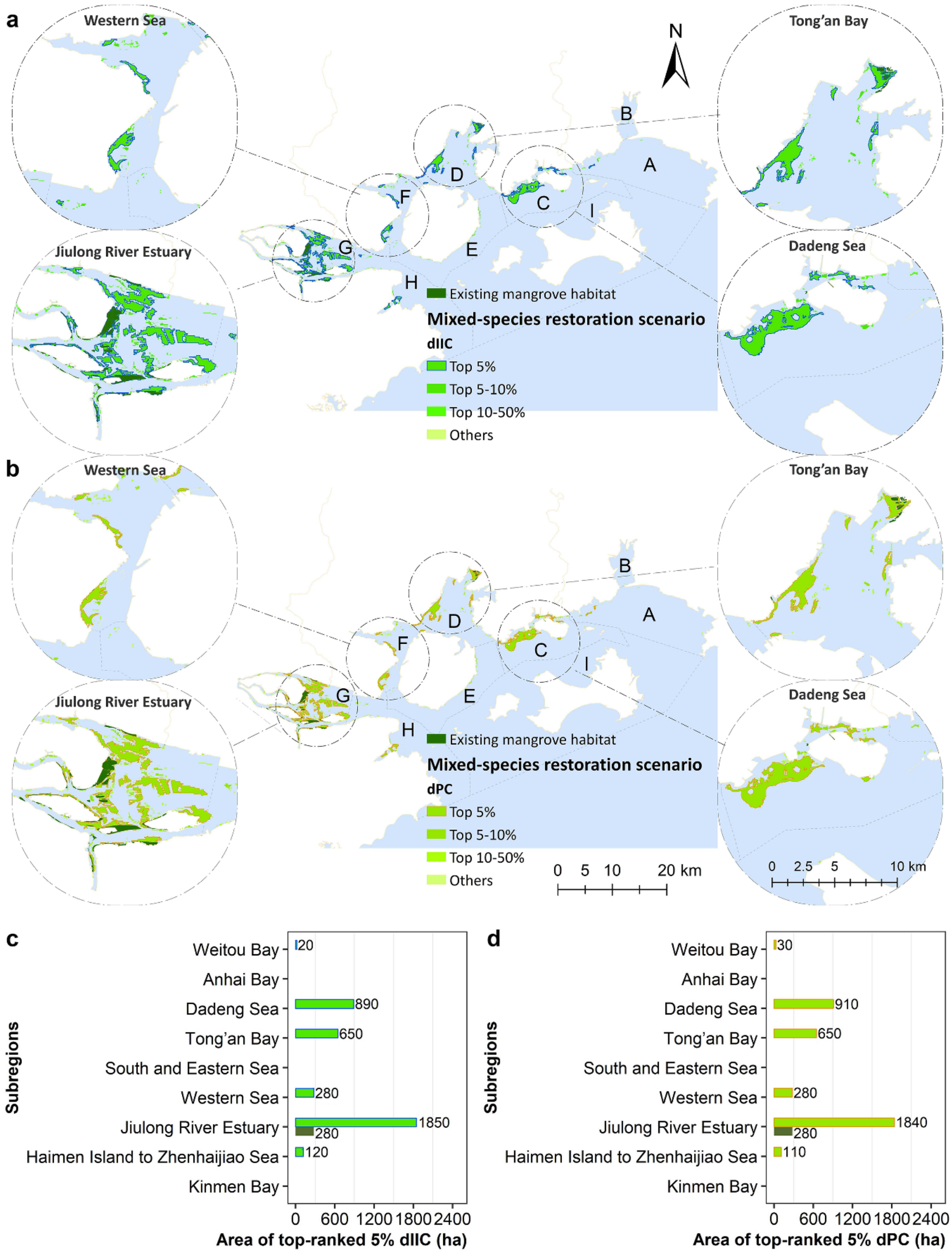

Figure 3. Patch importance assessment of restoration scenario. Panels (a) and (b) present the distribution map of *dIIC* and *dPC* values; panels (c) and (d) are bar charts for the area in highest 5% of *dIIC* and *dPC* values in the different subregions.

the possible impact of mangrove restoration on landscape connectivity and to identify priority restoration areas. We argue that by establishing the suitability for different species and factoring landscape connectivity may help in designing restoration interventions that are more effective and can have broader benefits for the broader ecosystem. The proposed approach and its results can inform future mangrove restoration actions in the study area, but more importantly can be adapted in other geographical contexts to inform restoration efforts.

Below we discuss some of the most important findings related to (a) differentiated potential between species and restoration approaches, (b) variable effect of mangrove restoration on habitat connectivity, and (c) priority areas and strategies for

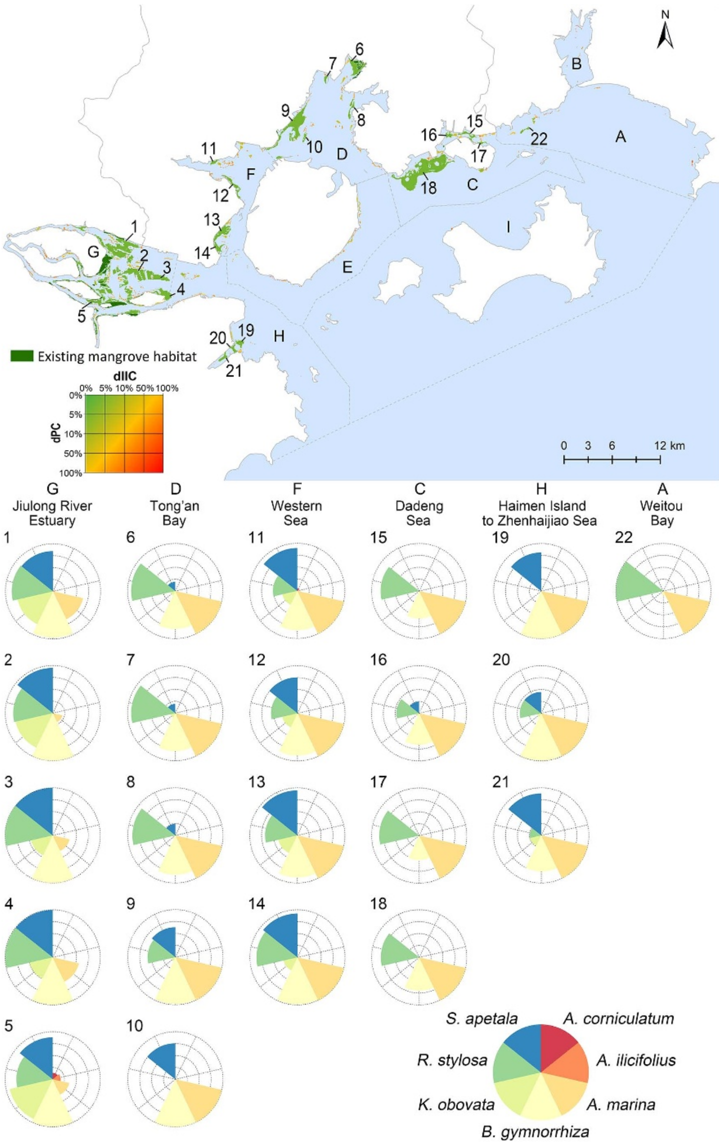

Figure 4. Map of the priority patches for mangrove restoration. The map shows the patches with the top 5% values for the *dIIC* and *dPC*. The flower diagrams illustrate the suitable species for each patch. The length of the slices in each pie chart indicates the fraction of suitable area for each species in each specific patch. Dash lines in the flower diagram (from inside to outside) denote the fractions for 25%, 50%, 75% and 100%, respectively. The proportion of some species may be too small to distinguish in the flower diagrams.

mangrove restoration, and identify implications for policy and practice in LXB and beyond, and suggest future research directions.

When it comes to the differentiated potential between species and restoration approaches, our analysis clearly shows that the total area suitable for species-specific restoration accounts for 72% of the suitable areas when not considering species (table S2 in supplementary information), which points to the real risk of overestimating the extent of mangrove restoration sites and the actual potential of mangrove restoration efforts to enhance biodiversity and ecosystem services. Furthermore, our results also show very different potentials for restoration between mangrove species. The potentially restorable areas for *A. marina, B. gymnorrhiza, R. stylosa* and *S. apetala* are much larger than those for *A. corniculatum* and *A. ilicifolius* (figure 1). This finding is supported by the fact that *A. marina* is one of the most common native species in Xiamen Bay (Lin *et al* 2005) and *S. apetala* is the most common exotic species used in mangrove restoration due to its strong adaptability (Ren *et al* 2009).

In terms of variable effect of mangrove restoration on habitat connectivity, the results from the connectivity analysis suggest that both connectivity indices (*IIC* and *PC*) improved significantly in the post-restoration scenario (table 3), which can have broader ecological benefits, such as providing nursery for fish (Olds *et al* 2012), increasing avian biodiversity (Buelow and Sheaves 2015), and improving carbon capture and storage (Bryan-Brown *et al* 2020). However, improved connectivity indices varied among subregions (table 3), implying that the specific subregions (i.e. Jiulong River Estuary and Dadeng Sea)

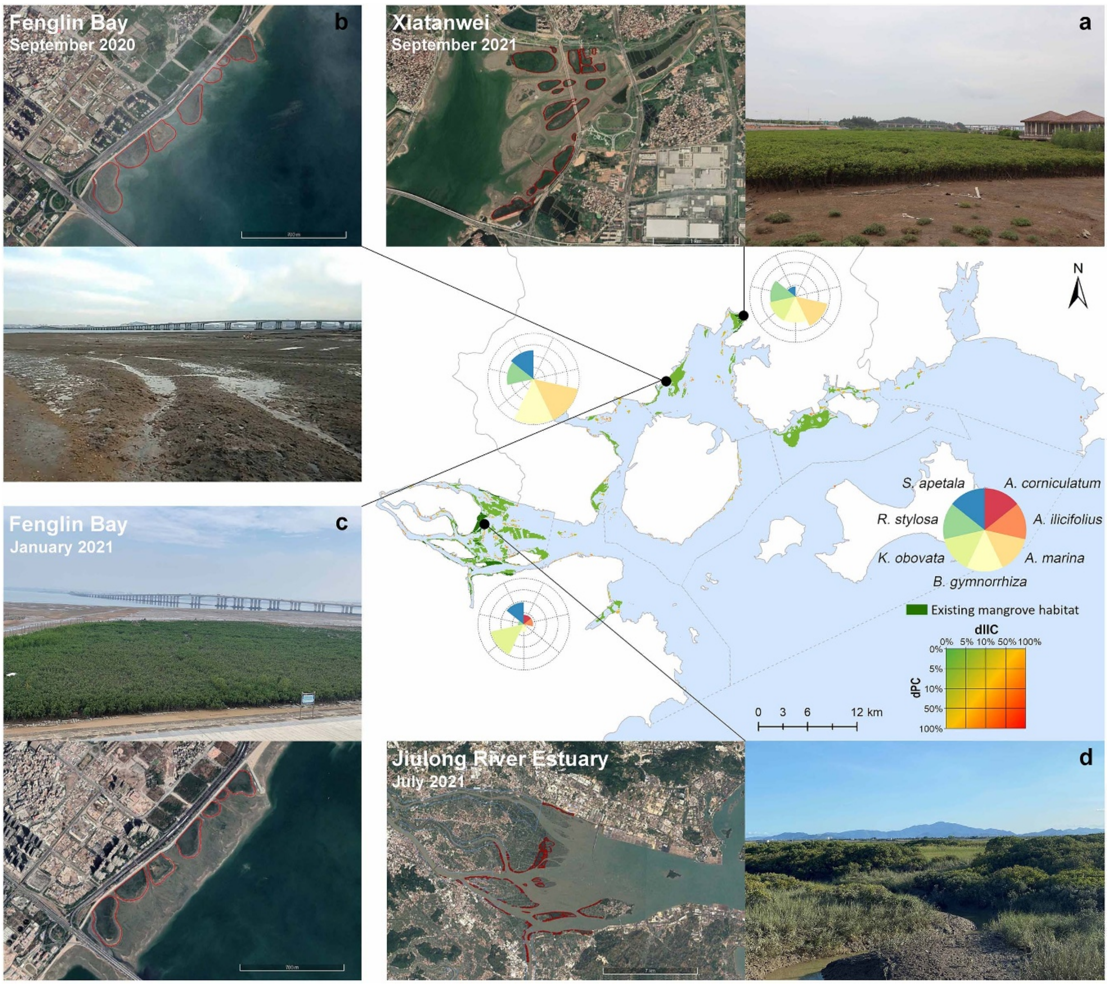

Figure 5. Maps and suitable species in existing mangrove areas derived from the validation exercise. Panels (a) and (d) denote the existing mangroves at Xiatanwei and Jiulong River Estuary. Panels (b) and (c) show the state before and after the mangrove restoration project at Fenglin Bay. The flower diagrams illustrate the suitable species in the three validation areas as predicted from our analysis. The length of the slices in each pie chart indicates the fraction of suitable area for each species in each specific patch Dash lines in the flower diagram (from inside to outside) denote the fractions for 25%, 50%, 75% and 100%, respectively. Satellite Image Map for Xiatanwei, Jiulong River Estuary and Fenglin Bay: Image © 2021 Maxar Technologies.

should be prioritized in future mangrove conservation and restoration projects. It is worth noting that the *IIC* only considers the connectivity or non-connectivity between two patches, while the *PC* considers the dispersal probability of inter-patches, which reflects the potential level of connectivity between patches. As a result, the *IIC* is lower than the *PC* (table 3), which suggests that there is still room for improving the connectivity of mangrove habitats if managed appropriately.

The prioritization of restoration patches is necessary to efficiently allocate scarce financial resources for ecosystem restoration (Brown *et al* 2004) and biodiversity conservation (Bottrill *et al* 2008). Larger patches of habitat are expected to enhance landscape connectivity (Tiang *et al* 2021), as we find in figure 2. However, we have to point that a potential criticism of the *dIIC* and *dPC* is that they 'undervalue' the contributions of small patches in connecting elements and/or serving as stepping stones between different habitat patches (Ferrari *et al* 2007). Our study identified four small patches with an area of <1 ha ranking within the top 10% of *dIIC* values, indicating that they may contribute significantly to the functioning of the landscape network despite their small size (table S4 in supplementary information). As several studies have emphasized the importance of small patches for biodiversity (Lindenmayer 2019, Wintle *et al* 2019), we suggest that small patches with high importance should be considered in mangrove restoration planning.

The recommended species suitable for restoration in most of the priority patches are *A. marina, B. gymnorrhiza, S. apetala* and *R. stylosa*, followed by *K. obovata* (figure 4). It should be noted that in the specific context *S. apetala* is an introduced species from Southeast Asia. Due to its fast growth, cold resistance, stress resistance and protective capacity against storm surges and waves, this species has been widely used in large-scale mangrove afforestation in China since the 1990s (Chen *et al* 2009). However, recent studies of germination and floatation/dispersal and niche competition assessments have confirmed the significant invasive potential of the species (Chen *et al* 2021). In this sense it might be more sensible to use native mangrove species, such as *A. marina, K. obovata* and *B. gymnorrhiza*, in future restoration efforts in the area, while considering *S. apetala* with caution.

4.2. Implications and future research

The implications for mangrove restoration and future research can be reflected upon at two different scales: international level and local level. From an international perspective, our study provides a methodological approach to (a) identify priority mangrove restoration sites in terms of recovering landscape connectivity, and (b) offer more nuanced information about the most suitable species in these priority areas to support mixed-species restoration. The approach can be applied in practically all mangrove restoration contexts we could think of as long as the information about local environmental parameters and information about the effects of these environmental factors on local mangrove species are available/measured. This could improve mangrove restoration actions that receive impetus through the UN Decade on Ecosystem Restoration (2021–2030) and the post-2020 Global Biodiversity Framework.

However, we should note that tidal flat afforestation is not the only option for mangrove restoration. In fact, many tidal flat ecosystems both provide multiple, highly important services and are under threat (Murray *et al* 2019), with many mangrove experts expressing concerns over mass planting (IUCN Mangrove Specialist Group 2020). For this reason, we argue that although mangrove plantation is necessary in some contexts (e.g. in areas with frequent typhoons that sweep away natural recruits), natural regenerations or ecological mangrove restoration with modification of water flows should be considered as priorities in mangrove restoration actions.

In addition, it is important to understand the actual reasons behind mangrove loss in areas flagged for restoration, before the commencement of restoration actions (Hai *et al* 2020). In the case of the LXB, more than 90% of the natural mangroves loss can be attributed to conversion for agriculture/aquaculture and construction for docks and roads (Hu 2016a). In this context, abandoned aquaculture ponds can offer promising sites for mangrove restoration. Indeed, some experts have recently suggested that future mangrove restoration actions should mainly focus on aquaculture ponds (e.g. fish pond, shrimp pond) (Wang *et al* 2020). However, in our study it was difficult to perform this type of analysis due to the lack of relevant datasets. For this reason, in this study we only investigated possible mangrove restoration in tidal flats.

From a local point of view, our results can guide decision-making for mangrove restoration in the LXB from an ecological standpoint when deciding the restoration area and the corresponding suitable species. In December 2020, the Fujian Government released an implementation plan of special action for mangrove protection and restoration in the Fujian Province. This action plan aims to reforest and restore 424 ha of mangroves forests by 2025 in Large Xiamen Bay. Our results of 41 priority patches with 3420 ha could provide alternatives for decision-makers to locate the restoration sites. Future studies in the area should complement this suitability analysis with an investigation of the economic and social aspects of mangrove restoration to determine the allocation of the targeted 424 ha within the 3420 ha fit for mangrove restoration in the LXB as estimated in our analysis.

5. Conclusion

The UN decade on Ecosystem Restoration (2021–2030) and the post-2020 global biodiversity framework call for extensive ecosystem restoration actions. However, there is a generally low success rate in mangrove restoration actions, partly due to the failure to choose the right species for the right site and the overreliance on mangrove monocultures. To overcome such challenges in this study we proposed a new approach merging GIS-based suitability analysis and landscape connectivity analysis to improve the planning of mangrove restoration actions in order to both enhance their effectiveness, as well as inform the allocation of scarce human and financial resources.

Although the importance of considering the characteristics in mangrove species in restoration actions has been emphasized in the past, our study estimates that almost 30% of the identified suitable lands for mangrove restoration in Xiamen Bay (when not considering species) are in reality not suitable for species-specific mangrove restoration. This result highlights the critical need to consider species-specific characteristics in mangrove restoration planning. Based on the understanding of species characteristics, we developed a map that indicates the spatial heterogeneity of mixed-species mangrove restoration. Further employing landscape connectivity analysis in mangrove restoration planning will likely enhance ecological benefits and restoration effectiveness. Our approach is flexible and can be adapted in other geographical contexts to provide local decision-makers a tool to guide the selection of the appropriate location and species for mangrove restoration.

Data availability statement

Global seawater salinity data are available from HYCOM+NCODA Global 1/12° (www.hycom.org/dataserver/gofs-3pt0/analysis). Wind speed observations are available from the NOAA database (www.ncdc.noaa.gov/isd). This paper does not report original code.

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Conflict of interest

The authors declare no competing interest.

Author contributions

All authors contributed intellectual input and assistance to this study. J S conceived and designed the research. J S conducted suitability analysis, B Y conducted landscape connectivity analysis, L C conducted the validation fieldwork. J S wrote the first draft of the manuscript, and L C and A G contributed substantially to revisions.

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