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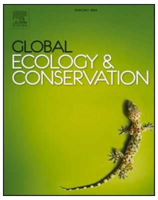

Original research article

Spatial scales matter in designing buffer zones for coastal protected areas along the East Asian-Australasian Flyway

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ABSTRACT

Coastal protected areas are increasingly threatened by urbanization, posing significant risks to wetland biodiversity. Consequently, the recognition of buffer zones as essential for reducing anthropogenic impacts on protected areas has grown. However, limited monitoring and research efforts have been directed towards areas beyond protected sites, despite their interconnectedness. In this study, we focused on waterbirds as ecologically important wetland species to provide evidence of the significance of monitoring and managing buffer zones. By integrating remotely sensed parameters and 3-year monthly waterbird surveys in and around the Mai Po Inner Deep Bay Ramsar Site of Hong Kong, a key stopover of the East Asian Australasian Flyway, we mapped waterbird occurrences for all and different waterbird guilds during winter and summer using random forest models. We found that suitable habitats were predominantly found within protected areas, yet ardeids, large wading birds, ducks and grebes also relied on buffer zones. Waterbird occurrences were influenced by the spatial extent of suitable habitats, with variations observed across different guilds and seasons. In the study area, maintaining at least 40 % open water within an 800-meter radius of key habitats better supports diverse waterbird guilds and should inform the design of waterbird-friendly landscape profiles for protected areas and their buffer zones. Our findings reinforce the significant contribution of protected coastal wetlands to waterbird conservation and highlight the growing importance of spatially relevant buffer zones in facilitating a gradual transition between protected and urbanized areas in supporting waterbird diversity amidst coastal developments.

1. Introduction

Coastal wetlands face escalating threats from urbanization, both directly through urban development and indirectly through associated human disturbances, posing significant risks to wetland biodiversity and ecosystem functions (Kennish, 2002; Lee et al., 2006). This situation is particularly severe along Asia's coastlines, where natural wetlands along the East Asian-Australasian Flyway

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(EAAF) are experiencing continuous loss and fragmentation (Bradshaw et al., 2009). Consequently, numerous waterbirds that rely on these areas for stopover and over-wintering sites are now listed as threatened and face declining population trends (Murray et al., 2014; Piersma et al., 2016). This emphasizes the importance of preserving remaining protected areas as the critical refuge for wetland biodiversity along EAAF (Zhang and Ouyang, 2019).

To ensure the function of protected areas, maintaining the ecological integrity of the surrounding areas is crucial. Buffer zones surrounding protected areas serve as supplementary habitats to wildlife, and often, habitat destructions in these buffer zones reduce the availability of suitable habitats, thereby increasing the risk of local extinction of wildlife populations (Cowlishaw, 1999; Pimm and Raven, 2000; Hansen and DeFries, 2007). This holds particularly true for species that rely on small protected areas but with large home ranges, such as waterbirds, which rely not only on the core part of the reserve but also on adjacent habitats (Woodroffe and Ginsberg, 1998). For instance, in the Pearl River Delta situated in the center of the EAAF, fishponds within buffer zones near wetland reserves serve as crucial foraging and breeding grounds for egrets, while also mitigating human disturbances and acting as corridors for waterbird movement (Young, 1998; Pang et al., 2020). Therefore, the ability of protected areas to conserve biodiversity is also influenced by land use changes and human disturbances in its proximity and the wider matrix (Hansen and DeFries, 2007; Schulze et al., 2018; Lee et al., 2020).

Despite the increasing recognition of the significance of buffer zones by policymakers, reserve managers, and scientists (Noss, 1983; Hansen and DeFries, 2007), the spatial extent and impact of management within these zones in achieving the overall conservation goals remain unexplored. It is important to recognize the interconnectedness between protected areas and buffer zones, emphasizing the need for a gradual transition rather than a sudden change (e.g., from a reserve to a built-up area) (Hansen and DeFries, 2007). Additionally, it is crucial to identify the key factors that promote waterbird usage in the buffer zone, including the type of habitat configuration and its condition (Paracuellos and Tellería, 2004). Understanding these influential factors on waterbird occurrences in protected areas and their extension into the surrounding buffer zones is essential for ensuring comprehensive waterbird conservation, particularly in the face of ongoing anthropogenic pressures across the landscape.

To inform landscape-wide conservation decisions, remote sensing technology is increasingly used and becoming a promising tool for conservationists (Kerry et al., 2022). With the increasing availability of remotely sensed data to the public, it has become possible to collect environmental parameters over large spatial scales with high resolution (Dubovik et al., 2021). This facilitates the assessment of landscape and habitat conditions. For instance, satellite images have been utilized to create habitat maps and project the extent and distribution of different waterbird species in coastal ecosystems (e.g., Wang et al., 2021). By resampling the data at various spatial scales, researchers can also understand the functional spatial units of various habitat characteristics that influence the distribution of the modeled species. Depending on the size of the studied wetland, habitat compositions within a radius ranging from 50 m to 10 km were used to identify relevant scales for waterbird habitat selection preferences (e.g., Li et al., 2021; Ma et al., 2023). This knowledge is crucial for determining the necessary habitat protection area for targeted species and identifying the spatial extent of management interventions that need to be implemented (Riva et al., 2023).

Besides the spatial extent, management interventions involve identifying habitat characteristics vital for different waterbirds with diverse needs (Ma et al., 2009). For instance, the density of pond vegetation, ranging from open water to dense vegetation, can have various impacts on waterbird occurrences. Dense vegetation, providing shelter and hiding spots, may attract rails (Jenkins and Ormerod, 2002). On the other hand, open water benefits shorebirds, herons, and egrets by offering improved accessibility and aiding in prey detection (Dimalexis & Pyrovetsi, 1997). Consequently, maintaining vegetation cover in the pond as a management practice can have distinct effects on different waterbird species and groups (Stralberg et al., 2009). Therefore, the key to optimal wetland management for multiple species lies in evaluating priorities and trade-offs among them. Moreover, while mapping individual species provides valuable insights, it may not fully capture the habitat preferences of the overall waterbird community. To overcome these limitations, a guild-level approach can be employed, whereby waterbird species are grouped based on their feeding strategies (Cumming et al., 2012). This functional grouping has the advantage of informing community-wide habitat management and conservation programs (Blaum et al., 2011). Given that many waterbird species along the EAAF are threatened, adopting a community-wide approach would have a greater impact and contribute to achieving an overall conservation outcome (Wang et al., 2021).

In this study, we investigated waterbird occurrences in the Mai Po Inner Deep Bay Ramsar Site and adjacent buffering areas in Hong Kong during winter and summer. We combined remotely sensed environmental parameters and monthly waterbird survey data of the study area to evaluate the effects of wetland habitat coverage on waterbird distribution. We hypothesize that habitat characteristics will influence waterbird occurrences, with effects varying depending on the species guild and the season. Also, the importance of these factors will vary with different spatial scales. We predict that waterbirds will primarily utilize wetland habitats within the protected area. However, as waterbirds are highly mobile species and require various resources throughout the year, dependent on their guilds, some species may also rely on artificial habitats, such as fishponds, in the buffer zone and during different seasons (Young, 1998). Through this research, we aim to gain insights into the factors and their spatial effects on influencing waterbird occurrences and to evaluate the role of buffer zones in waterbird conservation, in light of the anticipated increase in human disturbance due to further urbanization along the EAAF (Zhang and Ouyang, 2019).

2. Material and methods

2.1. Study area

The study area consists of the Mai Po Inner Deep Bay Ramsar Site (1540 ha) and a buffer zone (2300 ha), situated in Hong Kong and adjacent to Shenzhen, China (Fig. S1). Physically, the coastlines of the two cities enclose the landward side of the Inner Deep Bay mudflat. The two highly populated cities (with populations of 7.5 and 13 million) are part of the world's largest megalopolis the Guangdong-Hong Kong-Macau Greater Bay Area, which has a population of 70 million and experiences rapid urban development. Despite being situated in this megalopolis, the study area is an important subtropical stopover and wintering site for migratory waterbirds along the East Asian-Australasian Flyway, holding a total of 15 globally threatened or near-threatened waterbird species and $\geq$ 1 % of the global or regional population for five species (Table. S2). The high abundance and diversity are attributed to the high diversity of wetland habitats, including fishponds, *gei weis* (intertidal shrimp ponds), mangroves, and intertidal mudflats in the Ramsar Site (more details in Pang et al., 2020). Moreover, over 700 fishponds are still present in the buffer zone of the Ramsar Site (HKBWS, 2023), which serves to maintain the integrity and functioning of the wetland ecosystem.

In this study, we consider the Ramsar Site as "the protected area" because of restricted access and dedicated management plans under the Ramsar Convention. The buffer area was designated by the local planning authority, which implements land use planning guidelines to control developments within the area.

2.2. *Waterbird surveys*

The coverage of waterbird surveys is crucial for mapping species occurrences. However, monitoring data often neglect wetland habitats present in buffer zones (Cayuela et al., 2009; Hull et al., 2011). To gain a comprehensive understanding of waterbird occurrences and habitat usage across the entire wetland landscape, we used monthly waterbird count surveys conducted by the Hong Kong Bird Watching Society in the studied area, covering both the protected area and its buffer zone (HKBWS, 2023) (Fig. S1). The programme was supported by the Agriculture, Fisheries and Conservation Department of the Hong Kong Government. We included monitoring data collected between 2019 and 2022 to investigate the spatial distribution of different waterbird guilds in the study area. We focused on winter (November to February) and summer (May to August) because the waterbird community is transient during spring and autumn when migration is active. The importance of the area to migrating waterbirds is not within the scope of this study.

Synchronized surveys were conducted during the day along 15 fixed, non-overlapping transects distributed across the study area by trained surveyors. The surveyors recorded the abundance of all waterbird species using binoculars and/or telescopes, covering 791 ponds or intertidal mudflat areas (i.e., survey stations) (Fig. S1a). In each station, we recorded waterbird species and their abundance as occurrence data to build species distribution models (described in the following sections). To maintain survey consistency, all surveyors had over 3 years of birdwatching experience and received training provided by the Hong Kong Bird Watching Society. All surveys were conducted simultaneously as far as possible to reduce double counting during high tide when the intertidal mudflat was largely submerged (tidal height at 1.7 m or above). During this period, waterbirds move closer to the observation hides located at the edge of the mudflat, allowing a more accurate count of waterbirds.

2.3. *Waterbird guilds and occurrence data*

Since habitat selection of waterbirds is mainly based on their feeding mode and habitat condition (Cumming et al., 2012; Li et al., 2022), birds were categorized into six guilds in this study that represent different foraging niches (e.g., invertivore, carnivore, omnivore, and herbivore) and habitat preferences (e.g., water column, shallow water, and benthic feeders), including (1) cormorants (carnivore/ water column), (2) ardeids and large wading birds (carnivore/ shallow water), (3) ducks and grebes (omnivore/ water column), (4) rails and coots (invertivore/ water column), (5) shorebirds (invertivore/ benthic feeder), and (6) gulls and terns (omnivore/ shallow water) (Table S1). The Great Cormorant (*Phalacrocorax carbo*) was singled out as a guild not only for its unique diet and habitat preferences compared to other guilds but also due to management considerations, as most conflicts between waterbirds and fishermen in the studied area were related to cormorants.

The occurrence data obtained from the waterbird surveys were used as dependent variables, including all waterbird species combined and the six functional guilds. Since the waterbird count surveys were counted monthly, data from a total of 12 surveys were available for each season (four months for each season in three years). The presence or absence of each bird guild during each survey was translated into a relative frequency of occurrence ranging from 0 (observed in none of the surveys) to 1 (observed in all surveys). While the field survey primarily focused on wetlands suitable for waterbirds, pseudo-absence points were added based on the habitat map (described in the next section) to expand the range of environments available for model fitting (Barbet-Massin et al., 2012). Considering the built-up area class as an unsuitable background for waterbirds based on prior biological knowledge of the species, 80 points were randomly drawn from these pixels and assigned with an occurrence value of 0 (Chapman et al., 2019). The number of pseudo-absences was limited to less than 10 % of the total 871 observations in this study to minimize any potential over-prediction in areas farther from the occurrence points.

2.4. *Remotely sensed variables*

We analyzed the waterbird survey data (dependent variables) in relation to the distributions of different natural and human habitats in the study area (independent variables; Table S2). A habitat map with a 10-m pixel size was obtained from a previous habitat mapping exercise in Hong Kong, which adopted WorldView-2/3 satellite imagery acquired in 2019 as the major input and was validated with extensive field-collected data (Kwong et al., 2022). The 21 habitat classes provided in the map were aggregated into six habitat classes to match the objective of this study (Table S3; Fig. S2). To avoid edge effects in areas near Shenzhen, the habitat map was expanded and filled using a Sentinel-2 satellite image with the same 10-m spatial resolution acquired in the same year.

Variables were computed for every pixel as the proportion of each habitat class, including mangrove, marsh, mudflat, water, woodland, and built-up area, within a specific distance (radius) from target pixels. The values ranged from 0, where no target habitat was found within the radius, to 1, where all pixels belonged to the target habitat. Another variable was computed by considering the diversity of habitat types within the radius using the Shannon Diversity Index (Shannon, 1948). To account for potential variations in ecological processes across spatial scales, the variables were created using multiple distances from target pixels (50, 100, 200, 400, 800, and 1600 m radii, using the focal function in the terra package in software R), following the methods in Murphy et al. (2010). A total of 42 variables were created using the above method – 7 habitat variables (including six habitat classes plus one diversity index) multiplied by 6 spatial scales.

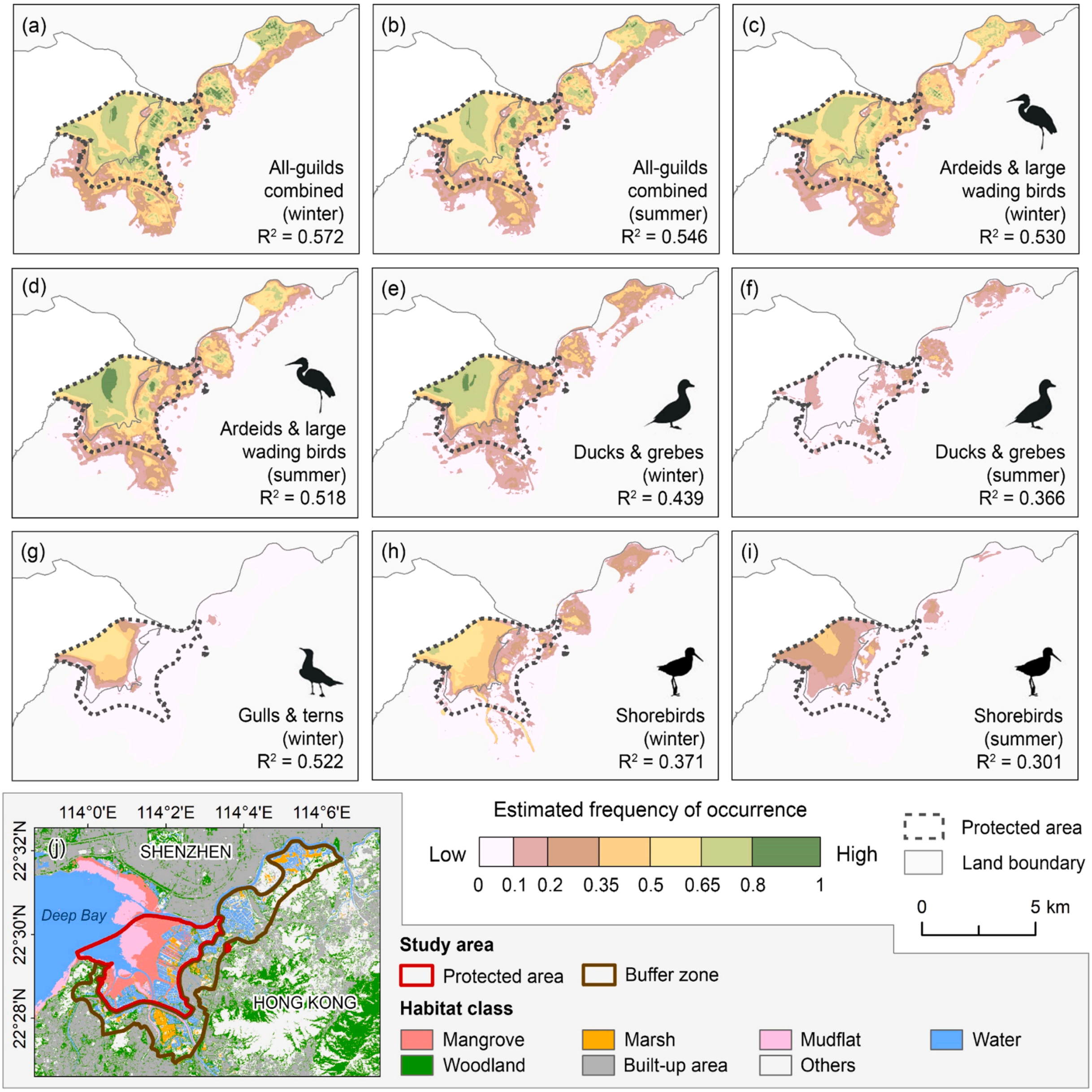


Fig. 1. (a–i) Map displaying estimated suitable areas for different waterbird guilds and seasons in the study area (Mai Po Inner Deep Bay Ramsar Site and its buffer zone). These areas were determined using a random forest modeling framework. The accuracy of the models was assessed using cross-validated coefficients of determination (R-squared), and only models explaining at least 30 % variances are shown. (j) Habitat map of the study area used to create predictor variables for the random forest model. An enlarged version of the habitat map can be found in Fig. S2.

2.5. Species distribution model

Random forest regression was implemented to estimate waterbird occurrence from the independent variables (Breiman, 2001). It is one of the state-of-the-art machine learning algorithms, with diverse applications in recent studies (Belgiu and Drăguţ, 2016; Sheykhmousa et al., 2020). Its advantages include no assumption about data distribution, robustness to outliers and noise, and the capability to analyze numerous input variables and produce variable importance metrics (Rodriguez-Galiano et al., 2012). Random forest models were developed for each waterbird guild during winter and summer. To examine the effects of habitat coverage at different spatial scales, model performances were first evaluated using independent variables created from a single spatial scale as inputs. They were compared to final prediction models developed using a combination of variables from all scales. Considering the relatively large number of input variables in the latter approach, subsets of the variables were selected using three steps to enhance the model interpretability.

First, Pearson's correlation coefficients were calculated for each pair of input variables. The pair of most correlated variables were identified and the one with a higher correlation coefficient with the "second most correlated variable" was removed. The process was iterated until the correlation coefficients among all remaining variables were less than 0.9. Second, the *rf.modelSel* function in the *rfUtilities* package in software R was used to select the most parsimonious models with the largest explained variation and the fewest parameters (Murphy et al., 2010; Severson et al., 2017). This process generated 17 models from 10 % to 90 % subsets (incrementing by 5 %) of variables and selected the one with the highest adjusted R-squared value, which balanced the explanatory power and the number of predictors. Third, the *rfPermute* package in software R was used to estimate the significance of importance metrics for each predictor variable by permuting the response variable. Insignificant variables with p-values larger than 0.05 were removed. After these three steps, the numbers of independent variables were reduced to 23 or fewer for all calibrated models (Table S4).

The random forest models estimated the waterbird occurrence for every pixel within the study area and facilitated the visualization of the spatial patterns on maps. Model fit were evaluated using a 10-fold cross-validation repeated 5 times to generate R-squared metrics. To determine the coverage of suitable habitat areas for each waterbird guild, the predicted occurrence values were further transformed into binary maps by adopting a simple threshold of "half of the maximum predicted occurrence value of the guild". This choice of thresholds addressed the varying levels of potential occurrences among species, and conventional methods for selecting species occurrence thresholds were not directly applicable in this study due to the continuous scales of the values (Liu et al., 2013). The random forest procedures were conducted using the *randomForest* package in software R 4.3.2 (Liaw and Wiener, 2002; R Core Team, 2023).

3. Results

Throughout the 24 surveys, we recorded 284,760 individuals, comprising 104 waterbird species across six different guilds. Of these species, 57 were recorded in both the protected area and buffer zone, 39 exclusively in the protected area, and 8 in the buffer zone (Table S1).

3.1. Spatial distribution of suitable habitat for waterbirds

The explanatory power of species distribution models, as indicated by the R^2 value, varied across seasons and guilds. Overall, higher model fits were observed in winter compared to summer across all models (Fig. 1). The best models were those with all waterbirds combined in winter ($R^2 = 0.572$) and summer ($R^2 = 0.546$). Model fit reduced when waterbirds were categorized into guilds, nonetheless, the models still performed relatively well for ardeids and large wading birds in winter ($R^2 = 0.530$) and summer ($R^2 = 0.518$), and gulls and terns in winter ($R^2 = 0.522$). Yet, the R^2 value of other models fell below 50 %, including models for ducks and grebes in winter ($R^2 = 0.439$) and summer ($R^2 = 0.366$), and shorebirds in winter ($R^2 = 0.371$) and summer ($R^2 = 0.301$). The predicted occurrence of these guilds thus needs to be interpreted with caution. For remaining models, including cormorants (both seasons), rails and coots (both seasons) and gulls and terns (in summer), since the R^2 values were even lower (less than 0.3), we believe that the associated results are less informative. Therefore, we excluded them from the later sections of the results and discussion.

The occurrence map revealed distinct spatial usage patterns among the selected guilds. Ardeids and large wading birds and ducks

Table 1

The predicted size of suitable habitat (in hectares) and its relative coverage compared to the overall area (%) are listed for all waterbirds and across different guilds within the protected area and the surrounding buffer zone during winter and summer.

Season	Guild	Protected area / ha (%)	Buffer zone / ha (%)	Total /ha
Winter	All-guilds combined	1182.3 (70.3 %)	498.3 (29.6 %)	1680.6
	Ardeids and large wading birds	1043.3 (75.3 %)	342.0 (24.7 %)	1385.3
	Ducks and grebes	764.1 (93.9 %)	49.8 (6.1 %)	813.9
	Gulls and terns	419.8 (100 %)	0.0 (0 %)	419.8
	Shorebirds	673.7 (90.0 %)	75.2 (10.0 %)	748.9
Summer	All-guilds combined	976.9 (75.3 %)	321.1 (24.7 %)	1298.0
	Ardeids and large wading birds	923.2 (78.0 %)	260.5 (22.0 %)	1183.7
	Ducks and grebes	11.1 (29.6 %)	26.4 (70.4 %)	37.5
	Shorebirds	284.3 (98.7 %)	3.8 (1.3 %)	288.1

and grebes were found in various habitats, such as fishponds, *gei weis*, and intertidal mudflats, while other guilds predominantly utilized intertidal mudflats. For the size of suitable areas, during winter, the largest areas were observed for ardeids and large wading birds (1384 ha), followed by ducks and grebes (814 ha), shorebirds (749 ha), and gulls and terns (420 ha). In summer, the suitable area dropped, with the largest for ardeids and large wading birds (1183 ha), followed by shorebirds (288 ha), and ducks and grebes (37 ha) (Table 1). When considering the all-guilds model (i.e., all waterbirds combined), the majority (>70 %) of suitable habitats were within the protected areas in both seasons (Table 1). However, it should be noted that considerable suitable habitats were present in the buffer zone, mainly represented by commercial fishponds. The buffer zone was important for ducks and grebes in summer (70 % of suitable habitat) and ardeids and large wading birds in summer and winter (>22 %) (Fig. 1).

3.2. Model performance in predicting bird occurrence across spatial scales

Model performance was compared using variables at different spatial scales (Fig. 2). The model performance tends to increase as the spatial scale increases, indicating that waterbirds are more influenced by habitats at larger scales or over longer radii. Generally, model performance reaches a stable level from 400 m onward, remaining similar up to 1600 m. However, the model for gulls and terns in winter continues to improve with increasing spatial scale. On the other hand, the model performance of ducks in winter and summer, and shorebirds in summer, declines when the spatial scale reaches 1600 m. Overall, the spatial scales relevant to different waterbird guilds vary, and the best model performance is achieved when variables at multiple scales are combined to build the model (Fig. 2).

Additionally, we found that significant variables that explain waterbird occurrence are distributed across spatial scales (Fig. 3). Habitat coverage variables such as water, woodland, and built-up area were mostly selected across different scales, with positive correlations for water and negative correlations for woodland and built-up areas. Mangrove and marsh habitats were only selected when the scale was larger (≥ 400 m radius), indicating their effects over a larger area. When considering different habitats together, high habitat diversity often showed a negative correlation with waterbird occurrences at large spatial scales, suggesting that waterbirds would generally prefer a continuous and large area of suitable wetland habitats. Few variables were selected at the 100 m and 200 m radii, indicating that habitats either have effects at finer scales (within 50 m) or larger scales (ranging from 400 to 1600 m). Finally, the correlation between variables and waterbird occurrences decreased with increasing spatial scale, indicating that the pairwise relationship between habitat and waterbird occurrence becomes less obvious at larger scales.

3.3. Habitat variables influencing waterbird occurrences

By examining the response curves of the correlated variables, we found that the variable water within 800 m had a positive effect, while woodland within 400 had a negative effect on all waterbirds and individual guilds for both summer and winter. We described the two variables here because they are found to be significant for all investigated guilds (Fig. 3). However, the threshold of the effects of water and woodland coverage varies across different guilds and seasons (Figs. 4 & 5). For example, water coverage had varying effects

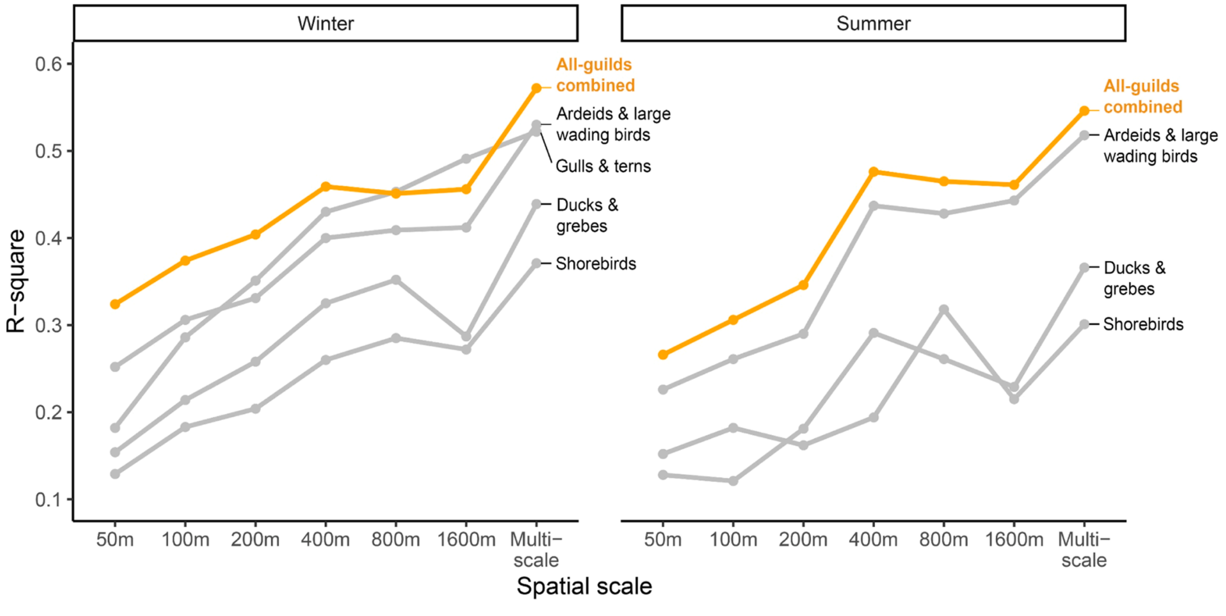
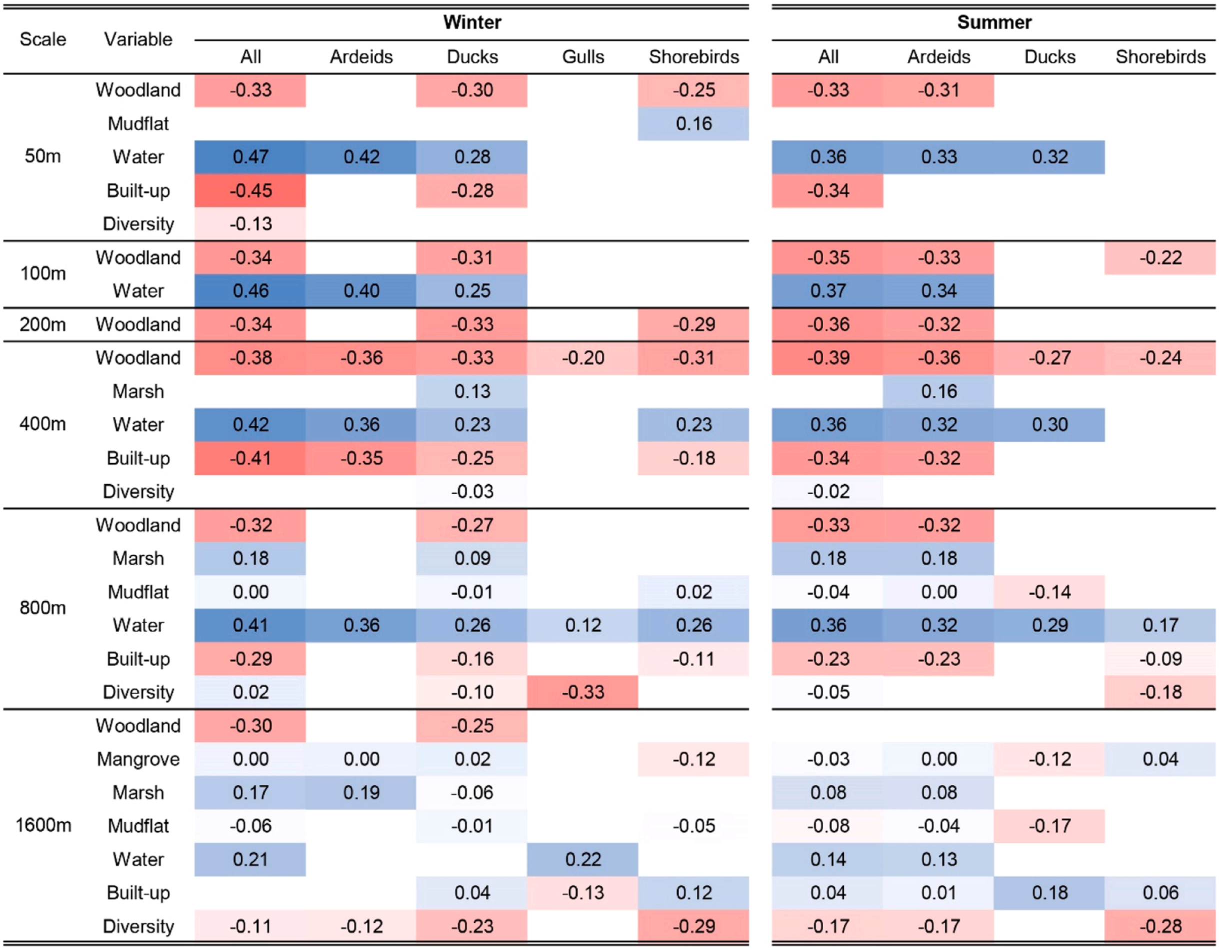


Fig. 2. Cross-validated R-squared values were calculated for the random forest models for all-guilds combined (orange lines) and individual guilds (gray lines) during both the winter and summer seasons. The spatial scales from “50 m” to “1600 m” indicate the use of habitat variables derived from a single spatial scale as inputs. “Multi-scale” refers to the final models developed using a combination of habitat variables from multiple scales. Further information regarding the dependent and independent variables can be found in Table S2.



Scale	Variable	Winter					Summer			
		All	Ardeids	Ducks	Gulls	Shorebirds	All	Ardeids	Ducks	Shorebirds
50m	Woodland	-0.33		-0.30		-0.25	-0.33	-0.31		
	Mudflat					0.16				
	Water	0.47	0.42	0.28			0.36	0.33	0.32	
	Built-up	-0.45		-0.28			-0.34			
	Diversity	-0.13								
100m	Woodland	-0.34		-0.31			-0.35	-0.33		-0.22
	Water	0.46	0.40	0.25			0.37	0.34		
200m	Woodland	-0.34		-0.33		-0.29	-0.36	-0.32		
400m	Woodland	-0.38	-0.36	-0.33	-0.20	-0.31	-0.39	-0.36	-0.27	-0.24
	Marsh			0.13				0.16		
	Water	0.42	0.36	0.23		0.23	0.36	0.32	0.30	
	Built-up	-0.41	-0.35	-0.25		-0.18	-0.34	-0.32		
	Diversity			-0.03			-0.02			
800m	Woodland	-0.32		-0.27			-0.33	-0.32		
	Marsh	0.18		0.09			0.18	0.18		
	Mudflat	0.00		-0.01		0.02	-0.04	0.00	-0.14	
	Water	0.41	0.36	0.26	0.12	0.26	0.36	0.32	0.29	0.17
	Built-up	-0.29		-0.16		-0.11	-0.23	-0.23		-0.09
	Diversity	0.02		-0.10	-0.33		-0.05			-0.18
1600m	Woodland	-0.30		-0.25						
	Mangrove	0.00	0.00	0.02		-0.12	-0.03	0.00	-0.12	0.04
	Marsh	0.17	0.19	-0.06			0.08	0.08		
	Mudflat	-0.06		-0.01		-0.05	-0.08	-0.04	-0.17	
	Water	0.21			0.22		0.14	0.13		
	Built-up			0.04	-0.13	0.12	0.04	0.01	0.18	0.06
	Diversity	-0.11	-0.12	-0.23		-0.29	-0.17	-0.17		-0.28

Fig. 3. The effects of different variables in explaining waterbird occurrences for all waterbirds and across different guilds in winter and summer along the studied spatial scales (50 m – 1600 m). Values and colors indicate the Pearson correlation coefficients between each pair of variables and waterbird occurrences. Blue colors show positive correlations and red colors show negative correlations, with stronger colors indicating higher magnitudes of the coefficients. Only variables that were significant and used in the multi-scale models are shown.

on different guilds and between seasons. The occurrence of wintering shorebirds increased only when more than 40 % of the land within 800 m of an area was covered by water, while a similar increase required 50 % water coverage during summer. In contrast, the occurrence of ardeids in winter increased when water coverage accounted for about 40 % of the land or more, but only 30 % in summer. Similarly, the effect of woodland coverage at a 400 m radius of an area also influenced waterbird occurrence differently, with effects being guild- and season-dependent. The occurrence of wintering shorebirds, ardeids and large wading birds sharply decreased when more than 5 % of land within 400 m of an area was covered by woodland. A general decrease was observed in ducks and grebes, while no effect was found in gulls and terns. In summer, a sharper decrease was observed in ducks and grebes at about 10 %, with a lesser decrease in ardeids and large wading birds, and no effect on shorebirds.

4. Discussion

Coastal wetlands, while often fragmented and influenced by urban development, are vital for numerous waterbird species. By combining data from remote sensing and standardized waterbird surveys, we mapped waterbird occurrences in the Mai Po Inner Deep Bay Ramsar Site and its buffer zone. We found that waterbirds were primarily concentrated in the protected area during winter and summer, however, the buffer zone provides a considerable proportion of suitable habitats for certain guilds of waterbirds. Importantly, we demonstrated that waterbird occurrences were influenced by types of habitat coverage up to 1600 m. This spatial scale effect underscores the importance of buffer zones in facilitating a gradual transition between protected and built-up areas. Our findings highlight the significant role of protected coastal wetlands and buffer zones in supporting waterbird diversity in human-modified landscapes.

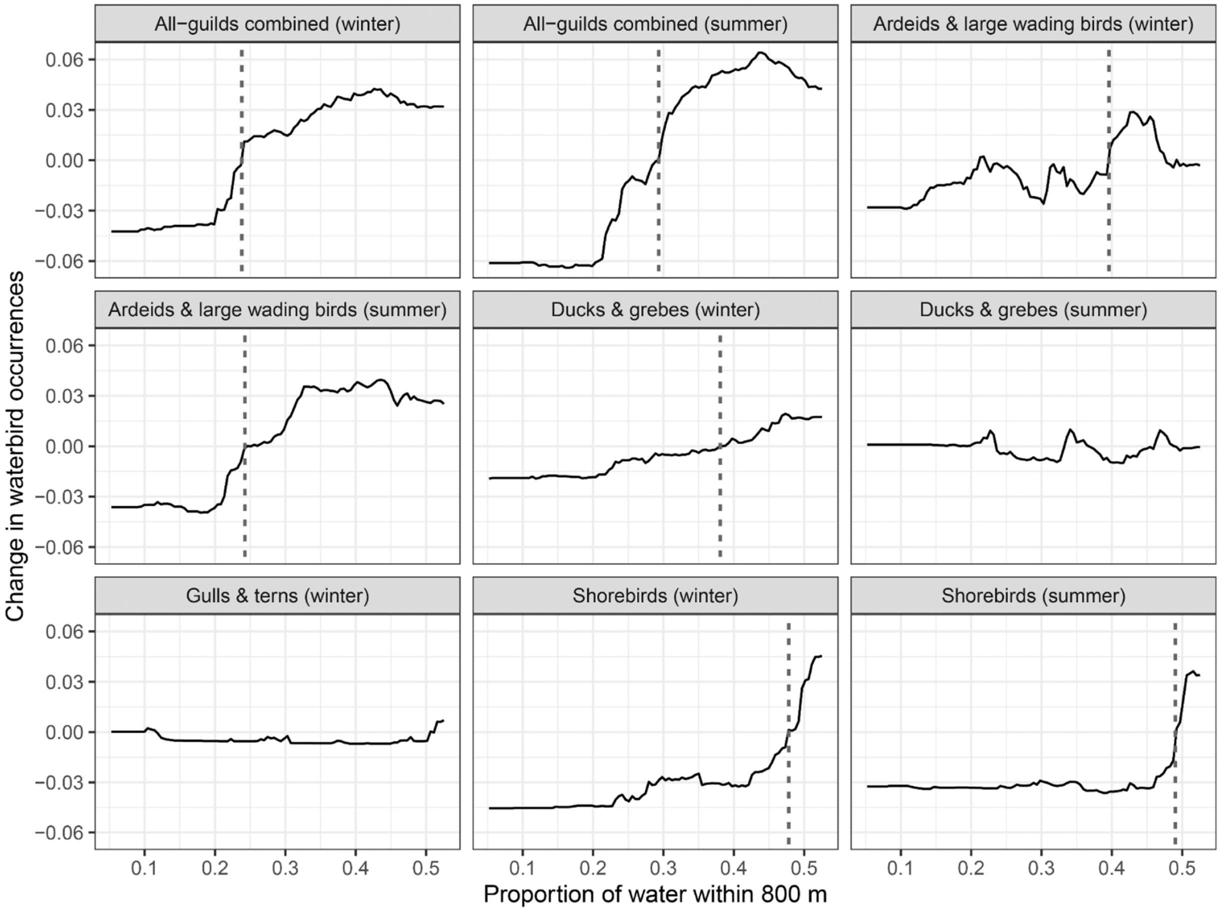


Fig. 4. Response curves depicting the relationship between waterbird occurrences and the proportion of water coverage within an 800 m radius for all waterbirds and across different guilds during winter and summer. Vertical dashed lines are added for some guilds to show possible thresholds that increasing water coverages had positive effects on waterbird occurrences (change in occurrences > 0).

4.1. *Importance of buffer zones for fragmented coastal wetland ecosystems along the EAAF*

Our results on the proportion of suitable habitat and spatial scale effect of habitat variables highlight the critical role of buffer zones to waterbirds in the study area. In the buffer zones, fishponds are the predominant open water habitat (Fig. 1). Although these artificial wetlands have a lower proportion of suitable habitat for most waterbirds compared to other wetland habitats found in the protected area, two guilds, ardeids and large wading birds and ducks and grebes rely on buffer zones. Over 20 % of suitable habitats for ardeids and large wading birds are located in the buffer zone during both summer and winter. This indicates that the buffer zone supports waterbirds throughout their lifecycle, providing additional suitable habitats as wintering grounds and breeding sites (Salwasser et al., 1987). This result is consistent with studies conducted in the same area on ardeid foraging behaviour. (Young, 1998; Pang et al., 2020). Notably, over 70 % of suitable habitats for ducks and grebes lie within the buffer zone during summer. However, such results need to be interpreted with care. It is important to note that grebes are the dominant species in this guild during summer, while most migratory ducks are absent (Table S1). Given that grebes, such as the little grebe (*Tachybaptus ruficollis*), use artificial wetland habitats for breeding (Keithmaleesatti et al., 2020), this may partly explain why a higher occurrence was found in the buffer zone dominated by fishponds compared to the protected area in summer. Nevertheless, this may also highlight that the buffer zones are crucial for the long-term viability of some waterbird species.

Given that the sizes of the protected areas directly affect bird presence (Timmers et al., 2022), understanding the spatial scale effect of factors influencing waterbird occurrences is crucial for evidence-based reserve management (Li et al., 2022). We show the effect of spatial scale varies between guilds. Generally, the proportion of habitats in a 400 or 800 m radius of an area had the strongest influence on waterbird occurrences (Fig. 2). However, the model performance of gulls and terns in winter improves with larger spatial scales up to 1600 m (Fig. 2). On one hand, this result highlights that the required habitat protection radius varies for different guilds, emphasizing the need to consider the spatial extent of management interventions when conserving waterbird species with different foraging niches, movement behavior, and habitat preferences (e.g., Li et al., 2021; Wang et al., 2020). On the other hand, this finding reiterates the importance of buffer zones in mitigating the edge effect and enhancing the resilience of protected areas (Gaston et al.,

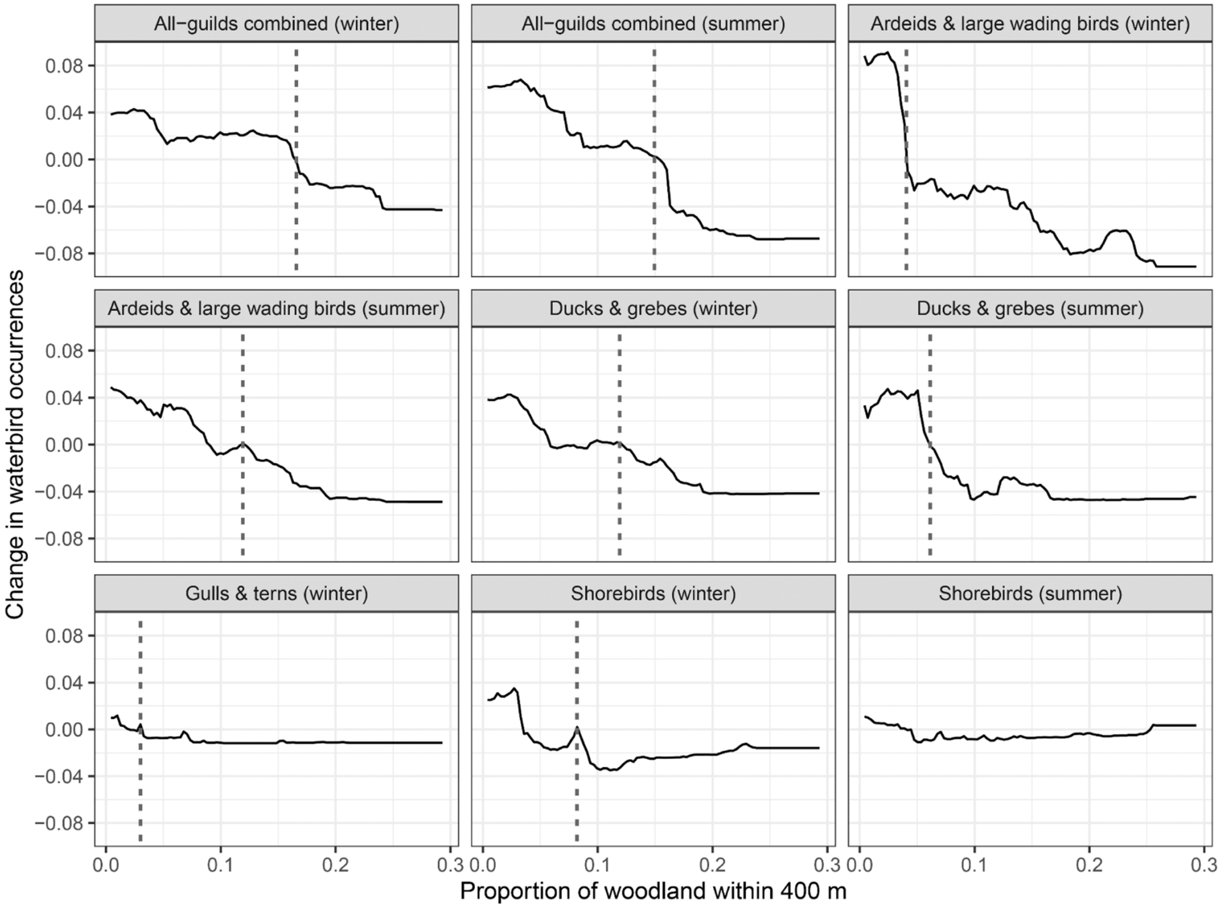


Fig. 5. Response curves depicting the relationship between waterbird occurrences and the proportion of woodland coverage within a 400 m radius for all waterbirds and across different guilds during winter and summer. Vertical dashed lines are added for some guilds to show possible thresholds that increasing woodland coverages had negative effects on waterbird occurrences (change in occurrences < 0).

2008, Hansen and DeFries, 2007). Given the extensive habitat range requirements of waterbirds, the absence of a "soft" transition facilitated by artificial wetlands in the buffer zones would create a sharp edge. The close distance between protected and built-up areas may have adverse impacts on waterbirds due to the increase in human disturbances (Brashares et al., 2001; Hansen et al., 2005). This holds particularly true for the studied Ramsar site, which spans 1500 ha and has the shortest radius between its centroid and the edge being only about 1400 m. Similarly, such limitations in conserving waterbird species would also apply to other Ramsar sites with sizes similar to or smaller than 1500 ha along the EAAF. Currently, at least 98 Ramsar sites along the EAAF fall under this criterion (Ramsar, 2023). To ensure the functioning of these sites, adequate preservation of habitats beyond the protected areas is critical (Hansen and DeFries, 2007).

4.2. Habitat variables that influence waterbird occurrence across spatial scales

Across the spatial scale relevant to waterbird occurrences in the study area, we found that waterbird usage increased with open water areas and decreased with coverage of woodland and build-up areas (all-guilds combined; Fig. 3). Additionally, waterbirds preferred homogeneous and large areas of suitable habitats, as indicated by the negative effect of surrounding habitat diversity at large spatial scales. These findings highlight that wetlands with continuous open water coverage and simple vegetation structure can enhance waterbird occurrences, consistent with previous studies on waterbird habitat preferences (e.g., Blackwell et al., 2008; Wang et al., 2020). However, it is also important to note that the above effects were guild- and season-dependent. The spatial scales relevant to different waterbird guilds varied, and the best model performance was achieved by combining variables across multiple scales to build the model (Fig. 2). This suggests that to aid management measures for conserving waterbird diversity, it is crucial to understand the relationship between habitat variables and the scales that influence waterbird occurrences across different guilds and seasons.

To apply such knowledge, it is essential to determine the specific spatial scale and magnitude at which the above factors have a consistent influence on informing land use planning and conservation measures. For instance, even though open water habitat is identified as a significant predictor across the focal spatial scales, its consistent effect is observed at the 800 m scale for both guilds and seasons (Fig. 3). Based on the response curves of water coverage at the 800 m scale, we further found that several waterbird guilds, including ardeids and large wading birds, ducks and grebes (winter only), as well as all-guilds combined, had higher occurrences at location with at least approximately 40 % water coverage within an 800 m radius in both seasons (Fig. 4). This suggests that, as one of the considerations, ensuring that at least 40 % of the land within an 800 m radius of the focal area is covered by open water can help provide suitable habitats for selected waterbird guilds in both winter and summer. Similarly, the response curves of woodland coverage at the 400 m scale suggest that, in addition to open water habitat, maintaining lower woodland areas, specifically less than 5 % of the land within a 400 m radius of the focal area, would also be beneficial for the usage of different waterbird guilds (Fig. 5). These estimates of landscape compositions can then serve as a reference when designing a landscape profile that is more suitable for waterbird usages for protected areas and their buffer zones.

Interestingly, we found that only a few variables at the 100 m and 200 m scales were deemed important for waterbirds compared to the scales of 50 m and 400 m onwards (Fig. 3). This suggested that waterbirds may consider and prioritize habitat usage at two different spatial scales: a larger landscape-level scale when searching for suitable habitats during flight and a smaller (e.g. pond-level) scale when feeding on the ground. On one hand, this finding reinforces the importance of understanding waterbird usage at a large spatial scale for establishing ecologically relevant buffer zones. On the other hand, it highlights the significance of local factors in determining waterbird occurrences (Haas et al., 2007), even though pond-level abiotic or biotic factors (e.g., vegetation coverage and food availability) were not included in the current model. This may partly explain the relatively low R-squared values for certain guilds in winter and summer. Given that conservation actions can be more effective when considering both landscape- and local-level factors (Paracuellos and Tellería, 2004), we recommend collecting local parameters in the future, such as those reflecting wetland quality, in addition to landscape-scale parameters obtained through remote sensing.

In addition to identifying important environmental parameters, species occurrence data used to build and validate species distribution models are equally important (Cayuela et al., 2009). Therefore, establishing standardized and regular monitoring programs in both protected areas and buffer zones becomes essential. However, it may not be feasible in many places due to a lack of coordination and financial support (Cayuela et al., 2009). Therefore, we strongly advocate allocating more resources to systematic monitoring efforts and harnessing the potential of the growing citizen scientist communities for data collection (Tulloch et al., 2013; Horns et al., 2018). The collected data, as demonstrated in this study, will be essential for developing evidence-based conservation measures and understanding the factors that influence species diversity in the face of rapid urbanization.

5. Conclusions

By using waterbirds as a model taxon, our study emphasizes the importance of considering the effects of different habitats at various scales and the significance of buffer zones around protected areas in wetland ecosystems affected by urbanization. Since conflicts between wetlands and development are expected to increase, maximizing the ecological value of existing wetland ecosystems – both protected areas and their buffer zone – is increasingly important. To achieve this, a landscape-wide approach that focuses on wetland habitat features favouring waterbird diversity at the appropriate spatial and temporal scales is necessary. For instance, 40 % water coverage within an 800 m radius of an area has been shown to support waterbirds from different guilds across seasons. Maintaining such habitat features in protected areas and their buffer zones is essential for maintaining a wetland landscape favourable to waterbird usage. Additionally, aquaculture ponds, for example, spanning over 9500 km^2 along the coast of China (Duan et al., 2021), could play a crucial role in providing open water habitat for waterbirds along the EAAF.

With the increasing availability and spatial coverage of remote sensing and geographic information systems, as well as standardized ecological monitoring data, incorporating conservation goals and strategies into regional and urban planning processes becomes feasible (Dubovik et al., 2021). Our approach to mapping waterbird distribution highlighted the importance of considering spatial scale. It is not restricted to wetland reserves but applies to other protected areas and species threatened by land-use changes in surrounding landscapes to inform the development of evidence-based conservation programmes. This holistic integration is crucial for ensuring the long-term persistence of suitable habitats for animal populations under the protected area systems (Schulze et al., 2018), especially for small-sized reserves and species with large home ranges, in the face of habitat loss and escalating human disturbances associated with urbanization in subtropical and tropical Asia (McDonald et al., 2008).

Ethics statement

If this manuscript involves research on animals or humans, it is imperative to disclose all approval details.

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CRediT authorship contribution statement

Roger H. Lee: conceptualization, data curation, funding acquisition, investigation, methodology, project administration, visualization, writing – original draft, writing – review and editing; **Ivan H.Y. Kwong**: conceptualization, investigation, methodology, formal analysis, visualization, writing – original draft, writing – review and editing; **Tom C.H. Li**: data curation, project administration, writing – review and editing; **Paulina P.Y. Wong**: investigation, methodology, writing – review and editing; **Yik-Hei Sung**:

conceptualization, investigation, methodology, writing – review and editing; **Yat-Tung Yu**: conceptualization, data curation, funding acquisition, project administration, writing – review and editing.

Declaration of Competing Interest

The authors, Roger Lee on behalf of Ivan Kwong, Tom Li, Paulina Wong, Yik Hei Sung, and Yat Tung Yu, of the article titled "The importance of buffer zones for coastal protected areas along the East Asian-Australasian Flyway," submitted to Global Ecology and Conservation, declare that:

They have no conflicts of interest or competing financial interests related to the research, authorship, or publication

This work is all original research carried out by the authors. All authors agree with the contents of the manuscript and its submission to the journal. No part of the research has been published in any form elsewhere.

The research featured in the manuscript does not relates to any other manuscript of a similar nature that we have published, in press, submitted or will soon submit to Global Ecology and Conservation or elsewhere. The manuscript is not being considered for publication elsewhere while it is being considered for publication in this journal.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2024.e03357.

Data availability

Data will be made available on request.

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