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REVIEW

Bird migration and the conservation of the global environment

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Abstract I have collaborated with Asian and American scientists on satellite-tracking the migration of birds in East Asia for nearly 20 years. We have tracked the migration of about 20 bird species, including cranes, storks, swans and hawks. We have used the results in a variety of applications, from showing migration routes and the relative importance of each staging site to more advanced analyses including using various data overlays to examine habitat use and the connectivity and network structure of migration pathways. We have also studied the effects of climate change on population trends of swans satellite-tracked from their wintering areas in Japan to their breeding ground in Russia. Satellite-tracking is a powerful research tool to study the detailed migration routes, seasonal differences in migration pattern, locations of important sites, and the conservation issues that migratory birds encounter. Migratory birds establish a link not only among natural environments in different countries along their migration routes but also among people in different countries. Further interdisciplinary cooperation is needed to develop tracking technology, and more international collaboration is required to promote migration studies.

Keywords Climate change · Conservation · East Asia · Migration · Satellite-tracking

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Introduction

Migratory birds encounter many problems during their migration. These include habitat destruction, hunting, chemical pollution and collisions with aircraft. These problems may reduce the chance of survival or reproduction of birds. Habitat destruction leads to habitat and food loss in breeding, staging or wintering areas (Askins 2000). Hunting and chemical pollution reduce the chance of survival or reproduction of the birds (Kerlinger 1995; Colborn et al. 1996). In collisions with aircraft, they may not only lose their own lives but also cause a heavy loss of human lives (Leshem and Bahat 1999). Migratory birds may also carry some infectious disease viruses such as West Nile fever and avian influenza (Tambyah and Leung 2006; LaDeau et al. 2007). The infected birds may lose their own lives or spread the viruses over a wide area. Therefore, it is important to study their migration routes, stopover sites, destinations, migration patterns through time and habitat use.

In the early 1990s, the new technology of 'satellite-tracking' became available for studying bird migration (Higuchi 2010). In this technology, once we deploy satellite transmitters, called platform transmitter terminals (PTTs), on the birds, we can receive information on their locations over time through the Internet from the Argos worldwide tracking and environmental monitoring service. At least two satellites are operational at any time; these move through an 850-km trajectory above the earth's surface at a speed of one orbit every 100 min. Data received and stored by the satellites are transmitted to ground stations in the US and France, and then transmitted to the Argos Global Processing Centers, where the data are converted into latitudinal and longitudinal position information (see Olival and Higuchi 2006; Higuchi 2010, for details on the satellite-tracking system). Using satellites as research tools enables data to be recorded over large spatial scales, far greater than the range capabilities of more traditional telemetry systems.

For nearly 20 years, I have collaborated on satellite-tracking bird migration with Russian, Mongolian, Chinese, Korean, Indian and American scientists (Higuchi et al. 1991, 1992, 2004; Higuchi and Pierre 2005; Yamaguchi and Higuchi 2008; Higuchi 2010). Satellite-tracking is especially well suited to Asian-based research because of the extremely large land area, sensitive political situations and the many urgent conservation problems in the region. We have satellite-tracked the migration of about 20 species of cranes, storks, swans, geese, ducks and hawks. We are interested in migration routes, migration patterns through time and habitat use of threatened birds in East Asia, with the aim of contributing to the conservation of focal species and their habitats.

In this article, I review the results obtained from our work, focusing on migration routes, important areas for migratory birds, and the effect of climate change on the population of migratory birds. I will discuss the links among natural environments in different countries along their migration routes as well as among human lives in different countries, and will describe future issues concerning the relationship among the birds, the environment and human activities. This article draws from and extends Higuchi (2010), adding further information.

Transmitters and their deployment

We used satellite transmitters or platform transmitter terminals (PTT) made by NTT, North Star Science and Technology, and Microwave Telemetry, which weighed no more than 3% of the target species' body weight. The transmission frequencies of satellite transmitters were set at 401.65 MHz ± 30 kHz. Duty cycles were set with the desired length of tracking period in mind for battery-powered PTTs (e.g., Higuchi et al. 2004). A solar-powered battery can be expected to last 2–3 years but maybe less, depending on the bird species being tracked and on environmental conditions.

We deployed the PTT on the bird's back with a harness. Our harness consisted of two Teflon-treated ribbons, which were sewn to each of the two anterior corners of the PTT. The ribbons met at the keel of the bird's sternum, where they crossed and passed through a small tube and were sewn together with a surgical suture (Nagendran et al. 1994) or nylon thread. We expected the PTTs to fall off once the thread deteriorated over 6 months to a year if attached with a surgical suture, or 2–3 years if attached with a nylon thread. For swans, we attached the PTT to a neck collar, which weighed 70–80 g total. The neck collar was expected to fall off through deterioration 2–3 years after deployment.

We categorized location data into seven Location Classes (LC) with respect to accuracy: from Z (least accurate), to B, A, 0, 1, 2 and 3 (most accurate) (Keating et al. 1991; Service ARGOS 1994). Accuracies for the least accurate location classes, A, B and Z, could not be estimated using the ARGOS system. In general, we used LC 1–3 for data analysis, which are reported with one standard deviation accuracies of 350–1,000 m, 150–350 m, and <150 m, respectively. We included LC 0, A, B and Z data only when they were spatially and temporally close to LC 1–3 location estimates.

Migration routes identified

The migration routes of certain species have been well studied, and some of the examples are introduced here. The groups treated are ducks, swans, cranes and hawks.

Ducks

Mallards *Anas platyrhynchos* were tracked from many regions in Japan (Fig. 1). Migration routes differed greatly, not only among individuals from different wintering sites but also among individuals from the same wintering site, although Mallards from the same wintering sites followed the same general migration routes.

One Mallard that departed from northern Hokkaido, the northernmost main island of Japan, moved along the Kuril Islands and reached the Kamchatka Peninsula in Far Eastern Russia. Six Mallards from central Japan traveled northward and crossed the Sea of Japan. All six of these birds reached the southeastern area of Far Eastern Russia. One bird reached northern Khabarovsk (51°22′N, 137°02′E), and then turned east and reached the north end of Sakhalin Island.

Mallards from southern Japan traveled northward, and most crossed the Sea of Japan just like the Mallards from central Japan. However, some birds went north along the eastern coastline of the Korean Peninsula. Most birds stayed near the border between North Korea and China. Three birds moved farther inland and reached points near the border between Inner Mongolia (China) and Russia. In some cases, birds exhibited a sharp change in direction during migration. After crossing the Sea of Japan directly, one Mallard moved northward from the north end of the coastline of North Korea, reached the border between Russia and China in northern Heilongjiang Province (45°39′N, 132°45′E) and then turned sharply west and finally arrived at the border between Russia and China in southern Chitinskaya (49°25′N, 119°37′E).

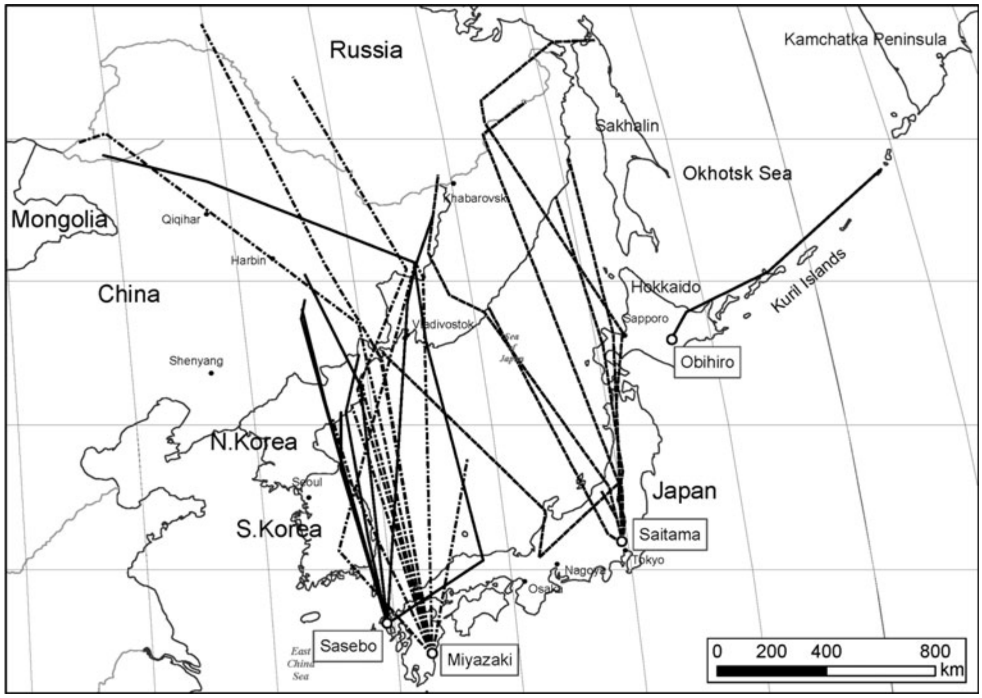

Fig. 1 Spring migration routes of Mallards *Anas platyrhynchos* satellite-tracked from a wide range of Japan in 2005–2007. Based on the data used by Yamaguchi et al. (2008)

A total of 102 Pintails *Anas acuta* deployed with PTTs migrated from Japan and made landfall elsewhere (Hupp et al. 2011). Most Pintails migrated first to Sakhalin or Kamchatka. Many Pintails that migrated to Sakhalin subsequently moved to stopovers in Kamchatka or the Magadan region facing the Okhotsuk Sea, with a small number migrating along the Kolyma River in Russian tundra. A small number of Pintails (4) remained on Sakhalin during the summer. Pintails that reached Kamchatka either directly from Japan or via Sakhalin made non-stop trans-oceanic flights of at least 1,200 km.

From Kamchatka, most Pintails next migrated to Chukotka and the surrounding areas, northeastern end of the Far Russia, although 32% of the Pintails that arrived in Kamchatka remained there during summer. Pintails that migrated to Magadan and the surrounded areas primarily next migrated along the Kolyma River, although 6 of the 21 Pintails that arrived in Magadan remained there for the summer.

Differences in migration routes of Pintails that summered in different regions were apparent. Pintails that arrived at summer sites in Kamchatka and Chukotka migrated almost exclusively through Kamchatka, either directly from Japan or via Sakhalin Island.

Swans

Four Whistling Swans *Cygnus columbianus* were tracked from Kuccharo Lake (45.17°N, 142.33°E) in 1990. The lake is not a wintering site for the swan, but one of the major stopover sites where thousands to more than 10,000 swans stay during their spring and autumn migrations. All four swans migrated along similar routes. They went north along Sakhalin and stopped over in northern Sakhalin or around the mouth of the Amur River. One female was successfully tracked to the mouth of the Kolyma River, which was in the breeding range of the arctic region. In 2009, another seven Whistling Swans were tracked again in spring from Lake Kuccharo. They took similar routes, migrating north along Sakhalin and stopping over in some areas of Sakhalin and around the mouth of the Amur River. They finally reached the area around the mouth of the Kolyma River (Fig. 2).

Thus, the mouth of the Amur River and the east and west coasts of Sakhalin (51.5–51.6°N, 143.3–143.9°E and 51.4–51.6°N, 142.0°E, respectively) appear to be important stopover sites for the swans.

The spring migration of eight Whooper Swans *Cygnus cygnus* was successfully satellite-tracked to their breeding ground in Russia in 1994 and 1995 (Kanai et al. 1997). The swans were released from the Kominato sea coast (40.94°N, 140.98°E), northern Honshu, Japan, a well-known wintering site of the swans. They migrated through southern Hokkaido, northeastern Hokkaido, Sakhalin and the lower Amur River. The presumed breeding sites were distributed along the lower Amur River, the north coast of the Okhotsk Sea, the middle reaches of the Indigirka River, and the lower Kolyma River. Their breeding ground was located in more southern areas than that of the Whistling Swans. The Tokachi River (42.74–42.92°N, 143.40–143.65°E), Aniva

Fig. 2 Spring migration of Whistling Swans *Cygnus columbianus* satellite-tracked from Lake Kuccharo, northern Japan in 2009

Bay (46.51–46.78°N, 142.24–143.38°E) and the lower Amur River (52.19–53.20°N, 139.46–140.80°E) were important stopover sites for the swans. About half the tracked swans rested in these areas for 2–40 days.

Cranes

In 1992–1993, nine White-naped Cranes *Grus vipio* were successfully tracked to their breeding grounds (Higuchi et al. 1992, 1996; Higuchi and Minton 2000). Two routes were identified: one led to the Three River Plain in northeastern China via the Korean DMZ, Kumya and Sonbong in North Korea, and Lake Khanka in China; the other led to the Zhalong National Nature Reserve in northeastern China via the DMZ (Fig. 3a). The autumn migration was tracked by Higuchi (1994) and Higuchi et al. (2004). Eleven cranes were tracked from Daursky Nature Reserve (50°N, 115°E), Khingansky Nature Reserve (49°N, 129°E) and Muraviovka Wildlife Refuge (49.92°N, 127.60°E) in south-central Russia in 1991–1993. They reached Poyang Lake in China (28.95–29.20°N, 115.86–116.10°E) and Izumi in Japan (Fig. 3b). The main stopover sites along the route to Poyang Lake were the mouth of the Yellow River (37.44–37.69°N, 118.53–118.98°E) and Wuhan (31.15–31.20°N, 116.18–116.20°E). The main stopover sites along the route to Izumi were Lake Khanka and the Three River Plain.

Higuchi et al. (1998) studied the autumn migration of Red-crowned Cranes *Grus japonensis* from Khingansky Nature Reserve in 1993 and from Lake Khanka Nature Reserve in 1993 and 1994 (Fig. 4). Two from Khingansky and seven from Lake Khanka were tracked for their entire migration to the wintering grounds. The cranes from Khingansky and Lake Khanka had different migration routes. The route from Khingansky led to coastal China via Heilongjiang Province, Bohai Bay, Tangshan City and the Yellow River Estuary. The route from Lake Khanka led to the Korean Peninsula via the Tumen River and the river mouth at Odaejin-nodongjagu. The important stopover sites were Panjin (40.90°N, 121.50–127.90°E), Tangshan (39.10–39.20°N, 118.80–119.00°E), the Yellow River Estuary (37.30–37.80°N, 118.80–119.00°E), Yangcheng (33.00–33.40°N, 120.60–120.90°E), the Tumen River (42.40–42.60°N, 130.60–130.80°E), Kumya (39.41–39.5°N, 127.30–127.50°E), Anbyon (39.00–39.10°N, 127.50–127.60°E), and Cholwon (38.20–38.30°N, 127.10–127.30°E).

In 1998 and 1999, another five cranes were tracked from wetlands along the Amur River in the Russian Far East (Tamura et al. 2000). There were two routes, one of which led to Yangchen Beach on the coast of China, and the other to the Korean Peninsula. Tamura et al. (2000) suggested other important stopover areas for the cranes: the Amur River basin (49.0–50.1°N, 127.6–1303.4°E), the Liao River delta (41.0°N, 121.8°E), and the Han/Imjin Estuary (37.6°N, 126.6°E).

Eleven Siberian Cranes *Grus leucogeranus* were tracked from the lower Indigirka River (71°N, 144–148°E) in the autumn of 1995–1996 (Kanai et al. 2002). All the cranes migrated along a similar route. They moved to Poyang Lake via the Qiqihar-Baicheng area, the Shuangtaize River delta and the Yellow River delta. These four areas (the Qiqihar-Baicheng area, Aumannykan area, Shuangtaizi River delta and Yellow River delta) are considered to be the most important stopover sites.

Hawks

Seven Grey-faced Buzzards *Butastur indicus* were tracked between their breeding and wintering grounds (Higuchi, in preparation). In spring, the buzzards departed from their wintering sites in southern South-West Islands, in southernmost Japan. They traveled northward along the island chains stretching to Kyushu, the southernmost main island of Japan. Then they veered east and crossed the island of Shikoku to reach Honshu, the largest main island of Japan. After that, the routes diverged and the birds headed for different breeding sites in Honshu. We could track two

Fig. 3 Spring migration routes in 1992 and 1993 (**a**), and autumn routes in 1991–1993 (**b**) of White-naped Cranes *Grus vipio*. The spring migration was successfully tracked for 9 cranes from Izumi, southern Kyushu, Japan. The autumn migrations were successfully tracked for 11 cranes from Daursky Nature Reserve, Muravivka Wildlife Refuge, and Khingansky Nature Reserve. From Higuchi et al. (1996), (2004), and Higuchi (2010)

successive spring migrations of three birds. The two spring routes were very similar and all the birds returned to the same breeding sites. For the bird breeding in Niigta, central Honshu, there were only 1 or 2 days difference in the departure and arrival dates between the years.

In autumn, the buzzards retraced the route they had taken the previous spring. The buzzards breeding in Tochigi, central Honshu, for instance, flew along the Pacific coast and reached Kyushu via Shikoku. The birds of Niigata on the Sea of Japan coast, on the other hand, migrated through the mountainous regions in central Honshu, and flew across Shikoku into Kyushu. All the birds flew through the southernmost Peninsula in Kyushu on their migration to the South-West Islands. One bird was tracked down to northern Taiwan, and another bird reached as far as the Batan Islands in the northern Philippines.

Since 2003, Higuchi et al. (2005) and Yamaguchi et al. (2008) have tracked the migration of 28 Oriental Honey-buzzards *Pernis ptilorhynchus* from central and northern Japan. Their migration route was totally different from that of Grey-faced Buzzards. In autumn, after departing their breeding areas in Japan, they migrated west across about 700 km of the East China Sea, then moved through inland China, Vietnam, Laos and Thailand and reached the Malay Peninsula (Fig. 5a). All the birds continued moving from the Malay Peninsula, but the directions and terminal points differed among individuals. After reaching Sumatra, 18 birds changed their travel direction to the northeast. Only 2 individuals arrived in the Philippines, through Borneo, and 16 individuals ended their migration on Borneo and the surrounding islands. The other 10 moved along the Malay Archipelago and ended their migration at Bankga Island, central Java, and Flores Island, respectively.

The spring migration was continuously tracked for 22 of the 28 honey-buzzards (Fig. 5b). From their wintering sites to the end of the Malay Peninsula, the birds mainly followed the same routes used during autumn migration. They migrated northwestward along the Malay Archipelago and the Malay Peninsula, then moved to inland China after going north through Thailand, Laos, and Vietnam. The routes in inland China were located north of those used during the autumn migration, before the birds reached the end of Korean Peninsula. Unlike during the autumn migration, the birds detoured around the East China Sea by going down through the Korean Peninsula and crossing the Korean/Tsushima Strait to reach Japan. Before travelling to China, all the birds stopped for several weeks in Southeast Asia.

As a consequence, individual honey-buzzards visited most or sometimes *all* East Asian countries during their complete migration cycle of autumn and spring.

Fig. 4 Autumn migration routes of Red-crowned Cranes *Grus japonensis* tracked from Lake Khanka, Far East Russia in 1993 and 1994, and from Khingansky Nature Reserve, southeastern Russia in 1993. Two cranes from Lake Khanka and seven from Khingansky Nature Reserve were tracked, but only a few route lines are shown here because some routes greatly overlapped. From Higuchi et al. (1998) and Higuchi (2010)

Differences in migration routes between seasons

Migration routes sometimes or often differ between spring and autumn, as shown in the case of the Oriental Honey-Buzzards. Why did the birds take such different migration routes at different seasons? Important factors are probably the weather and the distribution and abundance of their main foods.

We hypothesized that weather conditions, particularly wind conditions, were the primary cause of the seasonal difference in the migration routes of the Oriental Honey-buzzards. Yamaguchi et al. (in preparation) thought that the key area causing the seasonal difference was the East China Sea stretching about 700 km between the western end of Japan (Goto Islands of Kyushu) and eastern end of China (mouth of the Yangtze River). Because honey-buzzards usually fly by soaring and gliding, it would be difficult for them to traverse the 700-km water barrier without the benefit of tailwinds and thermals. Our analysis confirms the presence of relatively strong and stable northeasterly or north-northeasterly winds blowing over the East China Sea during the autumn. In contrast, wind directions are not stable in the East China Sea or Korea/Tsushima Strait during the spring.

The birds probably use relatively strong winds to traverse the oceans. The estimated wind strengths at the satellite locations of migrating individuals over the East China Sea or the Korea/Tsushima Strait were greater than the mean wind strength at each altitude, except over the Korea/Tsushima Strait during the spring season. These

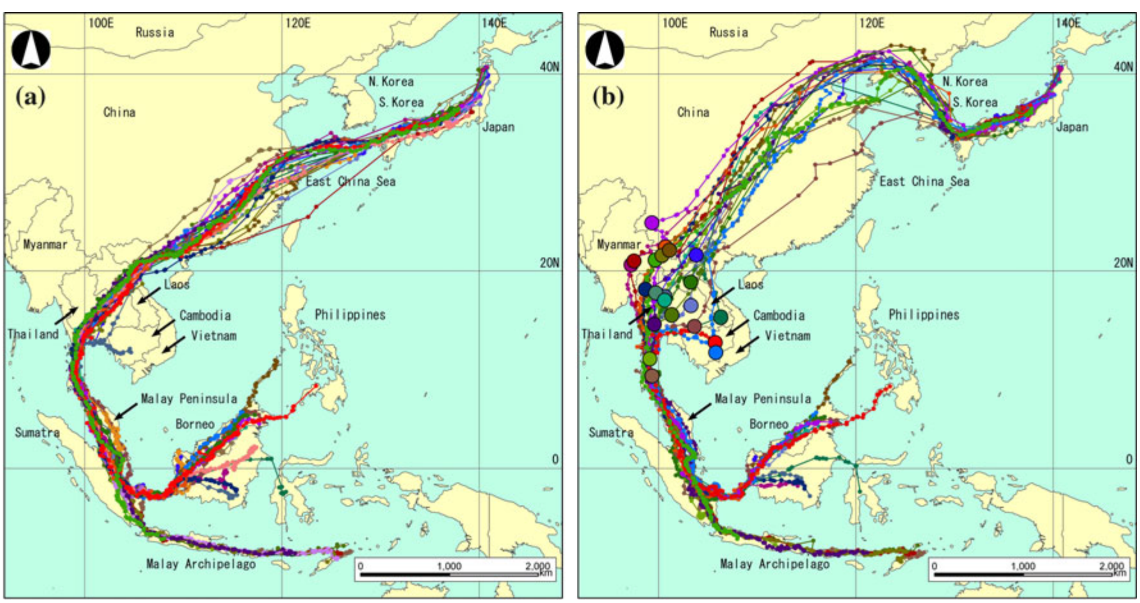

Fig. 5 Autumn (**a**) and spring (**b**) migration routes of 28 Oriental Honey-Buzzards *Pernis ptilorhynchus* tracked between 2003 and 2009. Each different *color* in the autumn and spring migration routes indicates the migration of the same respective individual. In the spring migration, the sites where the honey-buzzards stayed for more than 7 days are shown by *larger circles*. From Higuchi (2010) and further information

results suggest that it would be beneficial for the honey-buzzards to cross the East China Sea directly by soaring and gliding in autumn and to detour around the sea to avoid unstable wind conditions in spring. Furthermore, our data show that, while crossing the East China Sea in autumn, each bird travelled in strong tail winds and avoided bad weather conditions, such as headwinds and rainfall. The birds occasionally travelled in unfavorable weather conditions (weak or headwinds), particularly when passing through the Korean Peninsula and the Korea/Tsushima Strait in spring.

The autumn migration route across the East China Sea is likely to have evolved in response to the specific weather conditions over the sea.

Important migration areas identified

We can evaluate the importance of stopover, wintering or breeding site based on the number of birds visiting and/or length of stay. This information can be used to recommend conservation strategies for threatened species and their habitats. Areas identified as important are likely to be significant for conservation of the focal species, and can be allocated conservation priority accordingly.

For example, in China, satellite-tracking data have been used to identify the following important stopover and wintering sites for Siberian Cranes, Red-crowned Cranes, White-naped Cranes, and Oriental White Storks *Ciconia boyciana*: Bohai and Liaodong Bays, Poyang Lake, the Three Rivers Plain, Tianjin, the Qiqihar Baicheng area and the Yellow River delta (Higuchi et al. 1996, 1998, 2000, 2004; Kanai et al. 2000; Tamura et al. 2000). Tracking data have identified insufficiently protected areas that are important to cranes and storks, and have helped promote the conservation of these areas.

Data on the number of visiting individuals and the duration of their stays show that Panmunchom and Cholwon along the Korean DMZ are particularly important sites for migrating cranes in East Asia (Higuchi et al. 1996, 2004; Higuchi and Minton 2000). All White-naped Cranes tracked over the entire course of their spring migration stopped at one or more DMZ sites. Seven of the nine cranes tracked spent more than half their total migration period there (Fig. 6). Higuchi et al. (1998) also showed another aspect of the importance of the DMZ for Red-crowned Cranes. In Cholwon, along the DMZ, no satellite locations were received from outside the DMZ or the Civilian Control Zone (CCZ), in which land use and movements of people are less controlled than in the DMZ. The DMZ and CCZ provide an area of relatively little disturbance. The DMZ is of course completely off limits to civilians, and the CCZ to the south has controlled use by farmers, the military and construction workers. Apparently the level of control within the two areas leads to an environment with less disturbance than areas outside these zones. Adjacent to the northern border of the DMZ, North Korea does not maintain a zone similar to the CCZ, and thus the cranes may find too much disturbance in areas directly adjacent to the DMZ on the north side, as they do south of the CCZ in South Korea.

Habitat protection is relatively assured along the DMZ, as people cannot enter the DMZ or develop land there. Thus, the DMZ functions as a nature reserve or a nature sanctuary. However, if reunification is achieved on the Korean Peninsula, key sites will require enforced and meaningful protection to ensure the continued presence of breeding and wintering cranes (Higuchi et al. 1996, 2004; Higuchi and Minton 2000).

We usually say that there are no national borders for migratory birds. However, while national borders have no biological significance, the DMZ is clearly extremely important for birds migrating through East Asia.

Using satellite-tracking data on Oriental White Storks migrating from southern Russia to southern China, Shimazaki et al. (2004a) evaluated the importance of the location of stopover sites by quantifying how well connected the sites were at which birds spent time during migration. They suggested that the stopover sites situated on the shores of Liaodong Bay, Bohai Bay and Laizhou Bay in eastern China are less connected within the network than the other sites used along the migration route. This implies that these seashore stopover sites are at higher risk

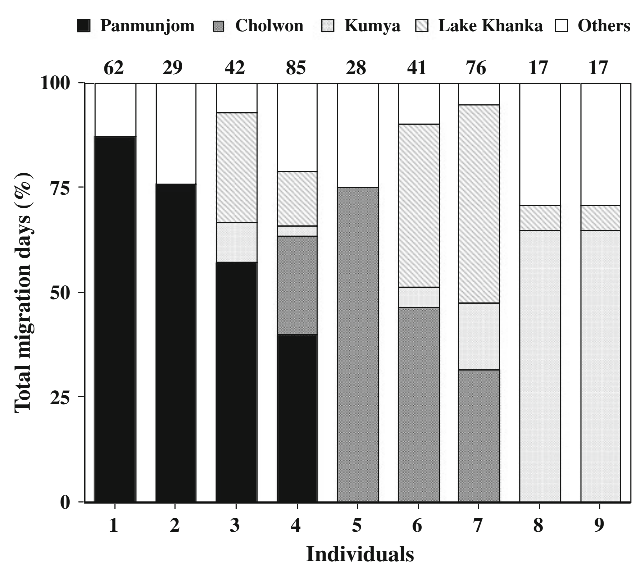

Fig. 6 Percent of migration days spent at each staging site for nine successfully tracked White-naped Cranes in spring 1992 and 1993. The numbers above the columns are the total days in migration of each crane. Higuchi et al. (1996)

of being isolated from the network of sites occupied on migration. Shimazaki et al. (2004b) also modeled a stay site network as an abstraction of the storks' potential migration routes from their breeding sites to wintering sites (Fig. 7), and applied network analysis techniques for exploring how the loss of stopover sites could affect the links between breeding and wintering sites. The results revealed that the number of potential migration routes could decrease exponentially as more stopover sites were lost under some specific patterns of attrition. It is suggested that, if the seashore stopover sites facing Bohai Bay in eastern China were lost, the storks' migration routes would be fragmented, and the wintering sites along the Yangtze River in southeastern China would be isolated (Fig. 7b).

This work provides insights into the requirements for a conservation framework that includes a well-connected network of appropriate habitats between breeding and wintering locations.

Migratory birds and climate change

Higuchi et al. (2009) studied the effect of climate change on the population trends of Whistling Swans, combining migration routes obtained from satellite-tracking and wintering population count data in Japan. The results are summarized as follows.

Whistling Swans arrive in Japan during autumn to overwinter, and return to northern Russia in spring. Since 1975, a nationwide count survey of Anatidae around January 15 has been conducted (Ministry of the Environment 1975–2008). The results show that the population of the wintering swans across the country was 1,745 in 1975 but began increasing rapidly in the 1980s and reached 40,485 (approximately 23 times more) in 2008 (Fig. 8). Niigata prefecture showed a significant increase in its swan population. The population of the swans there was only 69 in 1975 but reached 16,277 (approximately 236 times more) in 2008, accounting for 40% of the total across the country.

Satellite-tracking has shown that Whistling Swans wintering in Japan breed near Chaun Bay and the mouth of the Kolyma River in Russia, as described above. The swans lay eggs mainly in May and June. In autumn, they migrate down to Lake Kuccharo and Lake Ohnuma, Hokkaido, in the northernmost part of Japan, and fly to all the other parts of Japan. When migrating north to their breeding areas, they return to Lake Kuccharo and Lake Ohnuma in northern Hokkaido during March through May.

In order to show the effects of climate change on the swan population, we analyzed the relationship between the

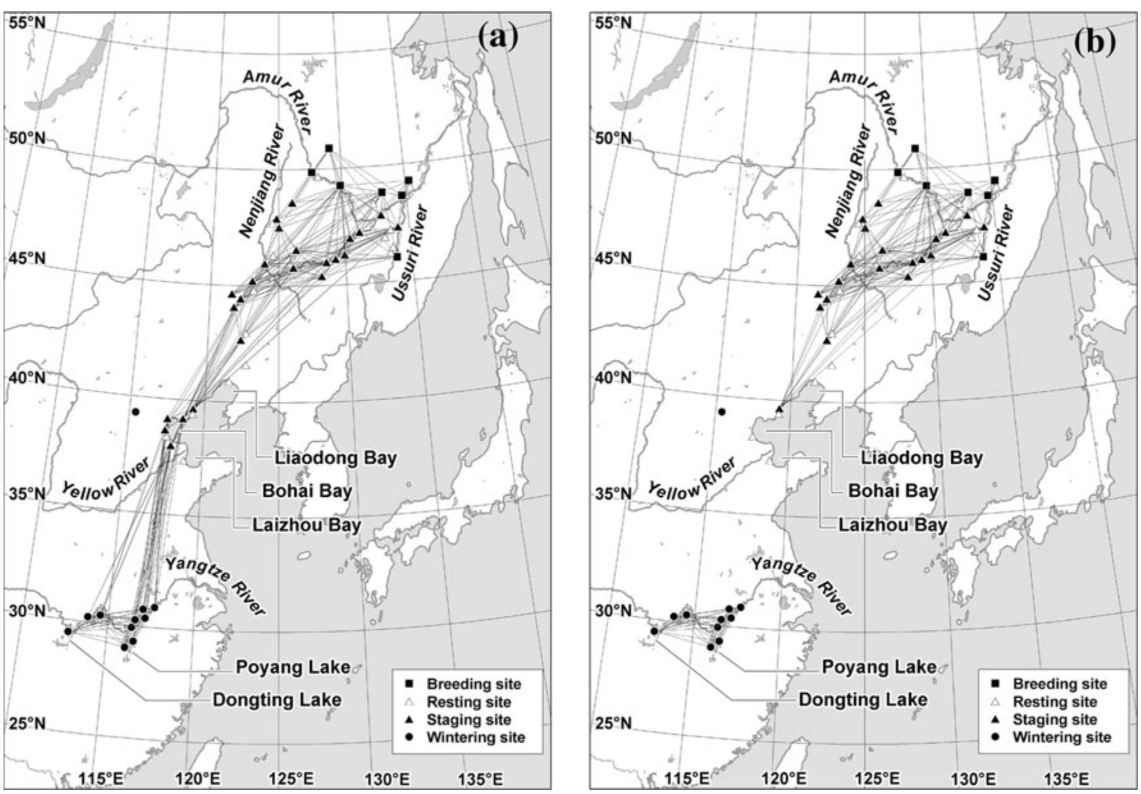

Fig. 7 The stay site network of Oriental White Storks *Ciconia boyciana*: **a** the network assumed with no staging sites removed; **b** the network assumed following removal of four sites facing Bohai Bay. From Shimazaki et al. (2004a, b)

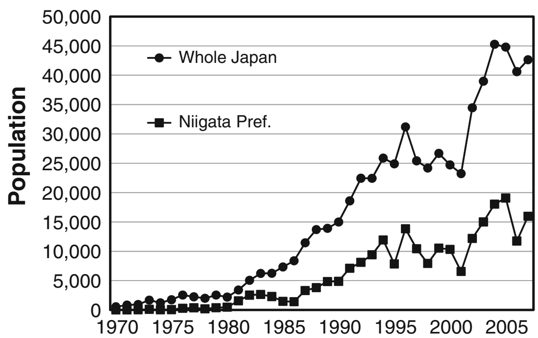

Fig. 8 Population trends of Whistling Swans wintering in Japan. From Higuchi et al. (2009)

population trends and meteorological factors from 1993 to 2005. We calculated the survival of the swans based on the proportion of white- and gray-plumaged individuals in 1 year and the previous year, and the best model, i.e., the best set of factors explaining the survival rates was selected through the Generalized Linear Model (GLM) based on Akaike's information criterion (AIC). The results showed that the snowfall in the wintering area, the air temperature in the breeding area and the air temperature in the staging area in spring affected the swan population. Namely, the survival of the swans increased with less snowfall in January to March in the previous year in Niigata, the wintering area; with higher air temperatures during May and June of the previous year in Chersky, the breeding area, near the mouth of the Kolyma River (68.8°N, 161.3°E); and with higher temperature during March and April in the previous year in Esashi (44.9°N, 142.6°E), the staging area located about 20 km from Lake Kuccharo.

If snowfall in the wintering area decreases, the birds can easily forage in paddy fields with more bare ground, increasing the survival of the swans. The increased temperature in the staging and breeding areas enables the swans to obtain sufficient food for breeding at an early stage, contributing to better survival and breeding success.

We also analyzed the relationship between the number of wintering young swans and meteorological factors. The data used for analysis were limited, but the results suggested that more young visited in winter when temperatures were higher in the breeding area the previous summer (Fig. 9). Probably, more young are produced in a warmer summer and come to Japan for winter as a result.

The temperature during May and June from 1974 to 2007 in Chersky has increased by about 3.8°C in the past 33 years (0.11°C per year). The temperature during the same period in Esashi increased by about 1.5°C (0.04°C per year). Snowfall during January through March in Niigata decreased by about 1.4 cm in the past 33 years (0.04 cm per year). The temperature during the same period in Niigata advanced by about 2.6°C in 33 years (0.08°C per year). Snowfall decreases with higher temperatures. The annual rates of temperature increase in these three areas are much higher than the 0.02°C average annual rate of temperature increase in the northern hemisphere.

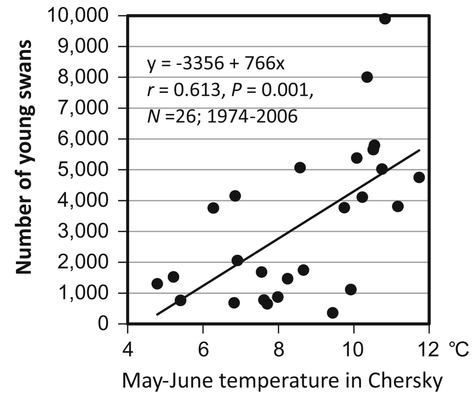

Fig. 9 The relationship between air temperature in the breeding area and the number of young Whistling Swans visiting Japan in winter. Based on data from Koike and Higuchi (2009)

Therefore, it is likely that the population trend of Whistling Swans is associated with the increase in temperatures (climate change) in the breeding, staging and wintering areas of Far East Asia.

Migrating birds: linking nature and people in different areas of the world

During my research on migratory birds, I felt strongly that these birds establish a link not only among natural environments in different countries along their migration routes but also among people in different countries. Here, I will discuss this link brought about by migratory birds and future issues concerning the relationship among the birds, the environment and human activities.

Each autumn and spring, enormous numbers of birds visit many areas along their migration routes. During migration, the birds obtain food and other things in these areas. Passerine birds eat insects and seeds in forests and grasslands, while shorebirds take sandworms, shellfish and crabs in tidal flats. Hawks prey on insects, frogs and snakes in forests and paddy fields; cranes, ducks and swans eat grass roots and seeds in wetlands and aquatic plants near water. Birds cannot continue their migration without such foods.

On the other hand, migratory birds are thought to play an important role in maintaining ecosystems in different areas through their food habits. If only a limited number of migratory birds exist, the population of certain insects, for example, may drastically increase in forests or grasslands through unbalanced nature in the ecosystem. In tidal flats or lakes, specific algae may grow densely and pollute the water.

These potential negative impacts are not well understood. During the course of evolutionary history, however, the ecosystems of different areas where many migratory birds stopover could not have functioned well without the existence of these migratory birds. Therefore, the population decline of migratory birds arising from habitat destruction in one area may cause an ecosystem to deteriorate in another distant stopover, breeding or wintering area. For example, the destruction of tropical rainforests in southeast Asia may decrease the number of tropical migratory birds that overwinter there and migrate to Japan in spring, resulting in unbalanced nature in forest ecosystems in Japan. The destruction of tidal flats in Japan may diminish the numbers of many shorebirds, and consequently cause wetland ecosystems to deteriorate in the Philippines, Australia or Russia.

Elucidation of these issues is a challenging subject for the future development of ornithology and ecology. Geographically, natural environments in different regions and countries exist separately, but in fact, are linked by migratory birds. The conservation of these birds is not only essential for their survival but also for the maintenance of remote ecosystems, eventually leading to the conservation of the entire global environment.

On the other hand, migratory birds also link people along the migration routes. Many people visit places along the migration routes to observe migratory birds. Each day during migration, hundreds or even thousands of people visit Shirakaba Pass in Nagano, Cape Irago in Aichi, and Cape Sata in Kagoshima, where Grey-faced Buzzards and Oriental Honey-buzzards fly over during migration. These people include not only hawk watchers but also many members of the general public. The general public cannot identify different hawk species but enjoy watching the migrating flocks, imagining their long journey for migration. Similarly, many people share the same experiences in different countries along the migration routes. People in Taiwan, Malaysia or Indonesia may enjoy watching the same flocks of the hawks that flew through Japan; in other words, migrating birds link different people in remote regions.

The most remarkable example of migratory birds being a link between people is the case where a Daurian Starling *Sturnus sturninus* became a link between an ornithologist and his son in North and South Korea, respectively. This example is summarized below Higuchi (2005).

It was before 1950. Wong Hong, an ornithologist in North Korea, and his youngest child, Pyong Oh, enjoyed watching birds and making skins together. When the Korean War began, the family was separated: the parents stayed in North Korea, while Pyong Oh and the other children went to South Korea. Afterwards, they could neither see nor correspond with each other.

After many years, Pyong Oh became a professor at Kyunghee University in South Korea. In May 1964, the Yamashina Institute for Ornithology in Japan received a letter from North Korea via Moscow. The letter was sent from an ornithologist of the Biological Institute of the Academy of Sciences. This letter said that he had found a banded Daurian Starling at Moranbon Park in Pyongyang that had a Japanese ring, and asked where the bird had been released.

The bird had actually been banded in Seoul, South Korea. It was Pyong Oh who had banded the bird. And it was Wong Hong, his father, who had inquired about the bird from North Korea. Thus, his father realized that his son had grown up to be an ornithologist in the South. Pyong Oh learned that his father was fine and continuing conducting bird research in the North. The bird's ring established a contact between the father and the son who had not met nor corresponded for many years. The demilitarized zone still divides North and South Korea. Birds, however, easily fly across this border. Thus, the Daurian Starling linked the father to his son even though the joy it provided was limited.

Migratory birds can be considered unique because there are few creatures that act as such a link between people. People living along the same migration route often share information on these birds. Such information is important in understanding the current state of the birds, clarifying the relevant conservation issues, and making action plans to solve their issues. By doing this, people share their delights and pleasures and realize the importance of connections with each other.

The benefits that migratory birds give us are of extraordinary value. Research on bird migration or ornithology that discovers such benefits is indeed a wonderful field of science.

Future challenges

Satellite-tracking proves to be a powerful research tool to study the migration of birds. Through this technology, we can show the details of migration routes, seasonal differences in migration pattern, and relative importance of each of the staging sites. Satellite-tracking is also very useful for clarifying the conservation issues that migratory birds encounter. Based on such information, we can make reasonable recommendations or good action plans for the conservation of focal species and their habitat (Higuchi et al. 2004; Higuchi 2010).

However, because of the weight of transmitters, satellite-tracking can be conducted only on large and medium-sized birds like cranes, swans, ducks, and hawks. As transmitters become smaller, the number of bird species that can be tracked is sure to increase. If additional improvements are made to battery life and location accuracy, it will become possible to obtain even more detailed tracking information for even longer periods of time.

Transmitters have been developed recently that use solar-powered batteries, which are expected to have a life of at least 2–3 years. This type of transmitter can reduce the weight of PPTs. The smallest solar-powered PTT weighs about 5 g, which is suitable to track birds in the 150–200 g range, such as medium-sized terns and sandpipers. Efforts have also been made to integrate the global positioning system (GPS) with the Argos system, known as the Argos/GPS PTT. Unlike an Argos PTT, a location can be specified using GPS systems as they receive coordinate data from satellites. In an Argos/GPS PTT, location data stored in the GPS are periodically retrieved through the Argos system.

GPS methods entail the use of many satellites, so they generally have greater location accuracy (to within dozens of meters with 1 standard deviation of the positional error) than the Argos system (150–1,000 m), and can provide many measurements per unit of time. Argos/GPS PTTs also have the benefit of reducing satellite usage fees because the data are sent over a shorter period of time. Although the tracking technology of system is ideal, the smallest solar-powered Argos/GPS PTT still weighs 22 g. Additional sensors can be used in conjunction with standard satellite-tracking PTTs. Integrated sensors are used to corroborate location findings. They include ambient light sensors to collect environmental data (e.g., temperature, air pressure, and altitude), or to record behavioral information (e.g., move or stay, heading and speed when the bird is flying). PTTs with such sensors are already available. However, the addition of sensors increases PPT weight, and the sensors may not function well in the field.

We expect to see several improvements in future, including the development of lightweight, high-performance devices that can be used on smaller birds and produced at lower cost. As highly accurate, less expensive devices come into use, a dramatic increase in conservation research on migrating birds can be expected.

Of course, satellite-tracking is not only the research tool to study the migration of birds. If we combine satellite-tracking results with other technologies such as radars and Geographical Information Systems (GIS) including satellite images, we will be able to obtain more detailed information on migration strategies and necessary conservation recommendations. Regular banding schemes and field observations are also necessary to confirm conclusions derived from relatively small numbers of birds that have been satellite-tracked. Further international and inter-disciplinary collaboration and cooperation will be required to promote such activities from now on.

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