〈Review Paper〉

The Status of Seabirds in Korea and Environmental Monitoring Methods using Seabirds

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Abstract − Seabirds have adapted to life in marine environments. More than 25% of the bird species observed in South Korea are seabirds, using the coast area of Korean peninsula as a stop-over and wintering, and breeding site. The aims of this review are to provide information about migratory and resident Korean seabirds and to discuss the methods that are currently employed to monitor the marine environment. In Korea, it has been reported that more than 400,000 individuals of seabirds breed on Nando Islet, Chilbaldo Islet, Guguldo Islet, Sasudo Islet, Hongdo Islet and Dokdo Islet. In 2010, approximately 160,000 seabirds also visited South Korea during the winter. Two of the main treats were introduced wildlife and habitat destruction by humans. Seabirds are monitored mainly at the population and individual levels. The assessment of population sizes and biomagnifications of pollutants are performed preferably at the community and population levels. Behaviour, growth, morphological characteristics, and breeding success is analyzed at the individual level and employed to gauge the health of the marine environment. In addition, we could suggest that molecular technique of seabirds successfully adopted to investigate the effects of pollutants and toxins in the marine environment.

Key words : seabirds, monitoring methods, marine environment, population, molecular levels

INTRODUCTION

Seabirds are defined as “marine birds living in and making their living from the marine environment which includes coastal areas, islands, estuaries, wetlands and oceanic islands” (Schreiber and Burger 2002). Sphenisciformes (penguins), Procellariformes (albatrosses, petrels, storm-petrels, fulmars, and shearwaters), Ciconiiformes (herons, egrets, and ibises), Pelecaniformes (pelicans, boobies, cormorants, and gannets), and Charadriiformes (shorebirds, gulls, terns, and guillemots) are broadly considered to be seabirds. Using the narrower Schreiber and Burger definition (2002), shorebirds in the orders Charadriiformes and Ciconiiformes that feed near coastlines or near shores cannot be considered as true seabirds. In this review, we used the broader definition of seabirds.

Generally, seabirds have longer life spans (20～60 years), a lower metabolism and mature latter than terrestrial birds (Schreiber and Burger 2002). For example, gulls usually start breeding after four years after they hatched. They are not breed every year and have a relatively small clutch (1～3 eggs) (Schreiber and Burger 2002). These characteristics render seabird populations vulnerable to biotic factors such as climate changes, abundance of preys (Wanless *et al*. 2005; Wanless *et al*. 2007), and introduced species (Lee *et al*. 2009b) and abiotic factors such as pollutions (Barrett *et al*. 1985; Guruge *et al*. 1997). As a biotic factor, introduced species often threaten seabird population. The introduction of predators such as cats and dogs has significantly reduced the breeding success of seabirds in a short period of time (Nam *et al*. 2004; Bellingham *et al*. 2010). Not only introduced animals, but also introduced plants can affect seabird

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population. In the Seychelles, Feare *et al*. (1997) found that an introduced plant, the epi blue (*Stachytarpheta jamaicensis*) induced the loss of breeding sites for the Stoody tern (*Sterna fuscata*). Demography and local population dynamics in seabirds can be regulated by food availability as well (Birkead and Furness 1985). Oro *et al*. (2004) investigated population dynamics of gulls on the Columbretes Islands, western Mediterranean. They found that emigration rate of young breeders in population was high under the poor availability of food and this can induce extinct of local population when food condition is poor.

Survival and fecundity of seabirds related to their ages. In the California gull (*Larus californicus*), young gulls produced a smaller number of chicks, but their survival was higher than old gulls. Old gulls produced more chicks, but their survival was lower than young ones. The great skuas (*Stercorarius skua*) produced the largest clutch around the age of 18 years old and after then, their clutch size declined (Ratcliffe *et al*. 1998).

As an abiotic factor, marine pollution can be responsible for both short-term and long-term effect on population. For example, in 1989, the Exxon Valdez Oil spills in Alaska reduced more than 30,000 marine birds (Piatt *et al*. 1990). After 9 years later, it has been reported that oil spills still influenced seabird population living in the water and shores of Prince William Sound (Lance *et al*. 2001). Indigested plastics and floatables are also major causes of mortality in seabirds (Schreiber and Burger 2002). The sharp fragments of plastics often damage the gut of seabirds, especially in procellariiform which do not regurgitate undigested pellets.

High sensitivity to environmental changes makes seabirds very useful indicators of the health of marine ecosystems (Furness and Greenwood 1993). Seabirds depend on marine environment during whole their life-spans and they can response the changes of food web in marine ecosystem as a top-predator. Thus, marine environment assessment can be performed by monitoring changes in seabirds' behaviour, breeding success, and population dynamics (Wanless *et al*. 2005; Wanless *et al*. 2007). They are also often used in the study of the extent of the influence of heavy metals and a variety of chemicals on the marine environment (Mochizuki *et al*. 2002). Gochfeld (2005) found that the development of learning ability and locomotive skills were significantly slower in lead-injected chicks than in the control group. Additionally, Bustness *et al*. (2001) and Colborn *et al*. (1993) reported that gulls with a higher blood level of endocrine-altering polychlorinated biphenyls (PCBs) had lower incubation rates than gulls with lower levels of PCBs. Their abidance on mudflats of coastlines or at sea and long life spans make them useful for monitoring the long-term contamination effects in a specific marine ecosystem. The biological effect of contamination on seabirds has extensively been studied in Japan (Guruge *et al*. 1996; Guruge *et al*. 1997; Mochizuki *et al*. 2002; Shinsuke *et al*. 2003), the United States (Ackerman *et al*. 2008), Canada (Bond and Diamond 2009), and several European countries (Veltman *et al*. 2006; Rodriguez *et al*. 2007; Paiva *et al*. 2008; Sanpera *et al*. 2008).

Since, South Korea has a long coastline and about 2,765 islets where seabirds forage and breed. And, more than a quarter of the bird species recorded in South Korea are seabirds and shorebirds (Lee *et al*. 2001), many of them breed and/or migrate through South Korea, our knowledge of the interactions between environmental factors and the birds' biology may be directly used for monitoring "healthy" marine environment in South Korea. Therefore, we decided to assess the current status of seabirds in the environmental monitoring in South Korea and compare them to other countries (Japan, the United States, and the European Union). We also discuss methods that are employed for the detection of impacts of marine environmental changes. In this presented study, we have chosen a set of specific references describing seabirds and their relevance in ecological study that, in our opinion, most extensively assess the current status of such a research.

RESULTS AND DISCUSSION

1. Seabird communities and research in Korea

Kwon (2009) and Lee *et al*. (2009b) reviewed that approximately 8,000 pairs of the streaked shearwater (*Calonecris leucomelas*), 600 pairs of the Temminck's cormorant (*P. capillatus*), 10 pairs of the crested murrelet (*Synthliboramphus wumizusume*), 50,000 pairs of black-tailed gulls (*Larus crassirostris*), 20,000 pairs of little terns (*Sterna albifrons*) and 120,000 pairs of Swinhoe's storm-petrels (*Oceanodroma monorhis*) currently reside on the Korean peninsula. They are distributed among several breeding colonies (Fig. 1). In the Swinhoe's storm-petrel, approx. 10,000 of breed on the Chilbaldo Islet, 125°47′E, 34°47′N (Lee and Won 1998),

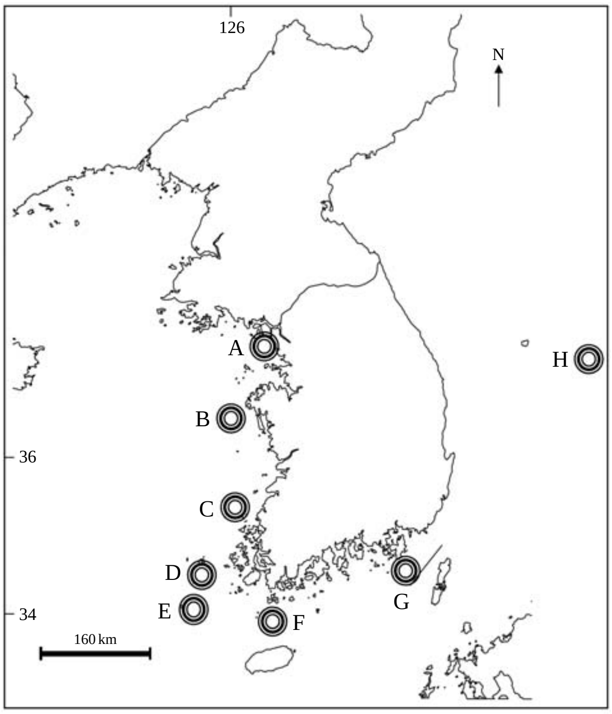

Fig. 1. Main breeding sites of seabirds in South Korea (A: breeding colony of the Saunders' gull and the black-faced spoonbill on the Songdo; B: breeding colony of the black-tailed gull on the Nando Islet; C: breeding colonies of the Swinhoe's storm-petrel on the Chilbaldo Islet; D: breeding colony of the Swinhoe's storm-petrels on the Chilsando Islet; E: breeding colony of the Swinhoe's storm petrel on the Guguldo Islet; F: breeding colony of the streaked shearwater on the Sasudo Islet; G: breeding colony of the black-tailed gull on the Hongdo Islet; H: breeding colony of the black-tailed gull on the Dokdo Islet).

and 100,000 pairs breed on the Guguldo Islet, 125° 12′E, 34° 41′N (Lee 1989). In black-tailed gulls, more than 10,000 individuals breed on the Hongdo Islet, 128° 43′E, 34° 31′N (Kwon 1998), and approx. 3,470 individuals breed on Nando Islet (Jo *et al*. 2001). 39,300 and 10,000 gulls breed on Chilsando Islet, 125° 17′E, 34° 18′N in 2004 (Kim 2004a) and on Dokdo Islet, 131° 51′E, 37° 14′N in 2005, respectively (Kim *et al*. 2007a). Furthermore, 6,000 to 10,000 streaked shearwaters breed every year on the Sasudo Islet (126° 38′E, 33° 50′N) near the south western coast of Korea (Kim 2004c) with a burrow density of 0.23∼0.37 nests per m^2 (Lee 2000). During the winter, more than 160,000 seabirds stayed in 2010 (NIBR 2010).

Although bird monitoring has been carried, population dynamics of seabirds have been rarely understood yet in South Korea because of a little information of their long-distance migration and large range of foraging trips. Well known breeding population of black-tailed gulls on Hongdo Islet has been increased while population of streaked shearwaters on Sasudo Islet has been decreased (Kang *et al*. 2008a). Some factors affecting breeding of seabirds have been studied. In the past 10 years, a significant breeding variability, mainly breeding failure, has been observed in populations residing on the Sasudo Islet and the Chilbaldo Islet. The main cause of this phenomenon is predation by rats (*Rattus norvegicus*) that were introduced to the Islet about 100 years ago (Lee 2000). On the Chilbaldo Islet, Swinhoe's storm-petrels are threatened by invasive plants such as *Miscanthus sinensis*, *Aartemisia princes*, and *Achyranthes japonica* (Lee *et al*. 2009b). These plants not only compete with *Carex boottiana* (petrels use these leaves to make the enterance to their burrows), but also may significantly reduce the birds' flying abilities as in case of *Achyranthes japonica*. For example, in three colonies on Chilbaldo, Sokuguldo, and Gaerindo islets during the 2008 and 2009 breeding seasons, at least 76 birds died because of affliction caused by *A. japonica* (Lee *et al*. 2009b). Taking into account the imminent environmental threat caused by invasive plants researchers and officers of Shinan County, South Korea have not only made an effort to remove these invasive species but also study the effects of invasive plant removal on the petrel population dynamics.

Another factor influencing breeding variability is industrialization process. For example, Saunders' gulls (*L. saundersi*), a species in the vulnerable species category of the IUCN Red List (IUCN 2010), were recently discovered to be breeding in a reclaimed area of the Songdo Island (126° 37′E, 37° 28′N), Incheon, Fig. 1 (Kwon and Chung 2009). In 2005, about 4% to 5% of the world's population of Saunders' gulls bred in the Songdo Island, with a breeding success of 29%. However, these breeding sites are currently claimed for a new town and industrial development, forcing the gulls to move out from this area (Kwon 2009; Kwon and Chung 2009). In the case of black-tailed gulls, egg collecting had been a major threat in Hongdo (personal observation) and Chilsando Islet (Kim 2004a).

The migration routes and breeding populations of black-faced spoonbills (*Platalea minor*), an endangered species accordingly to the IUCN Red-List, were monitored in South Korea between 2003 and 2009. Spoonbills travel for overwintering from South Korea to Taiwan, Hong Kong, and Japan (Lee 2009), and approximately 300 to 400 pairs breed on 15 islets of the west coast of South Korea. The earliest known breeding site was at the Yudo Islet (Won 1994) but recently, new breeding sites were documented on Yudo, Gakhoedo (Ueta *et al*. 2002), Bido, Sokdo, and Chilsando islets (Kim and Lee 2001; Kim and Kim 2005). Among other sites, the main breeding sites of the black-faced spoonbills are several islets near the demilitarized zone (DMZ). Additionally, two pairs of breeding spoonbills were also found on the Bido Islet in 2004 and 130 pairs in 2008. The recent study of population dynamics of the spoonbills' breeding colony on Yudo Islet (Lee 2009), the largest breeding colony in South Korea, showed a rapid decline from 60～70 pairs in 2006 to 10～30 pairs in 2008. Although the reason for the population decline is not clear, it is possible that population declined or move out from Yudo under the high-predation pressure caused by domestic cats, owls, and raccoon dogs.

In North Korea, the primary breeding sites of the spoonbills are Jungdo, Taegamdo, Sogamdo, and Tokdo islets (Park and Chung 2001). However, little is known about their population dynamics. The reclamation of mudflats (Park 2002b), the development of cities (Kwon and Chung 2009), pollution (Kim *et al*. 2007c), and impact of invasive species (Lee 2002; Nam *et al*. 2004; Lee *et al*. 2009b) all threaten the seabird population in South Korea. In the last 30 years, the available mudflat area in South Korea has been reduced considerably by reclamation projects (Park 2002b; MLTMA 2009). This leads to a situation in which shorebirds and gulls that foraged on mudflats have to struggle for food and eventually starve (Park 2002b). This situation is amplified by bycatch, which increases the mortality of many diving seabirds such as auks (Personal communication). In December 2009, hundreds of auks were found dead on the east coast of South Korea (News 2009). The cause of death was most probably injuries caused by fishing nets.

Since South Korea joined the Ramsar Convention on Wetlands in 1997 (ME 2008), 171.528 km^2 of coastal area has been protected by the Korean government (GREF 2009). Currently, nature conservation is well recognized as an ongoing effort of the National government (KNP 2009); local authorities such as Shinan-County (Lee *et al*. 2009b); Ulleung-County (Ulleung-County 2004); and scientists has resulted in a variety of comprehensive nature conservation programs. This approach has resulted in declaring the eight breeding colonies of Swinhoe's storm petrels, streaked shearwaters and black-tailed gulls - Guguldo, Sasudo, Chilbaldo, Sindo, Nando, Chilsando, Hongdo, Kanghwa and Dokdo islets - as protection zones by the Cultural Heritage Administration of Korea (CHAK) (Kim 2004c). These efforts are strengthen by the yearly activities of the National Institute of Environmental Research (NIER) and the National Institute of Biological Resources (NIBR) focused on wild bird surveys on the coast, islands, and wetlands of the Korean peninsula (NIER and NIBR 2008).

2. Environmental monitoring using seabirds

The current and commonly used methods for seabirds monitoring are presented in Table 1. Since, the size of the seabird population is a function to the state of the marine environment, defined by multiple factors, the analysis of the population dynamics at the community and population levels is currently one of the most popular approaches (Mitchell *et al*. 2004; Hallgrimsson *et al*. 2007). An example of such an approach is monitoring the dynamics of the brown skua (*Catharacta antarctica*) population on Bird Island, South Georgia, U.S., which exposed the population increase between the late 1950s to the early 1980s and a significant reduction between 2000 to 2004 (Phillips *et al*. 2004). The scrutiny of a variety of factors that could result in the observed variability determined that the population decline reflected diet alterations among Antarctic fur seals (*Arctocephalus gazelle*: higher-quality prey) to Northern giant petrels (*Macronectes halli*), Black-browed albatross (*Diomedea melanophris*), and penguins (lower-quality prey). The observed diet-population size correlations were strengthened by the analysis of the population dynamics of the yellow-legged gulls (*L. michahellis*) on the French Mediterranean coastline between 1982 and 2000. However, in this case the increase in the population size was due to the amplified availability of the anthropogenic food resources, such as landfills (Duhem *et al*. 2008).

Seabirds' breeding success may also reflect environmental changes and is often used to gauge the state of the marine environment. For example, the black-legged kittiwake (*Rossa tridactyla*) exhibited poor breeding success when the population of sandeels, their main prey item, declined (Wanless *et al*. 2005). Since seabirds breeding is also a derivative of unusual environmental conditions, such as local temperature variability, its timing may be directly affected by short-term climate changes. For example, during warmer arctic springs, the little auk (*Alle alle*) started breeding earlier while black-legged kittiwakes breed later than usual (Moe *et al*. 2009).

Table 1. International seabird studies at the community and population, individual, and molecular levels

	Monitoring for	Species
Community and population level		
Population size	Fluctuation in population Diet changes	Seabirds (Mitchell *et al*. 2004; Mavor 2008); lesser black-backed gulls (Hallgrimsson *et al*. 2007); black-legged kittiwakes (Wanless *et al*. 2007); yellow-legged gulls (Duhem *et al*. 2008)
Biomagnification in the food web	TBT	Marine food web (Strand and Jacobsen 2005)
Individual level		
Behaviour and growth	Pb: learning and locomotion, balance, begging, feeding, drop-wing Climate change Seasonal change	Laysan albatrosses (Burger and Gochfeld 2000); herring gulls (Burger and Gochfeld 2000); black-legged kittiwakes (Moe *et al*. 2009); rhinoceros auklets (Ito *et al*. 2009)
Morphology	PCB: feather loss, cross-bills, extranumerary limbs Heavy metals: abnormalities, smaller size Tebufenozide: mouthpart deformities	Seabirds (Gochfeld 1975)
Breeding success	Diet, habitat quality	Black-legged kittiwakes (Wanless *et al*. 2005)
Egg contents	PCBs; arsenic compounds	Red-throated loons (Schmutz *et al*. 2009); black-tailed gulls (Kubota *et al*. 2002)
Tissues (feathers, eggshell, muscle, bone) and organs (liver, kidney)	Heavy metals; butyltin	Roseate spoonbills (Beyer *et al*. 1997); great blue herons (Speich *et al*. 1992); Barau's petrels (Kojadinovic *et al*. 2007); herring gulls (Burger 1994); seabirds (Mochizuki *et al*. 2002), (Guruge *et al*. 1997)
Blood	Hg	Leach's storm-petrels (Bond and Diamond 2009); pied oystercatchers (Thompson and Dowding 1999)
Molecular level		
MT protein	Cd, Zn, stressors	Muscovy ducks (Nzoughet *et al*. 2009)

3. Marine pollution

Given the position of seabirds as the top predators in the marine food web, they are often used to monitor the marine pollution. The analysis of a population's dynamics at the community level results in the assessment of bioaccumulation of pollutants across the food web (Furness and Greenwood 1993). It is possible because the biomagnification of pollutants is directly proportional to a trophic level. Thus, one should expect higher concentrations of pollutants in predators than in their prey. It has been shown that organic pollutants accumulate to a greater extent in higher trophic levels, such as the glaucous gull (*L. hyperboreus*), than in lower trophic levels, such as zooplankton (Hop *et al*. 2002). An example illustrating this point is the study on seaweeds, the blue mussel (*Mytilus edulis*), and herbivorous birds in Danish coastal waters that retain lower concentrations of organotin compounds than the eider duck (*Somateria mollissima*) that feed on mussels and the great cormorant (*P. carbo*) that feed on fish (Strand and Jacobsen 2005).

Because vertebrates contaminated with environmental pollutants may show abnormal behaviour, growth, development, morphology, survival, hatchability, and productivity these are the features researchers analyze when assessing the level and long-term implications of the environmental contaminations. For example, laysan albatross (*Phoebastria immutabilis*) chicks in nests near buildings with flaking lead paint having have a six-fold higher lead concentration than non-exposed birds and drooped wings (Burger and Gochfeld 2000). Herring gulls (*L. argentatus*) with an abnormally high feather lead concentration had impaired locomotive ability, growth and balance as well as begging, and learning (Burger and Gochfeld 2000). It has been observed that contaminated birds may also be affected by a variety of morphological abnormalities. Thus, common terns (*Sterna hirundo*) living on Long Island, New York, U.S., and exposed to elevated levels of mercury and PCBs had feather abnormalities, crossed bills, and extranumerary limbs (Gochfeld 1975).

Feather samples may also be used for the analysis in long-term pollutant and dietary studies. The signatures of stable isotopes retained in feathers are known to reflect the bird's diet during the period of feather growth (Thompson and Furness 1995; Hebert *et al*. 1999; Knoff *et al*. 2002; Park 2002a). Additionally, the proportional relationship between the ratios of ^{15}N and ^{14}N ($\delta^{15}N$ values) reflecting diet and mercury levels in chick feathers has already been documented. The relationship of stable isotope values and the concentration of mercury in feathers can indicate the dietary origin of contaminations (Tavares *et al*. 2009).

The extent of contamination caused by different pollutants can be also measured in other tissues. This approach was used by Barrett *et al*. (1985) indicating the applicability of various tissues such as epidermis (feathers) or internal tissue (blood) or egg yolk that were used for contamination assessment. Avian eggs can also be utilized for the assessment of contamination. An example of such an approach is the analysis of causes of a significant decline in the breeding population of red-throated loons (*Gavia stellata*) in Alaska between 1977 and 1993. In this case the examination of the egg contents and blood plasma of adult birds showed that shells collected in the Arctic coastal plain of north Alaska had a greater level of toxins than those collected in other areas that affected the loons' reproduction (Schmutz *et al*. 2009). The maternal transfer can also be the cause of contaminations observed in eggs. An instance of such phenomenon was observed in black-tailed gulls on Rishiri Island, Japan, where the eggs of black-tailed gulls contained 10% of the level of arsenic compounds detected in their mothers (Kubota *et al*. 2002).

4. Genotoxicology of seabirds

Recent advances in the genotoxicology of seabirds and proteomics allowed for the application of molecular techniques in environmental monitoring. The single cell gel electrophoresis assay (comet assay) developed by Ostling and Johanson (1984) to quantify the extent of DNA damage in cells (Singh *et al*. 1988) allows for an assessment of both double- and single-strand DNA breaks, and is a well-established tool used in a variety of scientific disciplines, such as environmental genotoxicity testing (Pastor *et al*. 2001). This technique permits assessing damage caused by heavy metals such as Pb, Cd, Cu, and Hg (LeBlanc and Bain 1997). The example of employment of this approach is investigation of a biological impact of a waste spill in Spain (Pastor *et al*. 2004). In this case a significant genotoxic damage was documented in terrestrial birds such as the white stork (*Ciconia ciconia*) and the black kite (*Milvus migrans*) rising in contaminated areas. The study of the herring gull (*L. argentatus*) resulted that gulls living in Sweden and Iceland are exposed to genotoxic environemtnal polluations. The level of DNA adducts in the liver in gulls was higher than in fish (Skarphedinsdottir *et al*. 2010).

5. Environmental proteomics

'Proteomics' is the study of proteins such as their expression, structures and functions. The analysis of the proteomes of animals and plants allows for the detection of proteins whose expression is altered in response to environmental factors (Nesatyy and Suter 2007). Since the development of two-dimensional gel electrophoresis (2DE) (Margolis and Kenrick 1969), a quantum leap in proteomics research has occurred over the past two decades (Witzmann *et al*. 1995; Thiyagarajan *et al*. 2009). Sequential gels acquired at different physiological conditions allow the monitoring of both the proteome overall changes as well as changes in a specific protein of interest. Metallothioneins (MTs) are proteins that bind various metals, including physiologically important metals, such as zinc and copper, as well as xenohiotic metals, such as cadmium, mercury, and silver. Biological functions of tracking MTs include regulation of zinc, copper and oxidative stress. The physiological importance of MTs tracking has been shown by Lucia *et al*. (2009) in muscovy ducks (*Cairina moschata*). The ducks were exposed for 10 days to cadmium and showed a higher expression of MTs in kidneys and livers. A comparison of protein profiles between control and stressors allows the detection of specific changes in the proteome (Blackstock and Weir 1999). For example, analysis of stress can be performed at the cellular level for stress markers such as heat shock proteins; HSP70 and HSP60. It has been shown that the half life of HSP70 and HSP60 is longer than corticosterone (CORT) which is a hormone protecting against stress. HSP70 renders them more appropriate markers of chronic stress analysis (Heatley *et al*. 2000; Tomas *et al*. 2005). Bradley *et al*. (2002) compared proteomes in the gill tissue of rainbow trout (*Oncorhynchus mykiss*) before and after treatment with toxicants (stressors) for 21 days. Expression signatures of many proteins differed between treatments and controls, suggesting that the effects of specific stressors are reflected in the proteome dynamics. Proteomics techniques have been seldom applied to wild birds including seabirds yet. For the future, our better knowledge of specific proteins related to pollutants and environmental changes would help environmental monitoring easier. For instance, the expression of proteins in blood or tissue samples of seabirds may reflect the level of pollution at sampling sites.

During the past 60 years, South Korean ornithological studies have developed rapidly (Park 2002a). The aftermath of these activities is an increase in the understanding of population dynamics, toxicology, and the ecology of various migratory and resident bird species as shown below. Thus, the breeding ecology and behaviour of seabirds have been studied in several species such as streaked shearwaters (Nam 2003; Kwon 2005), black-tailed gulls (Kwon 1998; Lee *et al*. 2008), and Swinhoe's storm-petrels (Lee 1989; Lee and Won 1998). Also in Korea the diet and habitats of shorebirds and seabirds have been relatively well studied by Lee *et al*. on migratory waterbirds (Lee *et al*. 2002), yet there is little information is available about their population structure and dynamics as a function of environmental changes. There are only a few reports that employed seabirds to monitor environmental changes in South Korea.

As part of international efforts, also in Korea the fluctuations of seabirds' populations have been monitored at the community and population levels in order to detect changes in the marine environment to be used later for conservation purposes (Lee *et al*. 2004). For example, the population sizes and densities of seabirds have been used as parameters to evaluate a specific habitat's quality, for example, mudflats (Lee *et al*. 2004). Lee *et al*. performed a comparison of Swinhoe's storm-petrels nesting densities among Chilbaldo, Sokuguldo, Kuguldo, and Gaerindo islets in years 2008 and 2009. The results yielded a reverse proportional relationship between an invasive plant, *Achyranthes japonica*, and the nest density of the petrels on the Chilbaldo Islet (Lee *et al*. 2009b).

It has been shown that ongoing research on the breeding success in streaked shearwaters (Lee 2002), Swinhoe's storm-petrels (Lee 1989), black-tailed gulls (Kwon 1998), Saunders' gulls (Kwon and Chung 2009), and black-faced spoonbills (Lee 2009) monitored at an individual level may be utilized for the assessment of birds' habitat quality.

In conjunction with international trends indicating that seabirds may be used as indicators of marine pollution in the food web (Furness and Greenwood 1993; Swaileh and Sansur 2006), South Korean researchers performed studies on a varieties of migratory species. One study was the analysis of lead concentrations in the livers, kidneys, and bones of shorebirds travelling across Asian-Australian migratory flyways (Kim *et al*. 2007c). The observed concentrations of lead in Kentish plovers (*Charadrius alexandrinus*), dunlins (*Calidris. alpine*), and great knots (*C. tenuirostris*) were significantly higher than those observed in Terek sandpipers (*Xenus cinereus*). However, cadmium concentrations in the livers, kidneys, bones, and muscles were not significantly differed among shorebirds (Kim *et al*. 2007c). The observed differences can be due to differences in diets or habitats among the studied species.

The comparison of lead concentrations among different international locations indicated that lead levels in the kidneys and livers of dunlins residing on Yeongjong Island were much higher than those observed in dunlins from the Bristol Channel, UK, Texas coast, U.S.; or Ottenby, Sweden (Kim *et al*. 2007c). The results indicated that higher levels of lead in dunlins may have its source primarily in the breeding areas than in the wintering areas. This statement is supported by the observation that lead concentrations in sediments were much lower on the Yeongjong Island than in the Bristol Channel, UK.

The study of concentrations of toxic metals in the tissues of loons collected in Pusan, South Korea, indicated that the mean level of iron and copper in oil-contaminated, red-throated loons (*Gavia stellata*), Pacific loons (*G. pacifica*), and Arctic loons (*G. arctica*) was much higher than that observed in Arctic loons from Russia (Kim *et al*. 1996).

The study on the concentration of heavy metal in several shorebird species on the Okgu Mudflat, Gunsan, South Korea, which is a part of the East Asian-Australian migration flyway, revealed that lead concentrations in the livers of Kentish plovers, Mongolian plovers (*C. mongolus*), dunlins, and great knots were below the toxic level, whereas the lead concentrations in the livers of red-necked stints (*C. ruficollis*) exceeded toxic levels, thus exposing the values much higher than those observed in other shorebird studies (Kim *et al*. 2009). Also in Korea it has been observed that increased lead concentration may induce neurological changes in young birds. For example, chicks of black-tailed gulls breeding on the remote Hongdo Islet, that had higher-than-normal lead concentrations often became lost and pecked to death

Table 2. Seabird studies at the community and population, individual, and molecular levels in South Korea

	Monitoring for	Species
Community and population level		
Population size	Fluctuation in populations Dietary changes	Swinhoe's storm-petrels (Lee *et al*. 2009a); seabirds (Kwon 2009; Kwon and Chung 2009); streaked shearwaters (Lee 2002)
Individual level		
Behaviour and growth	Heavy metals Habitat quality	Black-tailed gulls (Lee 2003) Streaked shearwaters (Nam 2003)
Tissues (feathers, eggshell, muscle, bone) and organs (liver, kidney)	Heavy metals	Shorebirds (Kim *et al*. 2007b; Kim *et al*. 2009); loons (Kim *et al*. 2006)
Breeding success	Diet, habitat quality, disturbance	Swinhoe's storm-petrels (Lee 1989; Lee and Won 1998; Lee *et al*. 2009a) black-tailed gulls (Kwon 1998); streaked shearwater (Yoo 2002); seabirds (Kang *et al*. 2008b)

by neighbouring adults (Lee 2003).

A review of papers published over the past 10 years in the Korean Journal of Environmental Toxicology indicates that the bioaccumulation of marine contaminants has been rarely studied (Table 2). In contrast, studies on the toxicity of pollutants in marine organisms are quite popular. Knowing that bioaccumulation studies are required to evaluate the long-term effects of contamination on the marine food web this state of affairs is somehow puzzling.

So far molecular methods have not been applied for seabirds monitoring in South Korea. However, DNA expression and proteome profiles have been used to investigate the effects of toxins or heavy metals in other taxa. For example, the analysis of alcohol dehydrogenase expression in *Chironomus riparius*, as a function of exposure to cadmium and copper reveals a reverse proportional relationship between the expression level and heavy metal concentration (Park and Kwak 2009). So far, no South Korean researchers have employed proteomics to monitor the effects of environmental changes in seabirds.

More than half a century has passed since ornithology was established as a scientific discipline in South Korea (Kim 2004b). While the status of many terrestrial birds in South Korea are relatively well known, the distributions, breeding sites, and migration routes of Korean seabirds are still largely unknown. The global marine environment has changed rapidly over the past two decades and is influenced by industrial pollutants (Larsen *et al*. 2007; Turner 2010) and global warming is changing the sea surface temperature and levels (Serreze 2010). The extent of global warming and industrialization-induced changes require international cooperation to estimate the gravity of changes in the marine environment. One of approaches that may be used for this kind of research is monitoring seabirds.

In this study we have shown that the seabirds' population fluctuations, breeding success, migration, and contamination levels have been extensively used by South Korean as well as the international scientific community. Main causes affecting seabird population are introduced species, pollution and bycatch in South Korea. Although we know breeding ecology of some seabirds, there is a limitation to study population dynamics which can be used for monitoring marine environment. To understand population dynamics of seabirds, a long term study of population fluctuation and investigation of factors affecting seabird population are required for the future studies. Information of breeding and wintering area and stop-over sites of seabirds would be necessary to make an action plans and international networks to protect seabirds. For monitoring marine environment, it is useful to develop various methods in terms of the individual, population and molecular level. Only a study at the molecular level may allow us to detect the effects of environmental changes before population- or individual-level changes are apparent. Nevertheless, as shown in this work, South Korean scientists have embarked only on research that does not employ molecular techniques. Although the yielded results are of extreme importance, they reflect the *posteriori* state of marine environment. Since environmental changes affect the not only ecosystems but also the quality of life of humans only a combination of all the presented methods in seabird monitoring will contribute to a full understanding of the changes occurring in the marine environment.

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