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Long-term changes in population trends of wintering waterbirds in the Republic of Korea

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Summary

The population changes in waterbirds are recognised as a global issue. Many waterbird species, especially migratory ones, are undergoing population changes. Monitoring these changes is crucial for waterbird conservation. However, the lack of data to quantify these populations hinders comprehension of the factors responsible for these changes. Although a few studies have investigated the long-term trends of waterbirds in the Republic of Korea (ROK), most have concentrated on a limited number of species and groups. Understanding these changes enables us to identify which species are vulnerable and develop more effective conservation measures accordingly. This study aimed to investigate the population dynamics of waterbirds in the ROK from 2000 to 2024. Data from the Winter Waterbird Census of Korea were used to analyse trends across various waterbird groups and species. The results showed diverse population trajectories, with some species experiencing notable increases while others underwent severe declines. Among the observed trends, several globally threatened species, such as the White-naped Crane *Grus vipio* and Oriental Stork *Ciconia boyciana*, exhibited significant population growth. This is largely a testament to the effectiveness of conservation interventions aimed at these species. However, the study also identified population declines of some species, such as the Tundra Swan *Cygnus columbianus* and Common Pochard *Aythya ferina*, indicating pervasive threats due to habitat loss and degradation. Lastly, several recommendations are made regarding the identified population trends that should be used to guide future conservation efforts in the East Asian–Australasian Flyway. This study, with its comprehensive and detailed findings, reiterates the importance of long-term monitoring data for developing effective conservation measures.

Introduction

Waterbird population changes are recognised as a global concern (Piersma et al. 2016; Sung et al. 2021; Webster et al. 2002). Recent studies have reported a worldwide decline in waterbird populations (Amano et al. 2018, 2020; Wang et al. 2018). These changes are primarily attributed to factors such as habitat degradation, climate change, pollution, and human–animal conflicts (Amano et al. 2010; Pavón-Jordán et al. 2015). Many waterbirds are migratory species. Thus, waterbirds are particularly affected by habitat changes along their migration routes (Amano et al. 2010; Catry et al. 2013; Clemens et al. 2016; Howard et al. 2020). Migratory waterbirds that travel long distances suffer more serious pressures, including bad weather conditions and food shortages (Fox et al. 2019; Mott et al. 2023). Consequently, a wide variety of waterbird species are at risk of becoming extinct, posing a substantial threat to the balance of ecosystems across the globe.

Recent studies have also observed an increase in waterbird populations in certain regions, attributed to improved environmental, ecological, and anthropogenic factors (Bolam et al. 2023; Fasola et al. 2022; Kearney et al. 2023). In some areas, wetland restoration and the designation of protected areas have led to improvements in waterbird habitats (Yoo et al. 2011). For instance, wetland restoration projects have increased food availability and created suitable environments for breeding and roosting, contributing to population growth (Sung et al. 2018; Wang et al. 2014; Zou et al. 2019).

Monitoring waterbird population changes is crucial for waterbird conservation and the sustainability of ecosystems (Amano et al. 2010; Kingsford and Porter 2009; Zhang et al. 2015). By understanding these patterns of change, we can identify which species are vulnerable and develop more effective conservation policies (Austin et al. 2014; Shochat et al. 2010). Additionally, monitoring population changes acts as an early warning system for environmental changes, thereby enhancing our ability to respond to ecosystem transformations (Dakos et al. 2015; Heino et al. 2021). Many migratory waterbird species are experiencing rapid population changes worldwide, however, understanding the factors driving these declines is hindered by a lack of data to quantify waterbird populations (Henry and O’Connor 2019).

Research and observations provide evidence of ecological changes within waterbird populations. The Republic of Korea (ROK) is situated along the East Asian–Australasian Flyway (EAAF), attracting a diverse array of waterbird species. Approximately 58 shorebird species utilise this flyway during spring and autumn (Choi et al. 2022). Furthermore, 94 waterbird species have been observed during winter, including threatened species such as the Red-crowned Crane *Grus japonensis*, Mute Swan *Cygnus olor*, Chinese Egret *Egretta eulophotes*, and Black-faced Spoonbill *Platalea minor* (Kim et al. 2018; Lee et al. 2023; MacKinnon et al. 2012; NIBR 2023). However, a reclamation project in Saemangeum, i.e. reclamation of tidal flats and change in land use, has resulted in a sharp decline in the population of shorebirds, especially the Great Knot *Calidris tenuirostris* (Lee et al. 2018, 2020; Moores et al. 2016). These changes are not only causing a population decline but also leading to various fluctuations, including shifts in the distribution of species and alterations in migration patterns (Sanderson et al. 2006; Thomas et al. 2006). Although some studies have explored the long-term trends of waterbirds in ROK, most focus on limited groups and species, such as ducks, geese, and Whooper Swans *Cygnus cygnus* (Choi, Hur et al. 2012, Choi, Kim et al. 2018; Kim et al. 2016).

This study aimed to examine the annual changes in waterbird populations in ROK by utilising monitoring data spanning more than two decades. To the best of our knowledge, this is the first study to explore the population trends of major waterbird groups and species on a nationwide scale in ROK from 2000 to 2024. Systematic monitoring and data analysis are essential for understanding the status of waterbirds in ROK and implementing necessary conservation measures. The analysis of recently collected monitoring data enables us to identify trends in population changes among waterbird species in ROK, identify the most vulnerable species, and pinpoint areas currently experiencing issues. This facilitates the development of accurate and effective conservation policies and management plans to maintain ecosystem stability and sustainability in ROK.

Methods

Waterbird data collection

We utilised the waterbird data set obtained from the Winter Waterbird Census of Korea (WWCK) undertaken by the Korean Ministry of Environment and associated institutes, namely the National Institute of Environmental Research (1999–2007) and the National Institute of Biological Resources (NIBR) (2008–present) (NIBR 2024). From 1999 to 2024, surveys were conducted once in mid-January from 1999 to 2013. Starting in 2014, the survey period was extended from October to March of the following year (NIBR 2024). This data set includes information on the species and number of individuals observed in survey regions. Various wetlands, such as coastal areas, rivers, streams, lakes, estuaries, reservoirs, and reclaimed lakes, have been surveyed by the WWCK nationally in the ROK since 1999 (Figure 1). Lakes and slow-flowing rivers or streams in northern inland and high-latitude regions frequently freeze when winter temperatures remain low for an extended period. In central and southern regions, lakes and slow-flowing rivers or streams may partially freeze, but the ice does not become thick, or freezing occurs only in certain areas. When an entire water-body freezes, waterbirds migrate to other regions; however, if freezing is partial, waterbirds tend to concentrate in the unfrozen areas. The WWCK surveys each site for 2–3 days to prevent duplicate counts. These surveys typically take place in mid-January and involve approximately 100 teams of 200 well-trained observers working simultaneously. Given the vast experience of all observers, any differences in observation abilities are deemed negligible. The number of survey sites has increased from 69 in 1999 to 200 in 2024. Therefore, data from 1999 were not utilised in this study owing to the small number of survey sites. In 2000, there were 99 survey sites, and the number gradually increased, reaching 200 in 2015, and that level has been maintained since then (see Supplementary material Table S1). The total number of survey sites from 2000 to 2024 was confirmed to be 208 (Figure 1). In WWCK, the surveyed sites in regions known as representative habitats for wintering birds have remained largely unchanged. Changes in survey areas have occurred in locations of policy importance, e.g. areas with outbreaks of highly pathogenic avian influenza (HPAI) or where the wintering bird populations are small. Therefore, it is believed that these changes in survey sites will not significantly affect the population trend fluctuations of wintering birds arriving in the ROK. Of the 155 waterbird species recorded during the survey periods, only 68 were included in the analysis. If the annual population size is zero, it does not meet the data requirements for the Trends and Indices for Monitoring (TRIM) data analysis, and therefore, results cannot be derived. We excluded 87 species because of insufficient occurrence data for population trend analysis (Table S2). The recorded waterbirds were categorised into 16 taxonomic groups (geese, swans, shelducks, dabbling ducks, diving ducks, coots, cranes, grebes, shorebirds, gulls, murrelets, loons, storks, cormorants, spoonbills, and herons).

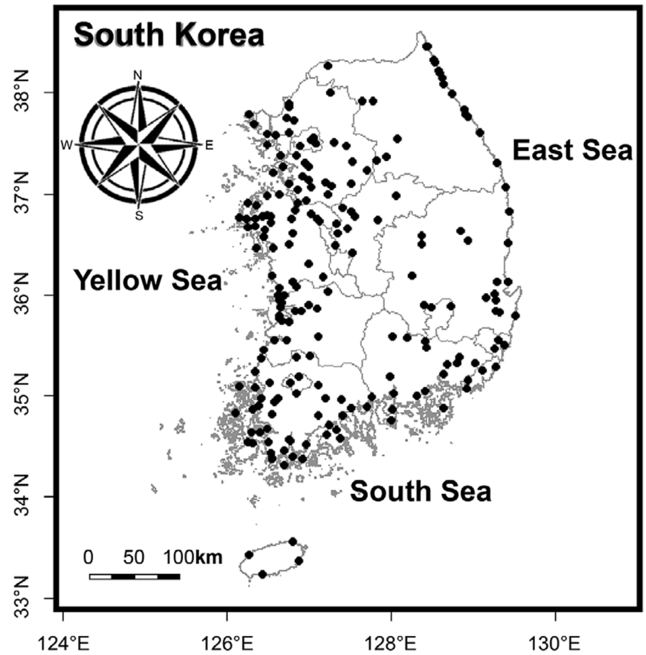

Figure 1. Map of monitoring sites in the Republic of Korea, as supplied by the Winter Waterbird Census of Korea (WWCK). It represents a total of 208 survey areas.

Long-term population trends

In long-term monitoring, specific areas may not be counted in certain years, or new areas may be added or disappear. To address

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this issue, one could compare only the areas monitored in all years; however, such an approach may not accurately capture population sizes and trends (Braak et al. 1994). The TRIM model is designed to analyse time series of counts, including predicting counts for years with missing observations, and is commonly used to estimate increases or decreases in animal populations (Pannekoek and van Strien 2001). Therefore, to understand the long-term population trends of waterbirds, we employed the TRIM method using monitoring data collected every January from 2000 to 2024, considering the variability in survey sites and missing values in our data. Subsequently, it produced an overall trend based on these indices. We considered survey sites as covariates in the analysis. To avoid underestimating standard errors, adjustments were made for overdispersion and serial correlation. The model was refitted without these corrections for species with low dispersion parameters (<1.0) or low serial correlation (<0.2). The imputed slope of the regression line for each species in the model was used as a metric to assess the overall trend in abundance.

The annual predicted population size for each year was extracted as the geometric mean through TRIM analysis and compared with the 1% threshold population size based on Ramsar Criterion 6 (Mundkur and Langendoen 2022).

At the species level, population fluctuations were analysed using TRIM, with the data divided into two periods: early (2000–2012) and late (2013–2024). Although not all waterbirds use rivers, a large-scale national project was conducted from 2009 to 2012, involving dredging, weir construction, and embankment maintenance in the four major rivers. i.e. Han River, Nakdong River, Geum River, and Yeongsan River. Furthermore, the construction of the Saemangeum seawall was completed in 2010 (Saemangeum Development Agency 2024). This project, one of the large-scale constructions undertaken in ROK, has induced changes in the water systems. Additionally, prior to 2012, various large and small reclamation projects, such as the Cheonsu and Asan Bay reclamation projects, were continuously undertaken along the west coast (Murray et al. 2014). An annual increase exceeding 5% was categorised as a "strong increase", whereas an annual decrease exceeding 5% was termed a "strong decrease". Increases or decreases within 5% were defined as "moderate". In addition, if -0.05 <lower confidence interval <0 <upper confidence interval <0.05, it was considered "stable"; otherwise, it was considered "uncertain" (van Strien et al. 2004). The population estimates predicted through TRIM analysis often exhibit high variability, so a trend line was ultimately added using Locally Weighted Scatterplot Smoothing (LOESS) regression analysis. The advantages of LOESS regression include capturing nonlinearity, providing a smooth trend line, and reducing the influence of outliers.

We compared the abundance of each waterbird species between the first (2000) and last (2024) survey years through the trend lines of LOESS regression. As many species had missing data, the first and last survey years varied. The following formula was employed for comparison (Paton et al. 2009; Sinha et al. 2011):

$$\text{Percentage change between the first and the last survey year} = [(M_{last} - M_{first})/M_{first}] \times 100$$

where M_{last} represents the count of the last survey year and M_{first} denotes the count of the first survey year.

The first count was rescaled to 100 in TRIM to analyse relative population trends. The analyses were conducted using the rtrim package (Bogaart et al. 2020) in the R program (R Core Team 2023).

Results

Population trends

According to the TRIM analysis of waterbird groups, the following trends were observed: coots, cranes, grebes, cormorants, and spoonbills showed a strong increase, whereas geese, swans, shorebirds, gulls, loons, and herons exhibited a moderate increase (Figure 2). Shelducks, dabbling ducks, and diving ducks showed a moderate decrease (Figure 2).

The TRIM results revealed variable overall population trends among waterbird species over the study period: strong increase (9 species), moderate increase (21 species), stable (13 species), strong decrease (2 species), moderate decrease (17 species), and uncertain (6 species) (Table 1 and Figure S1).

Among globally threatened species, the White-naped Crane *Grus vipio* (2,973.8%), Hooded Crane *G. monacha* (4,130.1%), and Oriental Stork *Ciconia boyciana* (726.6%) exhibited strong increases, while the Red-crowned Crane (339.8%) and Saunders's Gull *Saundersilarus saundersi* (191.6%) demonstrated moderate increases. Conversely, the Common Pochard *Aythya ferina* showed a moderate decrease (-51.2%) (Table 1 and Figure S1).

Excluding cases where population estimates were unavailable or not provided, the geometric mean of population sizes predicted through TRIM analysis from 2000 to 2024 showed that 34 out of 68 species had a population size greater than the 1% threshold (Table S2).

The top five waterbird species experiencing significant population declines were the Tundra Swan *Cygnus columbianus* (% change = -99.0%), Grey Plover *Pluvialis squatarola* (-55.4%), Siberian Scoter *Melanitta stejnegeri* (-95.9%), Black-necked Grebe *Podiceps nigricollis* (-101.0%), and Black-crowned Night Heron *Nycticorax nycticorax* (-50.1%). In contrast, the top five species showing significant population increases were the Hooded Crane (4,130.1%), Eurasian Spoonbill *Platalea leucorodia* (776.3%), White-naped Crane (2,973.8%), Pelagic Cormorant *Phalacrocorax pelagicus* (395.9%), and Great Cormorant *P. carbo* (1,420.9%) (Table 1 and Figure S1).

Representative waterfowl such as the Eastern Spot-billed Duck *Anas zonorhyncha* (-62.6%), Mallard *A. platyrhynchos* (-72.3%), Northern Pintail *A. acuta* (-58.3%), and Eurasian Teal *A. crecca* (-60.9%) exhibited decreasing trends. Moreover, the Bean Goose *Anser fabalis* (250.3%) and Greater White-fronted Goose *A. albifrons* (1,068.4%) showed increasing trends (Table 1 and Figure S1). The Baikal Teal *Sibirionetta formosa*, identified as the most dominant species based on cumulative abundance, exhibited relatively stable population fluctuations over the entire study period. However, a detailed temporal analysis revealed distinct trends. Since 2000, the population of Baikal Teal has increased rapidly, reaching its peak between 2008 and 2010. After 2010, a declining trend was observed, with a sharp decrease particularly noticeable around 2012. Since 2015, the population has remained relatively stable, showing fluctuations within a consistent range.

The species that showed an initial decreasing trend from 2000 to 2012, followed by a subsequent increasing trend from 2013 to 2024, included: Common Shelduck *Tadorna tadorna*, Ruddy Shelduck

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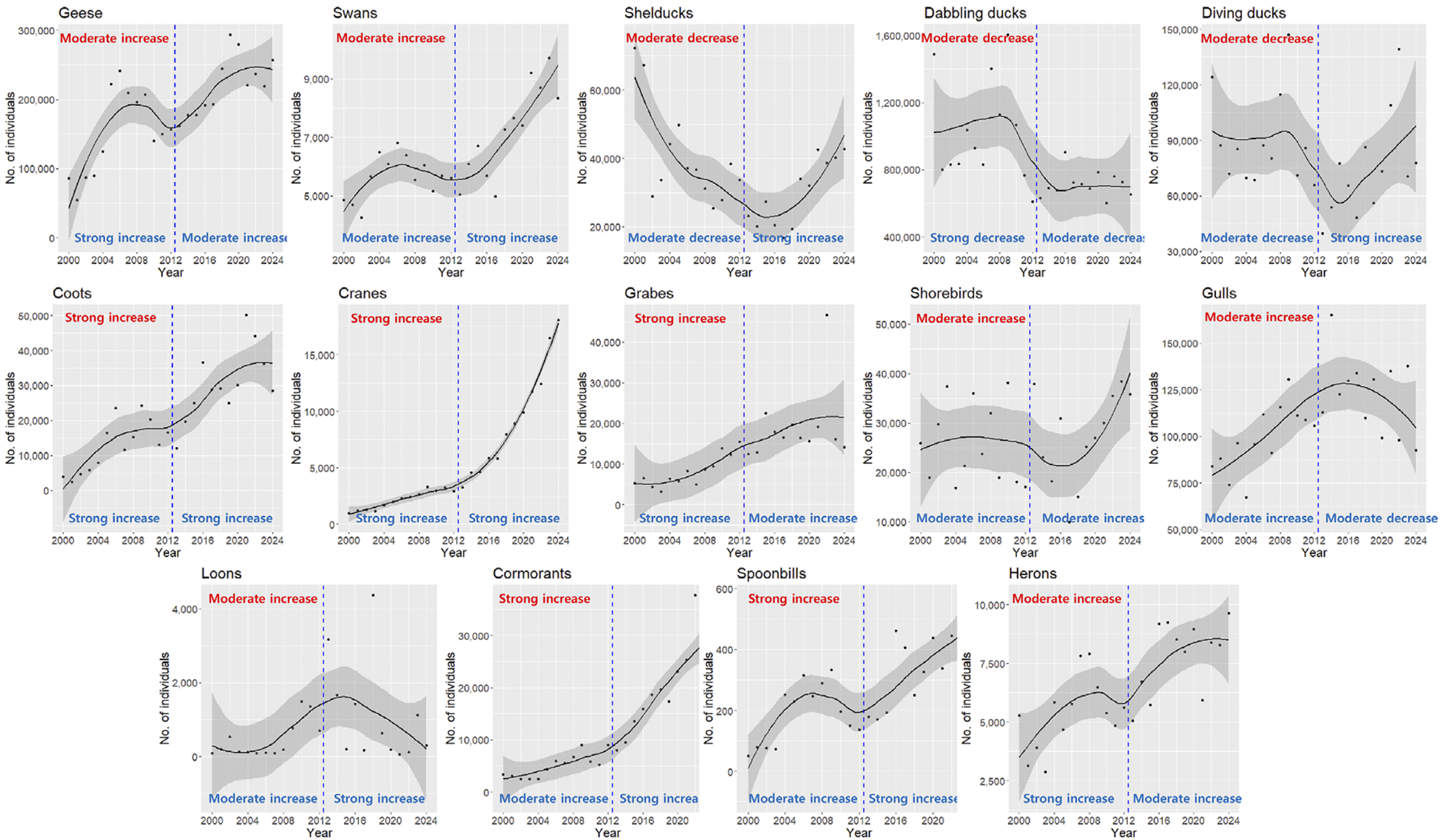

Figure 2. Population trends for waterbird groups from 2000 to 2024 in the Republic of Korea. The *y*-axis is an index value with 95% confidence limits derived from the Trends and Indices for Monitoring (TRIM) analysis. Through the TRIM analysis, the population trend from 2000 to 2024 is represented in red, while the early period (2000–2012) and the later period (2023–2024) are depicted in blue.

Table 1. Results of the TRIM and percentage change analyses. * p < 0.05, ** p < 0.01, *** p < 0.001

Taxonomic group	Common name	Scientific name	Slope[a]	SE[b]	Meaning[c]	% Change[d]	Red List[e]	Global trends[f]
Geese	Snow Goose	*Anser caerulescens*	–0.007	0.025	Uncertain	–24.940	LC	Increasing
Geese	Swan Goose	*Anser cygnoides*	0.037	0.028	Uncertain	619.070	VU	Decreasing
Geese	Bean Goose	*Anser fabalis*	0.031	0.005	Moderate increase***	250.286	LC	Decreasing
Geese	Greater White-fronted Goose	*Anser albifrons*	0.052	0.005	Moderate increase***	1,068.366	LC	Unknown
Swans	Tundra Swan	*Cygnus columbianus*	–0.232	0.046	Strong decrease***	–99.020	LC	Unknown
Swans	Whooper Swan	*Cygnus cygnus*	0.027	0.004	Moderate increase***	152.897	LC	Unknown
Shelducks	Common Shelduck	*Tadorna tadorna*	–0.014	0.004	Moderate decrease***	–18.689	LC	Increasing
Shelducks	Ruddy Shelduck	*Tadorna ferruginea*	–0.063	0.011	Moderate decrease***	–76.928	LC	Increasing
Dabbling Ducks	Mandarin Duck	*Aix galericulata*	0.008	0.007	Stable	–20.166	LC	Decreasing
Dabbling Ducks	Baikal Teal	*Sibirionetta formosa*	0.002	0.008	Stable	144.802	LC	Increasing
Dabbling Ducks	Northern Shoveler	*Spatula clypeata*	0.014	0.005	Moderate increase*	299.366	LC	Decreasing
Dabbling Ducks	Gadwall	*Mareca strepera*	0.010	0.004	Moderate increase*	63.225	LC	Increasing
Dabbling Ducks	Falcated Duck	*Mareca falcata*	0.002	0.005	Stable	66.347	NT	Decreasing
Dabbling Ducks	Eurasian Wigeon	*Mareca penelope*	–0.019	0.004	Moderate decrease***	9.653	LC	Decreasing
Dabbling Ducks	Eastern Spot-billed Duck	*Anas zonorhyncha*	–0.026	0.003	Moderate decrease***	–62.551	LC	Decreasing
Dabbling Ducks	Mallard	*Anas platyrhynchos*	–0.049	0.003	Moderate decrease***	–72.325	LC	Increasing
Dabbling Ducks	Northern Pintail	*Anas acuta*	–0.053	0.005	Moderate decrease***	–58.324	LC	Decreasing
Dabbling Ducks	Eurasian Teal	*Anas crecca*	–0.046	0.003	Moderate decrease***	–60.945	LC	Unknown
Diving Ducks	Common Pochard	*Aythya ferina*	–0.023	0.004	Moderate decrease***	–51.200	VU	Decreasing
Diving Ducks	Tufted Duck	*Aythya fuligula*	0.019	0.006	Moderate increase***	58.516	LC	Stable
Diving Ducks	Greater Scaup	*Aythya marila*	0.016	0.008	Moderate increase*	385.726	LC	Decreasing
Diving Ducks	Harlequin Duck	*Histrionicus histrionicus*	0.022	0.022	Uncertain	–1,592.602	LC	Increasing
Diving Ducks	Siberian Scoter	*Melanitta stejnegeri*	–0.126	0.043	Moderate decrease*	–95.917	LC	Decreasing
Diving Ducks	Common Goldeneye	*Bucephala clangula*	–0.011	0.006	Stable	201.923	LC	Stable
Diving Ducks	Smew	*Mergellus albellus*	–0.008	0.005	Stable	–27.705	LC	Decreasing
Diving Ducks	Common Merganser	*Mergus merganser*	–0.011	0.004	Moderate decrease*	13.412	LC	Unknown
Diving Ducks	Red-breasted Merganser	*Mergus serrator*	0.035	0.007	Moderate increase***	153.084	LC	Stable
Coots	Common Moorhen	*Gallinula chloropus*	0.067	0.015	Moderate increase***	538.062	LC	Stable
Coots	Eurasian Coot	*Fulica atra*	0.091	0.006	Strong increase***	10,097.052	LC	Increasing
Cranes	White-Naped Crane	*Grus vipio*	0.123	0.007	Strong increase***	2,973.795	VU	Decreasing
Cranes	Red-crowned Crane	*Grus japonensis*	0.056	0.004	Moderate increase***	339.831	VU	Decreasing
Cranes	Hooded Crane	*Grus monacha*	0.163	0.017	Strong increase***	4,130.060	VU	Increasing
Grebes	Little Grebe	*Tachybaptus ruficollis*	0.000	0.003	Stable	–8.531	LC	Decreasing
Grebes	Great Crested Grebe	*Podiceps cristatus*	0.113	0.007	Strong increase***	939.044	LC	Unknown
Grebes	Horned Grebe	*Podiceps auritus*	0.009	0.017	Stable	–84.320	VU	Decreasing
Grebes	Black-necked Grebe	*Podiceps nigricollis*	–0.092	0.012	Strong decrease*	–101.026	LC	Unknown
Shorebirds	Eurasian Oystercatcher	*Haematopus ostralegus*	0.047	0.011	Moderate increase***	176.069	NT	Decreasing
Shorebirds	Northern Lapwing	*Vanellus vanellus*	0.022	0.008	Moderate increase**	161.724	NT	Decreasing
Shorebirds	Grey Plover	*Pluvialis squatarola*	–0.048	0.014	Moderate decrease**	–55.369	LC	Decreasing
Shorebirds	Kentish Plover	*Charadrius alexandrinus*	–0.028	0.012	Moderate decrease*	–42.397	LC	Decreasing
Shorebirds	Eurasian Curlew	*Numenius arquata*	0.057	0.010	Moderate increase***	321.670	NT	Decreasing
Shorebirds	Sanderling	*Calidris alba*	0.057	0.060	Uncertain	–17.012	LC	Unknown
Shorebirds	Dunlin	*Calidris alpina*	–0.009	0.008	Stable	84.162	LC	Decreasing
Shorebirds	Common Sandpiper	*Actitis hypoleucos*	0.013	0.007	Stable	21.645	LC	Decreasing

(*Continued*)

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Table 1. (*Continued*)

Taxonomic group	Common name	Scientific name	Slope[a]	SE[b]	Meaning[c]	% Change[d]	Red List[e]	Global trends[f]
Shorebirds	Green Sandpiper	*Tringa ochropus*	0.076	0.019	Moderate increase**	146.572	LC	Increasing
Gulls	Black-headed Gull	*Larus ridibundus*	–0.008	0.004	Stable	–17.742	LC	Unknown
Gulls	Saunders's Gull	*Saundersilarus saundersi*	0.046	0.008	Moderate increase***	191.572	VU	Decreasing
Gulls	Black-tailed Gull	*Larus crassirostris*	0.024	0.004	Moderate increase***	74.116	LC	Stable
Gulls	Mew Gull	*Larus canus*	–0.010	0.007	Stable	–56.544	LC	Unknown
Gulls	Glaucous Gull	*Larus hyperboreus*	0.028	0.008	Moderate increase*	130.017	LC	Stable
Gulls	European Herring Gull	*Larus argentatus*	0.028	0.003	Moderate increase***	97.549	LC	Decreasing
Gulls	Slaty-backed Gull	*Larus schistisagus*	–0.019	0.006	Moderate decrease*	–85.419	LC	Unknown
Gulls	Heuglin's Gull	*Larus heuglini*	0.105	0.029	Moderate increase*	488.138	LC	Unknown
Murrelets	Ancient Murrelet	*Synthliboramphus antiquus*	0.109	0.068	Uncertain	619.081	LC	Decreasing
Loons	Red-throated Loon	*Gavia stellata*	–0.039	0.014	Moderate decrease*	–23.520	LC	Decreasing
Loons	Black-throated Loon	*Gavia arctica*	0.064	0.025	Moderate increase*	16.888	LC	Decreasing
Loons	Pacific Loon	*Gavia pacifica*	0.055	0.037	Uncertain	–136.192	LC	Increasing
Storks	Oriental Stork	*Ciconia boyciana*	0.102	0.018	Strong increase***	726.594	EN	Decreasing
Cormorants	Pelagic Cormorant	*Phalacrocorax pelagicus*	0.123	0.025	Strong increase***	395.883	LC	Decreasing
Cormorants	Temminck's Cormorant	*Phalacrocorax capillatus*	0.070	0.008	Strong increase*	676.460	LC	Unknown
Cormorants	Great Cormorant	*Phalacrocorax carbo*	0.132	0.008	Strong increase*	1,420.935	LC	Increasing
Spoonbills	Eurasian Spoonbill	*Platalea leucorodia*	0.085	0.012	Strong increase*	776.297	LC	Unknown
Spoonbills	Black-faced Spoonbill	*Platalea minor*	–0.003	0.011	Stable	–37.254	EN	Increasing
Herons	Black-crowned Night Heron	*Nycticorax nycticorax*	–0.055	0.020	Moderate decrease*	–50.111	LC	Decreasing
Herons	Grey Heron	*Ardea cinerea*	0.033	0.003	Moderate increase***	180.229	LC	Unknown
Herons	Great Egret	*Ardea alba*	0.057	0.005	Moderate increase***	282.423	LC	Unknown
Herons	Little Egret	*Egretta garzetta*	–0.031	0.005	Moderate decrease***	–41.724	LC	Increasing
Herons	Pacific Reef Heron	*Egretta sacra*	–0.018	0.011	Stable	15.644	LC	Stable

EN = Endangered; VU = Vulnerable; NT = Near Threatened; LC = Least Concern.
[a]Imputed multiplicative slope.
[b]Standard error of imputed slope.
[c]Model-based meaning.
[d]Percentage change. The percentage change is the percentage increase (positive) or decrease (negative) in abundance by comparing the counts in the first (2000) and last (2024) years. An imputed slope >1 represents a population increase, whereas an imputed slope <1 represents a population decrease.
[e,f]Global status according to the IUCN Red List

T. ferruginea, Mandarin Duck *Aix galericulata*, Northern Pintail, and Common Pochard. Conversely, the species that exhibited an initial increasing trend followed by a subsequent decreasing trend included: the Common Merganser *Mergus merganser*, Red-breasted Merganser *M. serrator*, Black-headed Gull *Larus ridibundus*, Red-throated Loon *Gavia stellata*, Black-throated Loon *G. arctica*, and Pacific loon *G. pacifica* (Table 1 and Figure S1).

Among the nine shorebird species, seven species (Northern Lapwing *Vanellus vanellus*, Kentish Plover *Charadrius alexandrinus*, Eurasian Curlew *Numenius arquata*, Sanderling *Calidris alba*, Dunlin *C. alpina*, Common Sandpiper *Actitis hypoleucos*, and Green Sandpiper *Tringa ochropus*) exhibited an uncertain population trend during the early period (2000–2012). In the later period, four species (Northern Lapwing, Kentish Plover, Eurasian Curlew, and Dunlin) showed an increasing trend, while Common Sandpiper and Green Sandpiper maintained stable populations (Table 1 and Figure S1).

It was confirmed that some waterbird species, such as the Eurasian Coot *Fulica atra* (664.3%), Great Crested Grebe *Podiceps cristatus* (682.1%), and Great Cormorant (741.8%), have increased rapidly over the past 25 years (Table 1 and Figure S1). The populations of gulls, including Saunders's Gull, Mew Gull *Larus canus*, Glaucous Gull *L. hyperboreus*, Slaty-backed Gull *L. schistisagus*, and Heuglin's Gull *Larus heuglini*, showed increasing trends (Table 1 and Figure S1).

Discussion

The 68 waterbird species in ROK show various population trends. The number of species experiencing a population increase was 1.5 times greater than the number of species experiencing a population decrease out of a total of 68 species (see Table S2 and Figure S1). Particularly noteworthy, among the nine globally threatened species observed in ROK, five were identified with increasing trends. However, the Tundra Swan, which has rarely been observed, shows a decreasing trend in ROK, contrary to its increasing populations in China and Japan (Jia et al. 2016). Additionally, common species with large populations and widespread distribution globally (BirdLife International 2023), such as the Eastern Spot-billed Duck, Mallard, Northern Pintail, and Eurasian Teal, exhibited decreasing population trends. Considering the role of ROK as a wintering area,

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the population trends of waterbird communities in this region are distinct compared with countries such as Japan and China. Additionally, the analysis revealed that 50% of the species studied had a population size exceeding the 1% threshold of the Ramsar Criterion 6, confirming the importance of ROK as a habitat for waterbirds (see Table S2) (Mundkur and Langendoen 2022).

The four globally threatened species observed in ROK, i.e. the White-naped Crane, Red-crowned Crane, Hooded Crane, and Oriental Stork, are subject to active human protection and restoration strategies (Higuchi and Minton 2000; Higuchi et al. 1996; Park et al. 2011). For instance, cranes are provided with additional rice seed supplementation during wintering periods. Moreover, wintering sites are managed by environmental groups and local governments to safeguard the grounds (Cho et al. 2003; Jang et al. 2020; Kim et al. 2013). Of course, regional management for conservation can lead to a concentration of waterbirds, including cranes, which may pose a significant risk of increased vulnerability to HPAI (Seo et al. 2024b). Drought-induced reductions in wetlands in the breeding areas of cranes may contribute to population declines (Galtbalt et al. 2022; Gerber et al. 2015). In the Amur Basin, a crucial crane breeding area, severe and prolonged droughts resulted in a 98% reduction in wetland area by 2009 compared with 1995–1999 (Goroshko 2012). Nevertheless, the wintering crane population has increased in ROK because of human management efforts such as establishing protected areas and regularly providing rice grains (Yoo et al. 2011). However, they are exposed to the risk of HPAI due to high population density (Seo et al. 2024a). Furthermore, Oriental Storks have exhibited increased breeding populations (Yoon et al. 2023). Although the breeding population has become extinct, resident Oriental Storks have been consistently observed in winter as a result of a restoration project in ROK. Oriental Storks have been reintroduced through soft/hard-release programmes since 2015 (Ha et al. 2021). Notably, in the case of the Oriental Stork, reintroduction efforts have been on-going since 2015, and the population has continued to increase through natural breeding since 2016 (Ha et al. 2021). In addition, the immigration of wild storks from China and Russia played a major role in increasing the stork population during the wintering period (Yoon et al. 2023).

According to TRIM and LOESS regression, the population of Tundra Swans was estimated at 659 individuals in 2000 but drastically declined to only two individuals in 2024. Furthermore, it was confirmed that both the early (2000–2012) and late (2013–2024) stages exhibited significant population decreases (Figure S1). This species experienced a significant decrease, with fewer than 30 individuals observed since 2015, and currently is rarely sighted. Interestingly, the population trend of the Tundra Swan in ROK differs from that of China and Japan. Although it has sharply decreased in ROK, it has increased in China and Japan during wintering periods (Jia et al. 2016; Wang et al. 2019). Tundra Swans observed in ROK have primarily been recorded in estuarine environments, particularly in river estuaries, with the Nakdong River estuary, located in the southern part of ROK, being the most significant site. However, since the early 1980s, estuarine areas where Tundra Swans have been observed have undergone freshwater transitions due to tidal flat reclamation and the construction of estuarine dams. The freshwater transition of estuarine environments caused by the construction of these dams has led to changes in the distribution of aquatic plants (Kim et al. 2005). This is likely because of impacts associated with eutrophication, hydrological changes, and extensive aquaculture (Hong and Hong 2023; Park et al. 2023). Additionally, the reclamation of tidal flats in the Nakdong River estuary has significantly altered the distribution of key food plants such as seagrass (e.g. *Schoenoplectus* spp.) for Tundra Swans (Kim et al. 2005). Tundra Swans are now concentrated in specific regions in China and Japan (Cong et al. 2011; Jia et al. 2016; Wang et al. 2019). Therefore, the Tundra Swan was reclassified from "Endangered" Class II to Class I in ROK in 2017 (NIBR 2023).

The population of the Common Pochard has exhibited a moderate decline since 2000 during wintering periods in ROK. This species has undergone sharp population declines in western and central Europe (BirdLife International 2015), resulting in its reclassification from a species of "Least Concern" to "Vulnerable" on the global International Union for Conservation of Nature (IUCN) Red List in 2015 (BirdLife International 2015). A similar situation occurred in East Asia (Choi et al. 2012; Kasahara and Koyama 2010). This study also confirmed findings that support the population trends of this species. The population trends of the Common Pochard are negatively affected by both its breeding and wintering grounds (Carboneras et al. 2020; Mischenko et al. 2020). Significant declines in the breeding populations of Common Pochard across a wide range from western Russia to Siberia have been observed (Mischenko et al. 2020). These decreases can be attributed to several factors, including changes in land use at breeding grounds, prolonged drought, increased predator risk, increased hunting, and the depletion of potential food sources due to eutrophication of feeding areas (Carboneras et al. 2020; Fox et al. 2016; Mischenko et al. 2020). The Common Pochard is predominantly observed in Sihwa Lake, located on the central west coast of ROK (Lee et al. 2004). According to Lee et al. (2020), as the water depth of Sihwa Lake increased from 2002 to 2012, the number of observed Common Pochards exhibited an increasing trend. However, on a long-term time scale (2000–2024), a clear declining trend is evident (see Table 1 and Figure S1). Prior to 2012, the lake was known to have poor water quality (Statistics Korea 2024a). Under low water quality conditions, key food sources for Common Pochards, such as crustaceans, molluscs, and macrophytes, struggle to survive (Hwang and Kim 2003; Koo et al. 2008). This suggests that while the increasing water depth from 2002 to 2012 may have provided favourable habitat conditions for Common Pochards, the poor water quality likely resulted in a reduction in potential food resources, thereby decreasing overall food availability. Consequently, the population of Common Pochards during this period exhibited high variability. The decline and large fluctuations in the population appear to have started with the construction of the Sihwa Lake seawall. Sihwa Lake was formed as a result of the construction of an artificial seawall, built to create agricultural and industrial land. In other words, the overall decline in the Common Pochard population throughout the entire period is a phenomenon caused by coastal reclamation and the construction of the seawall (Murray et al. 2014).

The Eastern Spot-billed Duck, Mallard, Northern Pintail, and Eurasian Teal are among the most common dabbling ducks. They are known for adapting to different habitat conditions across a broad geographical range (Chatterjee et al. 2020; Lehikoinen et al. 2016; Sauter et al. 2012). However, from 2000 to 2012, the population of dabbling ducks declined sharply, after which it remained stable, showed a slight increase, or experienced further declines in ROK. Similar declines have been noted in various other locations, such as Japan, the USA, Spain, and Mexico (Hagy et al. 2016; Kasahara and Koyama 2010; Pérez-Arteaga and Gaston 2004; Sinha et al. 2011). Nevertheless, recent findings from China have shown that the populations of these species increase during the non-breeding season, except for the Eastern Spot-billed Duck (Wang et al. 2019). These ducks primarily breed in northern China,

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Mongolia, central Siberia, and eastern Siberia (BirdLife International 2023). Some of these breeding grounds have also experienced declines (Cao et al. 2008; Melnikov 2000). However, because of low human population densities in these areas, the decline in duck populations in the flyway could be attributed to factors associated with wintering grounds (Wang et al. 2019). In ROK, dabbling ducks' primary habitats include coastal tidal flats, saltmarshes, estuaries, lakes, and reservoirs, which are natural wetlands. Additionally, they rely on residual grains from rice-paddies located near these wetlands as a major food source (Choi et al. 2012; Nam et al. 2015). Until 2012, frequent coastal reclamation projects resulted in the conversion of tidal flats and saltmarshes into rice-paddies, leading to the severe destruction of their coastal habitats (Murray et al. 2014). Although the conversion of wetlands into rice-paddies increased the potential availability of spilled grains, the actual amount accessible to dabbling ducks was likely reduced due to competition with geese, which utilise the same resource. The continuous increase in geese populations suggests that dabbling ducks have been outcompeted for food resources (see Figures 2 and S1). Under these circumstances, the nationwide decline in rice-paddy area, along with the widespread practice of harvesting and packaging rice straw as bale silage for livestock feed, has led to limited availability of residual grains, constraining further population growth of dabbling ducks (Chung et al. 2021; Statistics Korea 2024b). Furthermore, the Four Major Rivers Project has resulted in increased water depth, loss of sand dunes, and the simplification of riparian structures, which are likely contributing factors to population decline. Consequently, the population has been maintained at less than 50% of the numbers observed in 2000 (Chung et al. 2021).

The increase in the Baikal Teal population from 2000 to 2010 has been attributed to the prohibition of hunting and the increased availability of food resources (Allport et al. 1991; BirdLife International 2016). In ROK, strict regulations on wildlife hunting and poaching have been in place since 1994 (Ministry of Government Legislation 1994). Additionally, from 1991 to 2010, the Saemangeum Reclamation Project transformed saltmarshes and tidal flats into rice-paddies (Saemangeum Development Agency 2024). This land conversion led to an increase in the availability of spilled grains, a primary food resource for Baikal Teal, creating favourable conditions for wintering and resulting in a sustained population increase. However, since 2007, the widespread adoption of an agricultural practice in which rice straw is harvested and packaged as bale silage for livestock feed, along with the continued decline in rice-paddy area in ROK, has likely contributed to a subsequent population decrease (Chung et al. 2021; Statistics Korea 2024b). Nevertheless, some flocks have been found to expand their wintering range to eastern China (Dou et al. 2013). Due to the limited availability of spilled grains resulting from the harvesting and packaging of rice straw, the Baikal Teal population has been maintained at a relatively stable level since 2015 (Barnett et al. 2004; Buckingham and Peach 2006).

The population trend for shelducks exhibited a moderate decrease. In terms of the Common Shelduck, although an increasing trend was observed in the late stage, it was decreased over the entire period. Shelducks utilise small invertebrates and plants as food resources in mudflats or saltmarshes (Viain et al. 2013). Therefore, shelducks primarily utilise coastal mudflats, estuaries, and brackish areas as their main habitats (Mander et al. 2007). Moreover, shelducks exhibit distinct foraging and resting site preferences within tidal flats. For foraging sites, they are known to utilise areas where freshwater inflow enhances organic matter availability, creating a sufficiently moist and soft mud surface (Ravenscroft and Beardall 2003; Viain et al. 2013). However, there has been a continual decline in the population due to habitat destruction caused by coastal reclamation across the entire western coast of ROK (Murray et al. 2014). Since 2016, the population of the Common Shelduck has been increasing around the southern mudflats of the western coast, yet the specific reasons for this increase remain unclear. It is suggested that further research should be conducted on the habitat quality of the southern mudflats of the western coast to better understand these trends.

The populations of Bean Goose and Greater White-fronted Goose in ROK experienced increasing trends. These species breed in Arctic regions, where a warm climate improves breeding conditions by decreasing spring snow cover and increasing and prolonging plant production (Jensen et al. 2008; Li et al. 2020; Nolet et al. 2020; Solovyeva et al. 2019). The wintering population in ROK has increased because of a strong increase in the breeding population (Zhao et al. 2020). Furthermore, it is believed that the availability of rice grains, a major food source for these birds, has significantly increased due to the expansion of agricultural land resulting from coastal reclamation and embankment projects (Kim et al. 2024). Additionally, these species utilise leftover rice seeds that are present in the wintering grounds before the arrival of dabbling ducks (H.K. Nam 2024 pers. obs.). Rice seeds constitute their main food source. In general, geese are more adept at exploiting farm crops than most duck species (Owen 1980); therefore, their autumn and winter habitat use is largely influenced by, and has significantly changed in response to variations in farming practices (Davis et al. 2014; Nam et al. 2015). These ecological characteristics contribute to the population increase by enabling flexibility in acquiring food resources during winter (Fox and Abraham 2017). In China and Japan, the populations of these species also show a steady increase; however, their winter distribution range has remained unchanged compared with the past (Deng et al. 2020; Li et al. 2020).

Among shorebird species, six species, excluding the Grey Plover, Kentish Plover, and Sanderling, have shown either an increasing or stable population trend (see Table S2). This trend is likely related to conservation efforts in the Yellow Sea, which includes the west coast of ROK and the eastern coast of China (Ma et al. 2013). The Yellow Sea is centrally located along the EAAF, providing crucial habitats for various waterbirds. In particular, the coastal wetlands of the Yellow Sea are almost entirely relied upon by non-breeding shorebirds utilising the EAAF (Moores 2007; Mundkur and Langendoen 2022; Wang et al. 2018; Xia et al. 2017). In ROK, from 2000 to 2012, population trends for eight shorebird species were identified as either declining or uncertain. However, after 2012, six of these species exhibited either increasing or stable trends (see Figure S1). Since the 1970s, large-scale reclamation projects have been carried out along the west coast of ROK for agricultural expansion, industrial complex development, and urban expansion. These reclamation activities negatively impacted migratory shorebirds arriving in ROK between 2000 and 2012 (Hua et al. 2015; Ma et al. 2013). However, shorebirds have been observed to shift their habitats to other nearby tidal flats adjacent to reclaimed areas (Lee et al. 2018). As a result, some shorebird species appear to have maintained stable or increasing population trends. Although some mudflats have disappeared due to land reclamation and seawall construction along the western coast, the remaining mudflats appear to be utilised stably.

Around 2012, significant changes in population trends were observed in many waterbird species (see Figure S1). This phenomenon appears across different groups of waterbirds and is attributed to environmental transformations in ROK's water systems, precipitated by prior coastal reclamation, construction of dykes, conversion of tidal flats and saltmarshes into rice-paddies and artificial lakes, and the deepening of inland rivers and transformation of riverbanks into monotonous, artificial structures such as bicycle paths due to the Four Major Rivers Project. These changes led to biological, physical, and chemical alterations in the aquatic environments (Jun and Kim 2011; Ko et al. 2016). Continuous disturbance from human activities until 2012 resulted in declining trends in most duck species, while others, such as the Whooper Swan, Eurasian Coot, Great Cormorant, Eurasian Spoonbill, Grey Heron *Ardea cinerea*, and Great Egret *A. alba*, showed population increases post-2012 due to the newly formed environments (see Figure S1). Although the population fluctuations in most waterbird species can be understood in terms of changes in the water system environment, the exact causes of fluctuations are difficult to ascertain in some species. For example, despite the deepened waterbodies following the Four Major Rivers Project, a continuous decline in the population of diving ducks such as Smew *Mergellus albellus* and Common Merganser has been noted (see Figure S1). In this case, rather than analysing at a national-scale spatial level, it would be more appropriate to examine the specific causes at a regional scale while also considering the life-cycle in detail.

There is insufficient scientific evidence to explain fully the wintering population trends of certain species, although significant issues such as the coastal reclamation, construction of a seawall, and the Four Major Rivers Project are all likely to have contributed. Apart from uncertain patterns, the population trends of gulls increased in ROK. This increase can be attributed to the decrease in winter temperatures in ROK because of cold waves, which may have prompted some individuals from northern regions to migrate southward to ROK (Anderson et al. 2019; Nisbet et al. 2017). However, the fluctuations in population size across a wide range of species do not reflect these significant population trends. Without precise knowledge of the factors influencing these trends, additional scientific studies or observations are necessary for more diverse and accurate explanations.

This study provides detailed insights into the population fluctuations of wintering waterbirds in ROK. However, an examination of population changes reveals that many species exhibit significant year-to-year fluctuations in abundance. These variations are believed to be influenced by factors such as changes in survey sites and modifications in the coverage of selected survey areas. Such large fluctuations remain a limitation of this study. In the future, long-term monitoring in fixed survey sites and standardised survey areas will be necessary to minimise the extent of population fluctuations.

Proposed conservation measures for ROK

The EAAF, one of the major long-distance migratory routes for birds, spans 22 countries and serves as the primary migration corridor for numerous individuals and species compared with other flyways (Shi et al. 2023). It is also the location of the most significant declines, including those of endangered species (Conklin et al. 2014; Milton 2003; Turrin et al. 2016).

(1) Cranes. Currently, the Cheorwon Plain, Suncheon Bay, and Junam Reservoir have been designated as protected areas at the national and local government levels. However, additional habitats should also be designated as protected areas. Since cranes forage in expansive wetlands and rice-fields, systematic management of wetlands in the Han River estuary, Ganghwa Island, and Cheorwon Plain is necessary. Furthermore, as cranes are migratory species that travel between ROK and North Korea for wintering, inter-Korean cooperation is essential to ensure the conservation of their habitats, including the Korean Demilitarized Zone (DMZ) and the Han River estuary. However, since there have been cases of HPAI occurring in cranes, it is necessary to expand the wintering areas to minimise crowding. In addition, investigating their breeding areas should be prioritised to obtain detailed data on their breeding status. This information will provide a comprehensive understanding of the life history of cranes and facilitate the identification of measures to improve their breeding grounds.

(2) Oriental Storks. It is essential to designate and manage key Oriental Stork habitats, such as Yesan County and Cheonsu Bay, as protected areas. Since the species primarily forages in rice-paddies, adopting and expanding environmentally friendly farming practices is necessary to reduce pesticide use. Currently, the availability of suitable breeding sites for the Oriental Stork is limited, therefore, artificial nesting towers should be implemented in key habitats to support breeding efforts. Furthermore, as the Oriental Stork inhabits regions across East Asia, including the Korean Peninsula, close international cooperation with China, Japan, and Russia is crucial for its conservation.

(3) Tundra Swans and Whooper Swans. Detailed studies on the ecological niche and related differences between these species are required. Although the population of Whooper Swans wintering in ROK has rapidly increased, Tundra Swans, which are expected to exhibit similar ecological characteristics, are rarely observed wintering in ROK. Identifying the reasons for these differences by examining their life history traits and elucidating the specific ecological niche differences between the two species is crucial.

(4) Common Pochards. It is necessary to improve the water quality of coastal reclaimed lakes such as Sihwa Lake, Ganwol Lake, and Bunam Lake. These lakes suffer from continuous degradation due to the lack of water circulation, leading to the destruction of the lake ecosystem. Therefore, improving water quality by opening the embankments can help restore the aquatic biota within the lakes and provide a suitable habitat for the Common Pochard, which relies on these organisms as a food source. Additionally, efforts should be made to prevent land reclamation and the construction of seawalls along coastal areas. At the same time, to enhance breeding habitats, it is essential to establish and manage protected areas in their breeding sites.

(5) Dabbling Ducks. To provide stable wintering habitats for these species, it is necessary to improve the quality of rice-field habitats. This can include retaining rice straw in post-harvest fields and continuously supplying rice seeds. Additionally, maintaining flooded fields is important to ensure a stable resting area. However, in the ROK, the continual outbreaks of HPAI during winter pose a significant challenge, requiring habitat improvement efforts to be implemented across a wide area. Furthermore, to prevent the continuous decline of rice-field areas, it is essential to provide financial support to farmers engaged in rice production to help maintain paddy-field areas. Additionally, to enhance water quality and promote the formation of sandbars and gravel beds throughout the rivers, the weirs constructed during the Four Major Rivers Project should be opened. Moreover, riverbanks should be restored in an eco-friendly manner to provide suitable resting sites for dabbling ducks.

(6) Shorebirds. To prevent the continuous degradation of intertidal habitats, further land reclamation projects should be prohibited. Additionally, the ROK should strengthen its existing Marine Protected Areas (MPAs) and Wetland Protected Areas (WPAs). Furthermore, expanding Ramsar-designated sites is necessary to enhance habitat management. As shorebirds require essential stop-

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over sites along the EAAF, it is crucial to designate additional Flyway Network Sites (FNS) alongside the already designated sites, such as Gochang Tidal Flat, Hwaseong Wetlands, and Daebudo Tidal Flat. Moreover, collaborative efforts among the countries bordering the Yellow Sea – ROK, the Democratic People's Republic of Korea, and the People's Republic of China – are essential to ensure the protection and conservation of the Yellow Sea ecosystem.

The establishment of protected areas has a positive impact on waterbird populations, however, it is not universally effective for all populations. Furthermore, merely designating protected areas is insufficient; systematic management and habitat conservation must be implemented concurrently to ensure effective conservation outcomes.

Owing to its geographical location, Korea is situated in the central part of the EAAF, serving as a hub for migrating waterbirds. Therefore, quantified data on waterbird populations observed in Korea can provide crucial information for understanding the changes in waterbird populations across the 22 countries along the EAAF. Furthermore, based on these results, a transnational bird conservation strategy should be devised in close collaboration with countries located along the EAAF.

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