

## Japanese Golden Eagle Conservation Science: Current Status and Future Needs

Rob OGDEN<sup>1)\*</sup>, Tomokazu FUKUDA<sup>2)\*</sup>, Takayuki FUNO<sup>3)\*</sup>, Mamoru KOMATSU<sup>4)\*</sup>, Taku MAEDA<sup>5)\*</sup>,  
Anna MEREDITH<sup>1,6)\*</sup>, Masaya MIURA<sup>4)\*</sup>, Haruki NATSUKAWA<sup>7)\*</sup>, Manabu ONUMA<sup>8)\*</sup>, Yuki OSAFUNE<sup>9)\*</sup>,  
Keisuke SAITO<sup>10)\*</sup>, Yu SATO<sup>11)\*</sup>, Des THOMPSON<sup>12)\*</sup> and Miho INOUE-MURAYAMA<sup>11)\*, \*\*</sup>

- 1) Royal (Dick) School of Veterinary Studies and the Roslin Institute, Easter Bush Campus, University of Edinburgh, Midlothian EH25 9RG, UK
- 2) Graduate School of Science and Engineering, Iwate University, 4-3-5 Ueda, Morioka, Iwate 020-8551, Japan
- 3) The Museum of Nature and Human Activities, Hyogo, 6 Yayoigaoka, Sanda, Hyogo 669-1546, Japan
- 4) Akita Omoriyama Zoo, 154 Hamadakatabata, Akita, Akita 010-1654, Japan
- 5) Iwate Prefectural Research Institute for Environmental Sciences and Public Health, 1-11-16 Kitaiioka, Morioka, Iwate 020-0857, Japan
- 6) Faculty of Veterinary and Agricultural Sciences, University of Melbourne, Corner Flemington Rd and Park Dr, Parkville, Victoria 3052, Australia
- 7) Graduate School of Environment and Information Sciences, Yokohama National University, 79-7 Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan
- 8) National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
- 9) Raptor Conservation Center, Ministry of Environment, 71-1 Kusatsuazayunodai, Sakata, Yamagata 999-8207, Japan
- 10) Institute for Raptor Biomedicine Japan, 2-2101 Hokuto, Kushiro, Hokkaido 084-0922, Japan
- 11) Wildlife Research Center, Kyoto University, 2-24 Tanakasekiden-cho, Sakyo-ku, Kyoto, Kyoto 606-8203, Japan
- 12) Scottish Natural Heritage, Silvan House, 231 Corstorphine Road, Edinburgh EH12 7AT, UK

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### ABSTRACT

According to current trends in census size and reproduction, the Japanese golden eagle (*Aquila chrysaetos japonica*) is at risk of extinction this century, leading the Japanese government to recognize the subspecies as endangered. It is now the focus of national conservation efforts, yet gaps remain in our knowledge regarding the reasons for the observed population decline and how best to improve the situation. Over recent decades, scientific research concerning golden eagle conservation in Japan, and in other parts of the world, has established a multi-disciplinary body of evidence that should support plans for species restoration. However, until now, these strands of research have been largely separate, limiting the potential benefits offered by an inter-disciplinary approach. In this paper, we provide an integrated review of Japanese golden eagle conservation science, including studies of ecology, genetics, veterinary health and habitat management. We assess the status and trends in the wild and captive populations; identify current and future conservation management interventions and discuss the opportunities for taking an integrated approach to Japanese golden eagle conservation science through *in-situ* and *ex-situ* viewpoint. This review, prepared by national and international experts in golden eagle biology and health, describes outstanding scientific questions alongside potential practical solutions. It sets out a framework for applied research that will provide the information and techniques required to successfully reverse the decline in golden eagle numbers, and hopefully secure the long-term future of the species in Japan.

Key words: conservation management, eagle, *ex-situ* conservation, *in-situ* conservation

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\* The Scientific Working Group on Japanese Golden Eagle Conservation

\*\* Corresponding author : Miho INOUE-MURAYAMA (E-mail: mmurayama@wrc.kyoto-u.ac.jp)

## INTRODUCTION

The golden eagle (*Aquila chrysaetos*) is an iconic bird species distributed circum-globally at temperate latitudes in the northern hemisphere. It features strongly in the cultural history and traditions of people from many regions including Europe, North America and Japan. While the total number of wild individuals remains relatively high and the species as a whole is classified as Least Concern by the IUCN Red List, its constituent populations are considered to be under greater threat with some countries experiencing severe declines in population numbers during the past hundred years. This is important from a conservation perspective for a number of reasons. Demographic declines in multiple isolated local populations increases the risk of extirpation at a regional scale; a trend that would rapidly threaten the survival of the species as a whole, but which is masked by the global nature of the species distribution. Loss of local populations can also lead to significant loss of genetic diversity within a species, reducing its resilience to ongoing environmental change. Again, this gradual loss of genetic diversity within species goes relatively unnoticed compared to the total census size of the species, but once lost cannot be recovered over a relevant conservation timescale.

The Japanese golden eagle (*A. c. japonica*) has been effectively isolated from the Asian continent since the end of the last ice age (~20k years before present) and lives in a densely forested steep mountainous landscape quite distinct from most other golden eagle habitats around the world. While any functional biological differences between Japanese and other golden eagle subspecies have yet to be established, anecdotal reports of morphological differentiation combined with its distinct demographic and ecological situation make it likely that Japanese golden eagles comprise a unique bird population of conservation importance. Declines in both the population and breeding success have led the Japanese government to recognize the species as nationally endangered and it is therefore the focus of considerable national conservation efforts.

The application of science to inform wildlife management is fundamental to modern conservation practice. Scientific data can be used to characterize the nature of population declines, investigate their various causes, support practical solutions and help forecast and monitor the outcome of

proposed conservation management interventions. A gradual accumulation of scientific data concerning golden eagle conservation in Japan, and in other parts of the world, has established a multi-disciplinary body of evidence that should support plans for species restoration. However, until now, these strands of research have been largely separate, limiting the potential benefits offered by an inter-disciplinary approach. In this paper, we provide an integrated review of Japanese golden eagle conservation science, drawn from leading researchers in Japan and the United Kingdom and brought together through a scientific workshop on golden eagle conservation research held in Japan in April 2018.

The review is structured into three parts: i) Understanding the reasons for population decline; ii) Management interventions for population sustainability; and, iii) Integration of wild and captive populations. Within each part, consideration is given to ecological, veterinary, genetic and habitat management research themes, to provide a comprehensive picture of existing knowledge, current needs and future options relating to the conservation of the golden eagle in Japan. The aim of the review is to present the golden eagle conservation community, led by the Ministry of the Environment, with the necessary information to plan and implement an evidence-based conservation strategy for the coming decades. The approach should also be applicable to conservation attempts for other endangered raptor species in Japan, and in other countries.

### Current estimates of population size and distribution

The Ministry of the Environment conducted the "survey of rare birds of prey" between 1997 and 2001, in cooperation with the Agency for Natural Resources and Energy, the Ministry of Land, Infrastructure and Transport, and the Forestry Agency. The survey results, announced in 2004 [1], revealed an estimated population size of 260 pairs of Japanese golden eagles within a total maximum population of 650 birds. These official figures have been used widely as a reference baseline for conservation management but are now considered to be out of date. According to the more recent "nation-wide golden eagle habitation/breeding situation survey", which "Society for Research of Golden Eagle Japan" (SRGE-J) has been implementing since 1981, it was estimated that in 2015, the newest estimation date, there were around 500 birds in Japan [2]. Importantly, in the 33 years up to 2015, 107 pairs

of Japanese golden eagles are reported to have disappeared. At a regional level, the Tohoku district environmental office of the Ministry of the Environment has also started gathering information on the habitat and breeding status of the Japanese golden eagle within the Tohoku district using a questionnaire, with 74 pairs confirmed in 2017 [3].

The Ministry of the Environment has surveyed the distribution of Japanese golden eagles since 1997 by field observation and a questionnaire sent to local bird watchers and field researchers [1]. This survey reveals that wild Japanese golden eagles are distributed mainly in the central to north part of Honshu mainland, especially in Iwate prefecture and the Koushin-etsu area (Figure 1). Previously, nests were observed on Kyushu and Hokkaido; however, currently, few breeding events have been reported on Kyushu, and nests are not confirmed on Hokkaido [4].

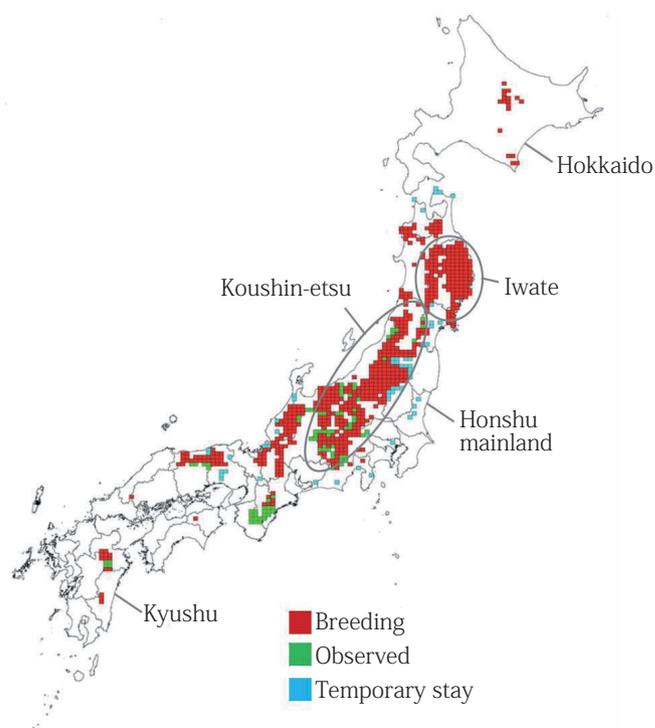
## 1. Understanding the reasons for population decline

The effectiveness of any conservation intervention is dependent on how well it addresses the underlying causes of the observed population decline. Without a thorough assessment of the historic factors that have led to the current population status of golden eagles in Japan, it is unlikely that future management actions will result in the long-term sustainable conservation of the species. While immediate interventions may be necessary to prevent short-term, acute population losses, it is also essential that appropriate research is undertaken and integrated across disciplines to generate a comprehensive understanding of why the Japanese golden eagle has declined in number over the past century or more. In this first section, various ecological, veterinary, genetic and environmental factors affecting Japanese golden eagle biology are considered in terms of their potential impact on recent subspecies demography.

### 1-1. Ecology

#### 1-1-1. Breeding success - Annual nest site surveys

Nest site surveys usually begin with detecting breeding pairs and locating their nests, and this step often requires considerable time and effort. Following the discovery of nest site locations, remote visual monitoring of the breeding process is the principle method to assess the reproductive performance of golden eagle populations. These surveys in Japan are typically carried out by local eagle watchers who mostly belong



**Fig. 1** The distribution of golden eagles in Japan based on survey data collected between 1990 and 2002 (modified from the Ministry of the Environment report, 2004). Wild golden eagles are distributed mainly in the central to north part of Honshu mainland, especially in Iwate prefecture and the Koushin-etsu area. The current distribution of breeding birds is likely to be smaller than shown here, for example there are no recent breeding records for golden eagles on Hokkaido. Maintaining and updating accurate distribution maps is essential for effective conservation management.

to the nationwide non-governmental organization, SRGE-J, established in 1981. Research implemented by government agencies is relatively rare and limited to certain time periods, except for Iwate Prefecture in the northern part of Japan where dedicated government researchers have continuously monitored all known nest sites since 2002 [5].

Although it is very difficult to complete an inventory of all breeding sites in Japan, the available information on nest distributions is considered sufficient to allow a rough estimation of the population. SRGE-J estimated the population of the golden eagle in Japan to be about 500, including immature birds, and they also report the conspicuous increase of abandoned breeding sites since 2000, suggesting a critical

reduction in the population [2]. This coincides with a decrease of productivity: one breeding pair produced 0.4-0.5 fledglings every year in 1980s, 0.2 fledglings in 1990s and 2000s, and fewer than 0.2 fledglings in 2010s [2]. Using mathematical modeling, Yui indicates that a productivity rate exceeding 0.31 fledglings every year is necessary for population sustainability [6].

Because nest site monitoring has usually been performed through discontinuous visual observation, the immediate causes of breeding failure are seldom ascertained. Continuous observations using technologies such as remote video monitoring system have been applied to a proportion of nest sites to reveal valuable information concerning the reasons for interruption in breeding activity, such as predation, extreme weather or food shortages [5].

#### 1-1-2. Prey availability - Prey use surveys

In Japan, the golden eagle's main preys are the Japanese hare (*Lepus brachyurus*), the copper pheasant (*Syrmaticus soemmerringii*), and snakes of various species [7], with snakes alone making up between 20% and 60% of the typical diet [7-9]. These percentages are much higher than those of any other subspecies widely distributed in the northern hemisphere [10]. In the Hokuriku region in the northwestern part of Japan, golden eagles switch from primarily hunting Japanese hares to hunting snakes after deciduous broad-leaved trees come into leaf [8]. However, the eagles receive fewer nutrients from snakes and digest them at a slower rate than the Japanese hare [11]. In addition, the amount of prey the eagles deliver to their nest sites dramatically decreases after they switch from hunting Japanese hares to hunting snakes [8]. As a result, the fledging date of nestlings fed many snakes, has been found to be delayed by up to 16 days and the fledgling birds were smaller than in the nests of pairs that did not switch prey during the nesting period. As golden eagles transit to specialized feeding on snakes as the leafing period advances, the corresponding reduction in food quantity affects the growth of their chicks.

In the 1970s, a golden eagle researcher in Iwate prefecture observed various prey species at the nest site during the leafing period (Sekiyama, unpublished data). In the 1980s, the SRGE-J reported that golden eagle's prey in Japan included 5 families, 10 genera, and 30 species [7]. Researchers first reported specialized feeding on snakes as the annual timing of

deciduous leafing advanced during the 1990s [8]. These long-term changes in prey use presumably affect the breeding and population status of golden eagles in Japan.

#### 1-1-3. Dispersal - Satellite tagging

The design of effective conservation management measures for the golden eagle in Japan relies on comprehensive knowledge of the life history of the eagles across their distribution, including patterns of juvenile dispersal and adult flight patterns and habitat use. Tracking the movement of individual birds can provide vital information concerning territory size, prey availability, mating patterns and the potential risks and causes of mortality in golden eagles. In Scotland, the movements and fate of golden eagles has been extensively studied through the use of satellite transmitters ('tags') attached to birds. Tags were deployed between 2004 and 2016, collecting data on 131 birds from fledging onwards, usually for around two to three years, generating spatial maps that summarise over half a million locations recorded during the study period [12]. Extensive analysis of the effects of tags on birds was performed but no evidence that satellite tagging of golden eagles in Scotland causes any harm to tagged birds, either physically, behaviourally, or demographically was discovered.

The Scottish satellite tagging study has provided a wealth of data on the movement of golden eagles, but also on their likely causes of death. The survival of young birds from fledgling through juvenile development to adulthood is a critical period in the life history of golden eagles and the satellite data was able to provide evidence of where, when and in some cases how juvenile mortality occurred. Such information would be highly informative to Japanese golden eagle conservation, where much remains unknown about the fate of juvenile birds after they have dispersed, but for whom the population data suggest are not surviving to successfully reproduce in adult life.

#### 1-2. Veterinary health

As apex predators, raptors can act as important sentinels and indicators of ecosystem health, through direct and indirect exposure (bioaccumulation) to pathogens and toxins. In golden eagle populations, the impacts of infectious diseases such as avian influenza, and non-infectious disease, such as the effects of toxicants including rodenticides, poisons, pesticides, and

heavy metals, are poorly studied and understood. However, it is known that such challenges can act in conjunction with other factors such as prey availability, environmental conditions and other stressors to influence immune status. Acute and sub-lethal exposure to toxicants are known to have detrimental effects on breeding and mortality in adult golden eagles and white-tailed eagles (*Haliaeetus albicilla*) [13, 14], depression of respiratory and immune systems, and decreased growth and reproduction of scavenging birds [15]. Golden eagles in Europe have been shown to have excessive but sub-lethal levels of lead exposure [16] and studies in Sweden have shown that this can have an effect on movement behaviour [17].

In Japan, large birds of prey such as Steller's sea-eagle (*Haliaeetus pelagicus*), white-tailed eagle, Japanese golden eagle and mountain hawk-eagle (*Nisaetus nipalensis*) are known to suffer poor health and sometimes mortality due to lead poisoning, which has become an increasing environmental issue since the latter half of the 1990's [18]. In Hokkaido, deer hunting is popular and the deer carcass is usually butchered at the hunting ground when the inedible parts such as the gunshot wound and internal organs are left behind. Birds of prey subsequently ingest fragments of the lead bullets, resulting in severe lead poisoning. Lead poisoning of birds of prey caused by lead bullets has been confirmed in nearly 200 cases since it was first discovered in Steller's sea eagle in 1996 in Japan. One characteristic of lead poisoning in eagles is that many adults die, probably due to the fact that ecologically dominant adults monopolize fresh carcasses rather than young eagles [18].

In Hokkaido, from February 2000, when regulations banning the use of lead bullets began, until April 2017, when the study period ceased, 88 Steller's sea eagles and 42 white-tailed eagles were recorded as suffering from high concentrations of lead. A survey of the origin of lead by stable isotope ratio analysis revealed that most lead poisoning in birds of prey is due to lead rifle bullets [18]. Currently, lead poisoning of birds of prey is still occurring. The situation indicates that lead bullets are being brought into Hokkaido by hunters from Honshu where there is no regulation on the use of lead bullets, despite the fact that high concentrations of lead have been confirmed in Japanese golden eagles and mountain hawk-eagles in Honshu through collaborative research between the Institute for Raptor Biomedicine and Hokkaido University [19].

In Scotland, an extensive project has been underway since

2016 to comprehensively investigate the health status of golden eagle populations for the first time, in response to inexplicably low productivity and poor fledging success for the species in different parts of Scotland. This is achieved by sampling dead individuals submitted through an established network of professional and voluntary raptor workers, and live fledglings on the nest, and application of standardised health screening protocols and sample analysis, including lead and other heavy metals, rodenticides and pesticides.

### 1-3. Genetic factors in population decline

#### 1-3-1. Genetic diversity and inbreeding

As populations decline, genetic diversity decreases and the level of inbreeding typically increases. In turn, inbreeding can reduce the fitness of offspring, lowering life-time reproductive success and contributing to further population declines. This process, recognized as part of the so-called 'extinction vortex', is very difficult to prove empirically, but represents a serious theoretical risk to population sustainability. It is therefore important to understand historic and current levels of genetic diversity and individual relatedness, and to establish a baseline for future comparison as part of conservation genetic management strategies. Genetic research on wild and captive golden eagles revealed that the two populations currently display broadly similar, reasonably high levels of genetic diversity [20]. Furthermore, molecular estimates of inbreeding coefficients for wild (Iwate;  $F=0.08$ ) and captive ( $F=-0.07$ ) populations were fairly low suggesting that there is no evidence of inbreeding in either population. However, results for the captive population are based largely on the founder and first generation (F1) individuals and inbreeding is expected to increase rapidly in future given the current skew in reproductive effort.

From a technical perspective, the current methods available for pairwise kinship analysis showed a large degree of overlap among different levels of familial relatedness [20], indicating that the 16-microsatellite DNA marker system in use has limited power to detect relatedness and accurately estimate inbreeding. To address this problem, genome wide large-scale data from thousands of single nucleotide polymorphisms (SNPs) has recently been generated, establishing the potential to reconstruct wild pedigrees [21, 22]. Given the limitations of the current molecular genetic tools, it is not possible to rule out a lack of diversity in the wild as a contributing factor in

population declines, however there is no strong evidence for inbreeding depression at this time. However, as the population continues to decline is increasingly likely that genetic factors will come into play.

### 1-3-2. Genome sequencing

To understand the demographic history and to reveal the starting point of population decline in Japanese golden eagles, a technique that uses the entire sequence of the golden eagle genome is currently underway. Pairwise sequential Markovian coalescent (PSMC) analysis [23] is being employed to estimate the effective population size from between ten thousand to ten million years ago in order to identify not only the start of population decline but also the time of separation of the Japanese subspecies from other golden eagles. Through analysis of historic population fluctuations, it is hoped that this research will provide insights into how genetic diversity has changed over time and help predict the outcomes of future population changes or management interventions, such as possible translocations from outside Japan.

### 1-4. Ecosystem and habitat factors in population decline

Japan is among the world's most densely forested countries. Nearly 70% of the land in Japan is forested. In the past, timber was the most important forest resource in Japan; it was used for firewood, charcoal, building materials, and pulpwood. In the 1940s, when the Japanese logging industry was the most active, deforested areas reached a maximum of 900,000 ha per year [24]. From the 1950s to the 1960s, the deforested areas replanted with nursery stock averaged around 350,000 ha per year [25]. However, in the 1970s, increases in timber imports caused the price of domestic timber to stagnate. As a result, the demand for domestic timber in Japan decreased, and rates of deforestation dropped to around 300,000 ha per year – one third of its peak [24]. In addition, after the 1980s, the planting of nursery stock declined from around 350,000 ha per year to around 100,000 ha per year [25]. The effects of these changes are that Japan's mountainous environment is covered in artificially dense plantation forest.

The golden eagle's foraging habitats in Japan include grassy and rocky areas as well as gaps in forests where typhoons or avalanches have caused trees to collapse; these habitats are now rare in forests. Before the 1980s, both deforested and nursery stock planting areas were distributed widely within

forests, which seemed to support golden eagle breeding and population status. However, the number of deforested and nursery stock planting areas dramatically decreased after the 1980s. This change in land use could be one of the critical factors in the population decline of golden eagles in Japan. To address this issue, the creation of deforested areas and planting areas for nursery stock with arterial forest thinning have been implemented for maintaining golden eagle foraging habitats in Japan; however, the results of such interventions are not yet known.

### 1-5. Summary

Overall, based on the evidence presented here, the primary reason for Japanese golden eagle population decline to date is considered to be reduced breeding success due to land use change that has resulted in a reduction in both the availability of optimal prey species and suitable habitat for hunting. The additional issue of lead poisoning may well be a contributing factor. While genetic diversity cannot be identified as having had a detrimental effect to date, the numbers of Japanese golden eagles are now so low that inbreeding may well begin to negatively impact population breeding success in the short to medium term.

## 2. Management interventions for population sustainability

Given our current understanding of the causes of Japanese golden eagle population declines, described above, a number of proposals have been made to improve the conservation of wild golden eagles in Japan. A number of these proposals have been implemented and experimental management strategies are being tested to evaluate their success. Other proposals have not yet been explored, or require further research work to assess their utility. In this section, a number of potential interventions for sustainable management are presented across the disciplines of ecology, veterinary health, genetics and landscape management; in each case their potential importance and effectiveness for supporting golden eagle conservation is discussed.

### 2-1. Ecology

#### 2-1-1. Supplementary feeding

The sustainability of raptor populations is known to be particularly vulnerable to deterioration in food availability, which may occur due to stochastic natural variation

or anthropogenic environmental change. Accordingly, supplementary feeding is a common option in raptor conservation programmes, of which there are many successful examples [26]. An official feeding programme for raptors in Japan has been conducted since 1984 by the Environmental Agency to support the Blakiston's fish owl (*Ketupa blakistoni*), and their population has recovered twice due to this programme in cooperation with other conservation measures such as the provision of nest boxes [27]. Since the Japanese golden eagle is also faced with a problem of food availability [28], supplementary feeding has been proposed as an immediate solution to their reduced reproductive success.

In Fukui Prefecture, a feeding programme for four breeding pairs of golden eagles was conducted from 1996 to 2000 [29]. Live disease-free rabbits and carcasses of various wild animals were used as prey and provided for the eagles approximately once a week at the major hunting grounds. Two breeding pairs displayed marked and slight improvements in breeding success, respectively, but two other pairs did not use the food provided. In Iwate Prefecture, two breeding pairs have been fed since 2009, but no clear improvement in breeding success has been detected even in the years when increased utilization of supplementary food was observed [5]. In other areas, unofficial supplementary feeding is likely to be performed, but there is no information available on the methods used or subsequent outcomes.

The cases in Fukui and Iwate suggest that the responses of the eagles to supplementary feeding are diverse and the expected positive response in breeding success was not necessarily realised, though further experiments using different amounts and intervals of food supply would be important to verify these findings. Providing food direct to the chicks in the nests may be more efficient than feeding to their parents in the hunting grounds, but that is unlikely to be a realistic option for the majority of the nests in Japan because of severe difficulty in accessing the nest sites. Nevertheless, ongoing development of techniques for supplemental feeding is important because it will likely be an essential component of future golden eagle conservation programmes, such as the release of the captive-bred individuals to the wild to reinforce the declining population. Supplementary feeding has been demonstrated as an important, short-term strategy immediately after the release of golden eagles and during winter months in Scotland [30].

## 2-1-2. Population Viability Analysis modelling in wild populations

The objective of Population Viability Analysis (PVA) is to determine whether certain species and populations are viable in their habitat [31]. PVA trials are increasingly used to provide ecological knowledge for decision-making in the conservation of endangered species. PVA requires estimates of population parameters such as the breeding success of the species and population, age-specific mortality rate, average life expectancy, and dispersal. Based on these inputs, a stochastic population dynamic model is used to assess the extinction probability of a population within a certain period of time. In addition to the extinction probability, PVA provides important information for conservation decision-making, such as the approximate timescale of population declines and the Minimum Viable Population (MVP) size. PVA can also predict the effect of conservation plans, allowing alternative proposals to be assessed. PVA performed using sufficient data is one of the effective tools that can aid the conservation decision-making process.

Initial PVA results for Japanese golden eagle populations inhabiting the Kitakami Mountains in Iwate Prefecture, estimate that assuming a closed population without dispersal, the extinction probability of the eagle is 31.0% over the next 50 years (Natsukawa and Maeda, unpublished data). However, in this analysis, the data available to set parameters such as age-specific mortality rate, average life expectancy, and dispersal in the Japanese golden eagle were not readily available and instead these parameters were estimated from previous studies of other subspecies (e.g. [32]). To avoid the assumptions involved in this approach, it is recommended to collect Japanese data for the aforementioned parameters and thereby improve the accuracy of the PVA. Furthermore, by conducting PVA throughout Japan, estimates of extinction risk and MVP can be used to help predict the effectiveness of national conservation planning for the Japanese golden eagle.

## 2-1-3. National population monitoring

Maintaining the long-term monitoring of golden eagle populations in Japan to generate reliable, comparable data on the numbers, locations and breeding success of birds is central to our understanding of conservation status and management planning for the species. The value of regular monitoring is hard to underestimate and is considered necessary to support

sustainable management of the species in the wild. At present, with some notable exceptions such as Iwate prefecture, most golden eagle monitoring studies are conducted by volunteers. This means that it would be impossible to devise effective conservation measures in the absence of enthusiasts and voluntary researchers who are dedicated to serious conservation research for the species. The increasing age of researchers currently conducting the surveys and the shortage of successors is considered a serious threat to the future of the long-term monitoring programme and therefore to sustainable management in general.

Despite the commitment of the current monitoring community, the level of information that can be obtained from distant visual observation of nest sites remains limited. To address this issue, several investigations are being conducted to evaluate alternative methods for detecting breeding success via comparison to direct observation. The installation of CCD (video) cameras and infrared automatic cameras (camera traps) that are combined with communication functions such as mobile radio and WiFi are being trialed, with care taken to minimise disruption to the birds. It is hoped that these studies will guide future long-term monitoring that can both relieve the pressure on the voluntary monitoring community while increasing the level of information obtained at each nest site. Such remote monitoring may also enable real-time detection and intervention in the case of severe risks posed to chicks, such as nest collapses or threats from predators, where nest-specific measures may be taken to improve survival; however, it should be noted that technological monitoring solutions require funding.

Beyond the installation of fixed monitoring technologies at multiple nest sites, the use of UAVs (Unmanned Aerial Vehicles (or drones)) is also being considered as a new method for golden eagle monitoring. The value of human intervention at nest sites, for example in repairing nests (improvement of nest structure), collecting dead chicks and unhatched eggs, or attachment of wingband markers, has been widely demonstrated [5, 33-36]. However, manual interventions require specialist techniques and involve climbing, extreme physical fitness and high altitude rope work; all of which have profound safety and high cost implications. Furthermore, without prior knowledge of what has occurred within a nest, manual inspection may result in wasted effort. The potential use of drones to visualise the nest from above and to assess the

situation in advance, would improve the efficiency of manual interventions. Depending on the requirements, techniques such as the collection of genetic samples (feathers or eggshells) may also be developed as applications for drones. The portable nature of drones may also significantly decrease the cost and effort of nest monitoring compared to fixed technologies. However, before the widespread deployment of such UAV solutions, studies are required to evaluate the potential for interference and conflict with adult eagles attending the nests.

It is striking that in Japan, to date, there has been no monitoring of golden eagles performed utilizing GPS transmitters and satellite tracking, despite their use in various other species in Japan and in golden eagles in Scotland (See Section 1.1.3). For surveying adult birds, it is suggested that consideration is given to the use of satellite tracking to learn more about the life history and movement patterns of the species in Japan.

Overall, given the conservation management importance of maintaining long-term monitoring records for golden eagles, and against a background of future limits on the number of manual inspections possible at nest sites, it is suggested that the evaluation and use of various technologies should be implemented to support enhanced, sustainable monitoring of individual birds.

## 2-2. Veterinary health

### 2-2-1. Post mortem examination

A range of veterinary applications within the field of conservation medicine is available to support golden eagle populations and should be considered as components of any sustainable management plan. Post mortem examination, including radiography, to establish the cause of death, is vital to improve our understanding of golden eagle health, and provide evidence for traumatic injury or illegal persecution. It also offers the opportunity to analyse carcasses for exposure to a variety of infectious and non-infectious agents which may be contributory factors to poor health or reproductive failure. Acquisition of fresh carcasses in a timely manner is challenging, especially in remote areas, and the establishment of co-operative networks and clear guidelines and routes for submission are required to facilitate such studies [37].

### 2-2-2. Live chick surveys

Where possible, live chicks on accessible nests should be

sampled and fitted with leg rings (and if required, satellite transmitters) to facilitate long term monitoring. Body weight, morphometric data, blood samples (haematology, biochemistry, serology, toxin analysis) and cloacal and choanal swabs (bacteriology, virology, parasitology) can be quickly obtained with minimal stress by experienced handlers and veterinarians using protocols developed for other raptor species [38, 39]. Examination of contemporaneous data from other sources on other variables such as weather, habitat, and prey species populations can be incorporated in multivariate analysis. Nutritional status can be assessed by body condition and blood parameters (e.g. glucose, uric acid levels; packed cell volume). Indications of prey species presented by parent birds can be assessed from remains in the nest, and any available castings [40]. In addition, both post-mortem and live sampling allow tissue or blood cells to be harvested for DNA analysis and the archiving of samples such as serum for future studies [39].

### 2-2-3. Disease surveillance

In order to implement a standardized set of health surveys across multiple birds, a set of protocols should be developed that describe the collection, analysis and result interpretation for samples obtained from live birds and post mortem individuals. Such veterinary surveillance protocols will allow any veterinarian working with golden eagles to collect comparative samples and data that can contribute to a population-wide survey of golden eagle health, enabling researchers to identify any associations between condition and environment, for example from evidence of exposure to toxins such as lead or chemical contaminants [41, 42].

## 2-3. Genetics

### 2-3-1. Examination of population structure

The use of different DNA markers (or regions) in the population genetic analysis of wild species allows conservation geneticists to assess genetic diversity and identify population structure across a species range. In the case of Japanese golden eagles, two regions of mitochondrial DNA (Control Region: CR, pseudo Control Region:  $\psi$  CR, [43, 44]) and sixteen nuclear DNA microsatellite markers [45] have been analysed to examine population structure. Mitochondrial DNA analysis revealed that the wild population maintains six CR haplotypes (types of DNA sequence) and three  $\psi$  CR haplotypes, producing nine CR +  $\psi$  CR haplotype combinations.

These haplotypes were observed from eight sample collection regions in Japan, but Iwate prefecture alone displays seven of the nine haplotype combinations. Microsatellite analysis revealed no population genetic structure among wild (Iwate) birds, wild origin rescued captive birds, and captive bred birds [20]. These results suggested that there is little or no phylogeographic structure within Japan, and consequently it is reasonable to manage the species as a single population unit. However, the majority of samples were collected from Iwate only and it is therefore necessary to expand the collection of reference samples across Japan to confirm this apparent lack of population genetic structure. Sample collection from nest sites remains challenging and expensive, as the nests of golden eagles are located in deep forests and on steep cliffs. One of the most important requirements for genetic monitoring is to establish effective protocols for sampling in the wild. Among the candidate solutions, there is particular interest in the use of drones for collecting feather samples from nests during the non-breeding season.

### 2-3-2. Ageing

Estimating the age of individuals in wild populations is beneficial to assess likely reproductive success. In the case of Japanese golden eagles, breeding success rate has decreased steadily from the 1970's, and is now around 20% across Japan [4]. One of the reasons for this might be an ageing adult population, but it is difficult to accurately estimate the age of individual birds and thus to determine the age structure of wild golden eagles. DNA-based analysis methods may be able to provide such information.

Age estimations using analysis of DNA methylation patterns have been reported for chimpanzee (*Pan troglodytes*) [46, 47]. Some studies have also applied this technique to avian species such as chicken (*Gallus gallus*) [48], great tit (*Parus minor*) [49], and barn swallow (*Hirundo rustica*) [50]. Most of the studies used blood samples, and demonstration of the technique using noninvasive samples is rare [51] and remains under development even in mammals. However, age estimation from DNA methylation has great potential to reveal age structure and reproductive ability in the Japanese golden eagle population using noninvasive DNA from feathers and feces.

### 2-3-3. Subspecies comparison

It was reported that the karyotype of Japanese golden eagle

( $2n = 62$ ) is different from the European golden eagle (*A. c. chrysaetos*) ( $2n = 66$ ), and this is because of the different number of microchromosomes (8 in Japanese and 10 in European) [43, 52]. This suggests the possibility of nuclear differentiation between the Japanese and other subspecies. Currently, one founder male that has given rise to offspring in the Japanese zoo population has been questioned by zoo keepers with regard to its subspecies identity different subspecies because of its body size and mtDNA haplotype data, and this entire family is currently excluded from breeding program. To solve these problems, it is necessary to understand whether or not any significant nuclear DNA differences exist among the subspecies. Research is currently underway to assess the karyotype (chromosomal number) among samples in Japan and from different subspecies.

In addition, the Japanese golden eagle is only a subspecies which has adapted almost exclusively to mountainous deep forest. To aid the recovery of this subspecies from current population declines, translocation of individuals from other subspecies is one optional solution. As habitats among subspecies differ and levels of local habitat adaptation are unknown, further investigation is required to reveal any functional genetic differences among subspecies when considering the effectiveness of inter-subspecies translocations.

#### 2-3-4. Cell line production

In terms of biodiversity conservation, primary cell banking is one of the options for ex situ conservation. The San Diego Zoo Institute for Conservation Research has pioneered the cell banking of zoo and wild animals within its Frozen Zoo®. In Japan, the National Institute for Environmental Studies (NIES) has been cryopreserving the primary cells of endangered species (mainly avian and mammalian species) since 2002. The NIES collections include cells derived from the skin tissue “Critically endangered species” such as the Japanese crested ibis (*Nipponia nippon*), the Okinawa rail (*Gallirallus okinawae*) and Okinawa Woodpecker (*Dendrocopos noguchii*). These same researchers have also given examples of the utilization of cells derived from endangered species for conservation applications, such as genetic rescue, through somatic cell nuclear transfer cloning, and establishing induced pluripotent stem cells [53]. Such techniques combine with cell banking and the establishment of golden eagle cell lines, will play an important role for the conservation of this species.

At present, there are no cell lines derived from the tissues of golden eagles; however, techniques for culturing primary cells and cryopreservation of cells from avian skin and muscle tissues have already been established. According to the information of Japanese Association of Zoos and Aquariums (JAZA), there are nine zoos housing the Japanese golden eagle [54]. These individuals are potential sources for tissue sampling. Establishing immortalized cells via gene transfection in zoo animals has been reported [55], thus there is a high possibility for establishing golden eagle cell lines from the captive population in Japan.

## 2-4. Landscape and habitat management

### 2-4-1. Linear felling

In Japan, with forested areas covering about 70% of the country, forestry has been one of the primary industries. However, with increasing import of foreign timbers, the price and the production of domestic timbers have been reduced, tree plantations have matured and this has led to a decrease of suitable open hunting grounds for the golden eagle, such as clear-felled lands and young plantations. Their breeding success in Iwate Prefecture is positively correlated with the availability of young plantations, shrub-lands and grasslands in their home ranges, including adjustment for the effects of weather and nest site conditions [56].

Constant provision of open areas by harvest felling is desirable to encourage reproductive success, but it is hard to achieve for most forests under the current social and economic conditions. As an alternative idea, linear-felling has received much attention. Linear-felling is a thinning method for afforestation areas, basically employed as logging 1-2 rows and leaving 2-4 rows intact. It provides stripped open areas as hunting grounds, which rarely appear in conventional selective-felling. It has been confirmed that populations of the Japanese hare, a principal prey of the golden eagles in Japan, increase after linear-felling [57-59], but as yet, the anticipated positive impact for hunting and reproduction of the golden eagle is indistinct, probably because the scale of experiments to date was not large enough in contrast to their natural home range. However, long-term observations have revealed that flying frequency of Japanese golden eagles tends to be higher in linear-felled sections comparing to the same section before felling and other intact areas [58], suggesting increased habitat use by Japanese golden eagles in linear-felled areas.

It should be noticed that linear-felling has modest effects for providing hunting grounds in comparison with clear-felling for harvest and that the benefits to Japanese golden eagles generally lessens within a couple of years of felling as forest gaps close. Therefore, improvement in the habitat quality using linear-felling would be more successful when employed repeatedly at an extensive scale. The Forestry Agency has recommended linear-felling as a standard management method in the national forests, but its spread into private forests is still limited.

#### 2-4-2. Artificial nest improvement

While prey availability is considered to be a major factor in the low productivity of Japanese golden eagles, it is also known that breeding failures are often caused by predation of eggs and chicks and by accidents such as the collapse of nests, and falling rocks and snow. In recent years, many Japanese golden eagles have been disturbed during breeding by heavy rain and snowfall brought by rapidly developing storms. For the protection of eggs and chicks from these harmful incidents, providing safe nests is an important issue, and many case studies have been conducted.

In the case of nests on rock cliffs, artificial structures such as eaves to shelter from rain and snow have been constructed, with the basal metal frames to prevent slippage of nest materials (e.g. branches and twigs) and fences to avoid mammalian predators, e.g. Asian black bear (*Ursus thibetanus*) [5]. Additional actions to maintain nest site conditions such as a reduction in excessive nesting materials, the felling of obstructive trees for eagles' passage and the digging out of rocks to enlarge the nesting shelves have been applied whenever necessary [60]. Although not many cases of tree nests are known, the stabilization of such nests by wooden or metal bars and mammal tree-climbing deterrents such as metallic trunk covers have been applied [5]. Techniques for avoiding snowfall onto tree nests are absent to date, and their future development is desired.

To date, there is no evidence that Japanese golden eagles display cautionary or avoidance behavior towards the artificial structures or the alterations in and around their nests, which are constructed during the post-breeding season. On the contrary, abundant evidence exists to show the success of nest improvements on breeding activity [5, 34, 61, 62]. Notably, because a pair of Japanese golden eagles uses only one nest for

breeding each year among several nests within their territory, the efficiency of the nest improvements should be considered from a long-term viewpoint, as although such operations may not have any effect in the subsequent breeding season, when the pair use a different nest, they are highly likely to return to the improved nest over a 3-4 year cycle.

Artificial nest construction at sites where golden eagles have never nested has not been reported, but it is technically possible. Some attempts at new nest constructions for Japanese golden eagles on the sites where the original nests have already disappeared were successful [5]. Furthermore, many attempts at new nest provision for the northern goshawk (*Accipiter gentilis*) and the mountain hawk-eagle at sites distant from current nests have yielded good results [63, 64], suggesting possible application to Japanese golden eagles. If attraction to artificial nests that are secure from storms and predators is realistic, their contribution to the conservation of Japanese golden eagles may be significant.

#### 2-5. Summary

A very wide variety of possible conservation interventions is being implemented or considered to help mitigate possible threats to the Japanese golden eagle. These have been presented here according to discipline, but may also be considered as either short- medium- and long-term approaches, or as established versus experimental solutions. Genetic rescue via cell-line biobanking represents a hi-tech and arguably futuristic approach, but one that may carry significant long-term benefits. Similarly, the benefits of including Japanese golden eagle conservation needs in tree-planting strategies will only be realized over a relatively long time period. In contrast, supplemental feeding or clear-felling may deliver immediate gains, although further evaluation of their impact is required. All of the suggested measures make sense but all incur cost; the challenge will be in appropriate assessment, validation, prioritization and funding of the different interventions proposed.

### 3. Integration of wild and captive populations

The value of captive populations of threatened species is increasingly recognized for the conservation of the species as a whole, including wild populations. Traditionally, the captive breeding and wildlife conservation communities have operated in isolation from one another, but modern conservation science

recognizes the need for these sectors to be integrated if the potential benefits of captive populations are to be fully realized. The Japanese golden eagle is the focus of an active zoo-based captive breeding programme which aims to support wild conservation management. This can be achieved in a number of ways, from direct exchange of individual birds through to providing research opportunities not available in the wild. In this section, the various opportunities to integrate wild and captive population management are discussed.

### 3-1. Sustainable captive management

#### 3-1-1. Breeding history, purpose and long-term JAZA breeding plan

The conservation of Japanese golden eagles is related to the whole ecosystem, and it is important to consider *in situ* and *ex situ* conservation from an integrated and comprehensive viewpoint. In 2017 the breeding success recorded in the wild was just 16.3%; it is necessary to learn more about how Japanese golden eagles breed to improve this situation. Breeding of Japanese golden eagles by zoos belonging to JAZA began with individuals rescued from wild in 1968, with the first breeding success recorded in 1989 [65]. In 1991, pedigree management by JAZA was started for a total eleven birds (7 males and 4 females) in four zoos. By the end of 2016, the population had increased to 48 birds (30 males, 17 females, and 1 unknown sex) in nine zoos. Among them, eight (3 males and 5 females) were of wild origin and 40 were zoo-bred. So far, the total number of registered individuals is 82, of which fifteen (6 males and 9 females) were wild-derived (rescued) individuals. Through rearing Japanese golden eagles in captivity, zoos are responsible for enhancing their conservation through raising public awareness and educating people in Japan about the endangered status of the Japanese golden eagle. However, the captive breeding programme must also consider management of the genetic diversity of captive Japanese golden eagles and provide opportunities to study and improve breeding success in the species.

Many challenges still exist in the captive breeding programme, such as only breeding from a limited number of founders which is causing a loss of genetic diversity, and the difficulty in expanding the number of individuals due to limited space in captivity. A long-term plan to achieve a large sustainable population of Japanese golden eagles in captivity is necessary to support their future both in zoos and in the

wild. Such a plan is being developed but requires a number of issues to be addressed relating to veterinary and population management.

#### 3-1-2. Veterinary management of captive birds

In captivity, mortality rates are highest before fledging (44.7%), with other specific causes of death post-fledging recorded as collision accidents (13.2%), circulatory system disease (10.5%), urinary system disease (5.3%), fungal infection (5.3%), senile deterioration (5.3%), reproductive system disease (2.6%) and digestive system disease (2.6%) [65]. To mitigate the major risk of nestling aggression, trials have been performed in which chicks were transferred from parental nursing to artificial nursing, protecting the chicks from aggression and increasing their survival rate. In addition to directly enhancing survival in captivity, experienced parents have been used to adopt chicks by relocating eggs or chicks from inexperienced pairs to experienced pairs in some breeding years. Pair to pair transfer has also been trialed to stimulate interaction of captive chicks with the wild-derived birds as preparation of future wild reintroduction. Through these activities, various veterinary medical and ecological information has been recorded which cannot be obtained in wild, and which can contribute to conservation of Japanese golden eagles.

#### 3-1-3. Implications of PVA results

Captive populations have an important role in *ex-situ* species conservation [66], including the Japanese golden eagle and would be central to any release of birds to reinforce the wild population in Japan. PVA indicated that the captive Japanese golden eagle population is unsustainable under the success rate of the current breeding program, with likely extinction within 200 years, with more than a quarter of its genetic diversity lost within 100 years. For establishing a sustainable captive population, simulations suggested a solution that would require both increasing the proportion of individual birds breeding and supplementation with two new individuals from outside the captive breeding program every ten years [20]. Increasing the number of mating pairs would increase the number of chicks and minimize loss of genetic diversity. However, the current number of founders is insufficient for long term sustainability, with the risks of inbreeding very likely to limit population growth. A system of individual exchange with the wild, so that two birds are released from captivity

to the wild and two birds removed from the wild to captivity, would maintain genetic diversity and avoid inbreeding. Sourcing wild birds can be challenging, however in Scotland, birds for translocation are obtained from the wild by removing the second chick on a nest in a breeding season, while in Japan, adult birds have occasionally been brought into captivity through the rescue of injured birds. Obtaining a minimum of two birds every ten years should be achievable, as part of an integrated management strategy using ongoing PVA modeling and including the agreement and close cooperation of the zoo and wild conservation communities.

### 3-2. Genetic survey of Japanese golden eagle populations

To optimize genetic management in the wild and in captivity, it is important to be able to determine the degree of genetic relatedness among individual birds. As outlined in section 1-3-1, attempts to estimate relatedness among captive birds has not been successful to date due to a lack of sufficiently powerful DNA analysis techniques. The use of next generation high-throughput DNA sequencing approaches would allow an assessment pairwise genetic relatedness, and this information can be used to assist breeding management. It will allow monitoring of genetic inheritance and reveal the effects of inbreeding over generations. This type of approach should be readily achievable in captivity, where researchers would have access to blood samples, but is more difficult in the wild where the analysis may be limited to the use of non-invasive samples with reduced quality DNA. Nonetheless, a consistent approach to genetic monitoring of wild and captive Japanese golden eagles should be attempted as an important step towards integrated population management.

### 3-3. Site selection and management of translocations

Integrated population management would depend on the critical points of transfer between wild and captive populations, specifically the point of release to the wild and, possibly, the point of capture from the wild. In both cases site selection would be an important consideration. The decision of where to release birds needs to account for multiple factors that influence their survival, while decisions regarding removal of birds from the wild would need to consider the effect on the wild population, as well as selection of the optimal individuals to include in the captive population. While such activities have not yet been attempted for the golden eagle in Japan, it is

likely that they will be required for sustainable management over the medium term. There is a wealth of conservation science experience from other species and in other countries that would be a useful basis for translocation planning. At a general level, the IUCN Reintroduction Specialist Group (now the Translocation Specialist Group) guidelines on conservation translocations [67] describes best practice in this area; specific experience of golden eagles translocation programmes is available from Scotland [68] and elsewhere. A full description of the planning process for conservation translocations is outside of the scope of this review, however the following points are raised for consideration.

The success of any conservation management intervention will depend to some extent on the level of community engagement and support for the plan; this includes both the release of birds to the wild and possible removal of birds from the wild. Effective communication and involvement of the local communities where translocation activities take place is therefore of fundamental importance, even if specific details of the project need to remain confidential.

Release sites should be selected on the basis of multiple criteria, including prey availability, nest site availability, individual welfare, levels of human disturbance, environmental health (including pollution) and opportunities for dispersal [67]. The selection of nest sites for removal of chicks from the wild should be made with consideration to the impact on the breeding pair, chick survival (if taken or if left), the local population, the health and welfare of the individual birds involved and, where possible, the genetic contribution of the chick to the captive population.

The key issue in any translocation is to conduct early and comprehensive planning. The criteria described above are not exhaustive and will differ on a case-by-case basis. However, they will all require inputs from conservation scientists operating in both the captive breeding and wildlife management communities.

### 3-4. Summary

An integrated approach to wildlife species management between the captive and wild conservation communities is intuitively sensible but achieving the level of cooperation required for successful outcomes is often challenging. The situation with golden eagles in Japan, in which close working relationships and a strong collaborative ethos this already

exists, presents an opportunity to demonstrate the value of a combined approach. In some disciplines, such as molecular genetics and veterinary health, near-identical skillsets and technologies are already employed in both environments and there are clear scientific and financial advantages to combine forces to support ongoing Japanese golden eagle conservation research. Given the status of both wild and captive populations, it appears likely that an integrated approach to management will be an essential part of any national solution.

## DISCUSSION

A great deal of scientific research has been performed to investigate the biology of the golden eagle in Japan and further afield, yet gaps remain in our knowledge regarding the reasons for the decline of the Japanese population and how best to improve the situation. No single approach is likely to succeed and the benefits of multi-disciplinary research will only be fully realized if they are integrated within an applied conservation framework. This review represents a first step in the coordination of conservation science for the Japanese golden eagle; as such it serves to identify as many outstanding research needs as practical solutions. Nevertheless, the process of bringing scientists together to discuss practical issues in conservation management is important and the outcomes of those discussions summarized here, if communicated effectively, should provide a valuable platform for developing golden eagle conservation strategies in Japan.

### Reasons for population decline

A number of factors appear to be combining to cause reduced breeding success and gradual, but continuous population decline. Insufficient nutritional intake has been identified as an immediate cause, due to a progressive change in diet composition from mammals to reptiles and an overall reduction in prey availability. These factors are likely to be associated with extreme winter snow cover and changes in land use (blanket forest, more intensive agriculture) for which surveys show that appropriate hunting sites for Japanese golden eagle are decreasing. From a veterinary health viewpoint, there is evidence of lead poisoning being a serious problem on Hokkaido and broader geographic analysis appears warranted. Genetic data indicates that the Japanese golden eagle population retains reasonable levels of evolutionary and contemporary diversity which are not likely to be the cause of

historic declines. However, genetic diversity is likely to collapse with further population reductions and inbreeding may start to impact individual fitness.

### Requirements for sustainable management

The sustainable management of the wild Japanese golden eagle population will depend on our ability to address the reasons for population decline outlined above. The short-term challenges of individual survival and reproductive success should be urgently addressed through trials and widespread implementation of strategies to increase food availability and practical support at nest sites, to maximise the chances of individual fledgling success. A number of options and solutions are already under consideration or have been proposed here relating to supplementary feeding, nest improvement, nest monitoring (including the use of advanced technologies) and land management that should all contribute to the short-term recovery of golden eagles if implemented at a sufficiently broad scale.

To ensure the medium-term recovery of the population, the ability to improve the overall health of golden eagles through evaluation of nutritional deficiencies or assessment of the risks posed by disease or environmental pollution is required. This could be achieved through the development and implementation of veterinary surveillance protocols similar to those used in Scotland and expanding on the analytical work currently performed for raptors in Hokkaido.

Longer-term security for the golden eagle will require the management of genetic diversity to control for the risks of inbreeding and outbreeding depression. This would be informed by further research into Japanese and non-Japanese subspecies, with specific attention paid to increasing the availability of samples across the Japanese golden eagle distribution. Genetic data, alongside more precise life-history information on the Japanese population, should be incorporated into a range-wide PVA, that is required to generate and test long term sustainable management scenarios.

### Integration of wild and captive conservation programmes

The captive population potentially represents a fantastic conservation resource, both in terms of an assurance population and as a source of vital information regarding the breeding biology, genetics, health and behavior of the golden eagle. To date, reproductive efforts in zoos have

been successful, where a lot of chicks are born, however the current risks of inbreeding and diversity loss in captivity are severe and need to be addressed within a generation. Active, integrated management of wild and captive golden eagles offers a potential solution to the challenges faced by both populations and coordination of activities across this interface is therefore strongly encouraged. Areas of mutual activity could include research into veterinary diagnostics and health surveillance, genetic diversity, long-term integrated population viability modeling and mapping of suitable release sites.

### Summary of recommendations for Japanese golden eagle conservation science (Table 1)

This review has examined the key issues currently facing Japanese golden eagle management and explored the scientific research available to support conservation of the species in the wild and in captivity. By collating this information and identifying gaps in our current knowledge, we hope to support decision-makers responsible for directing future research efforts and establishing long-term management policies. A summary of the current situation and future recommendations across different aspects of golden eagle conservation is presented in Table 1.

At a general level, the development of sustainable management policies for the Japanese golden eagle in Japan is hampered by a lack of data across most areas of golden eagle ecology, veterinary health and genetics. Many different research activities are underway, but they are often limited in geographic scope, or lack the level of detail required to draw firm scientific conclusions. This is no criticism of previous researchers who have operated, often voluntarily, in difficult conditions with few research resources.

For population monitoring, there are significant challenges associated with simply maintaining current data recording in relation to declining human resources and nest site accessibility, therefore a focus on initiating new field surveys that capture a broader range of information on diet, health, movement and genetic status is recommended, trialing and implementing appropriate technologies (satellite tagging, drones) to minimize costs and maximise essential management information (Table 1). To underpin such surveys, further applied research will be required to develop veterinary health surveillance protocols and methods for diet measurement and genetic analysis.

Alongside empirical data, the use of Population and Habitat Viability Analysis (PHVA) to generate predictive maps of suitable golden eagle habitat and forecasts of long-term population viability is likely to be an extremely useful management tool. The widespread international application of PHVA to species conservation has demonstrated how managers can use forecasts to examine current risks to the population as well as the possible outcomes of proposed management interventions. The usefulness of PHVA is directly related to the accuracy and completeness of biological and ecological model parameters and further research into these areas is therefore advised (Table 1).

Direct actions to support golden eagle survival and reproductive success, such as linear forest clearance and nest improvement are supported by existing research in Japan and overseas (Table 1). Where further evidence is needed before implementing such habitat management, measures can be increased across the country, and research to deliver the necessary data should be prioritised.

Lastly, it is recognized that the Japanese zoo community, through JAZA and its golden eagle conservation breeding programme, has an important role to play in the overall management of the species. The captive population faces a number of challenges to its expansion and long-term sustainability; however, it is expected that the breeding programme will contribute to wild population management through both future research and breeding for release (Table 1). It is therefore considered critical that this programme is integrated into wider conservation efforts and is included as part of the overall range of management activities to be supported in future.

According to current trends in census size and reproduction, the Japanese golden eagle, as a subspecies, is at risk of extinction this century. This outcome would represent a tremendous loss to Japan, not only as a key apex predator within the ecology of Honshu, but also as a cultural icon, whose disappearance would represent a sad indictment of species conservation policy at a national level. It would also contribute a significant threat to the long-term survival of the species worldwide. The recovery of wild golden eagle populations takes time, but has been successfully demonstrated in Scotland, following the development of conservation policies, implemented through active management and underpinned by long-term research programmes. Preventing the disappearance

**Table 1** A summary of current and completed Japanese golden eagle (JGE) research and recommendations for future work. Activities are categorized into the three management topics discussed in this review and are further divided into the disciplines of Ecology, Veterinary Health, Genetics and Ecosystem & Habitat Management.

| Management Topic                                       | Current activities / Research to date  | Future planned work / research requirements  |
|--|--|--|
| <b>1. Understanding reasons for population decline</b> |  |  |
| Ecology  | <ul style="list-style-type: none"> <li>• Annual nest site surveys for all pairs - in Iwate only</li> <li>• Prey use survey in Hyogo</li> <li>• Satellite tagging in Scotland for dispersal behaviour</li> <li>• Supplementary feeding – initial pilot study</li> </ul> | <ul style="list-style-type: none"> <li>• To update demographic data (age class, sex, and numbers)               <ul style="list-style-type: none"> <li>○ National nest site survey</li> <li>○ Questionnaire (10km) survey of JGE occupancy</li> </ul> </li> <li>• National research survey of JGE prey and diet</li> <li>• Satellite tagging in Japan for dispersal behaviour</li> <li>• Supplementary feeding at multiple nests – including drone feeding.</li> </ul> |
| Veterinary Health                                      | <ul style="list-style-type: none"> <li>• Post mortem and live chick surveys (UK)</li> <li>• Survey of toxins, pathogens and nutrition (Hokkaido; limited on Honshu)</li> <li>• Existing causes of death assessed opportunistically</li> </ul>                          | <ul style="list-style-type: none"> <li>• Post-mortem and chick surveys not considered practical in Japan</li> <li>• Extend survey of toxins, pathogens and nutrition levels throughout Honshu</li> <li>• Need to understand low reproductive rate. Develop nest analysis of egg shell, faecal samples pellet (using captive baseline controls)</li> </ul>  |
| Genetics   | <ul style="list-style-type: none"> <li>• Genetic diversity and inbreeding coefficients estimated for wild (Iwate) population – limited power of microsatellite markers</li> <li>• Genome sequence available for JGE</li> </ul>   | <ul style="list-style-type: none"> <li>• Perform genome-wide comparative assessments of inbreeding among populations, subspecies and potentially individuals, using SNPs of low coverage sequencing</li> </ul>   |
| Ecosystem and Habitat Management                       | <ul style="list-style-type: none"> <li>• Land use change – from patchy forest to blanket forest – over the last 30 years has reduced area and quality of JGE habitat</li> </ul>  | <ul style="list-style-type: none"> <li>• Determine habitat availability and habitat use by mapping remote sensing data and satellite tagging technologies</li> </ul>   |
| <b>2. Requirements for sustainable management</b>      |  |  |
| Ecology  | <ul style="list-style-type: none"> <li>• PVA on certain wild populations indicating significant (30%) risks of extinction (extirpation) based on non-JGE model parameters</li> </ul>   | <ul style="list-style-type: none"> <li>• Enhanced PVA modeling and broader population scope. Include evaluation of possible conservation management options</li> <li>• Drone use for monitoring and feather sampling</li> </ul>  |
| Veterinary Health                                      | <ul style="list-style-type: none"> <li>• Veterinary health not currently incorporated into routine conservation management</li> </ul>  | <ul style="list-style-type: none"> <li>• Develop surveillance protocols for generating individual and population level health indicators and recording data</li> </ul>   |
| Genetics   | <ul style="list-style-type: none"> <li>• Initial examination of population genetic structure completed. Very limited sample availability outside of Iwate. Many unknowns exist including relative relatedness and inbreeding among wild birds.</li> </ul>              | <ul style="list-style-type: none"> <li>• Development of effective protocols for DNA sampling from wild birds and nests               <ul style="list-style-type: none"> <li>○ Include feasibility study of drone use for feather samples</li> </ul> </li> <li>• Subspecies comparative work to examine local adaptive variation</li> <li>• Immortal cell line production for intact karyotypes</li> <li>• Research into age estimation</li> </ul>                      |
| Ecosystem and Habitat Management                       | <ul style="list-style-type: none"> <li>• Selective clear felling piloted. Research demonstrated usefulness</li> </ul>  | <ul style="list-style-type: none"> <li>• Artificial nest construction • Expanding and continuing JGE integration in forestry policy (e.g. clear felling)</li> </ul>  |
| <b>3. Integration of wild and captive populations</b>  |  |  |
| Ecology  | <ul style="list-style-type: none"> <li>• Initial PVA analysis of captive population sustainability completed</li> </ul>  | <ul style="list-style-type: none"> <li>• Long-term JAZA breeding for release plan to include PVA forecasts</li> </ul>  |
| Veterinary Health                                      | <ul style="list-style-type: none"> <li>• Captive breeding program utilizes standard zoo veterinary procedures to maintain individual health</li> </ul>   | <ul style="list-style-type: none"> <li>• Develop a zoo sampling protocol for multi-discipline analysis</li> <li>• Initiate a health survey of all captive birds (including blood tests)</li> <li>• Collect and collate wild bird and captive bird survey data</li> </ul>   |
| Genetics   | <ul style="list-style-type: none"> <li>• Limited sampling and DNA analysis completed to compare population level diversity in captive and wild populations</li> </ul>  | <ul style="list-style-type: none"> <li>• Initiate a genetic survey of all captive birds (bloods)</li> <li>• Collect and collate wild bird and captive bird survey data</li> </ul>  |
| Ecosystem and Habitat Management                       | <ul style="list-style-type: none"> <li>• No activities currently focused wild-captive management integration</li> </ul>  | <ul style="list-style-type: none"> <li>• Identify potential release sites and capture sites in the wild</li> </ul>   |

of the golden eagle in Japan will require the sustained effort of conservationists at local and national levels, working with the support of conservation scientists from a broad range of disciplines. This review summarises the current status of scientific knowledge and sets out a vision for continued applied research that should provide the information and technical solutions required to successfully reverse the decline in golden eagle numbers, and hopefully secure the long-term future of the species in Japan.

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総説 保全学

ニホンイヌワシの保全科学：現状と将来展望について

Rob OGDEN<sup>1)</sup>\*, 福田智一<sup>2)</sup>\*, 布野隆之<sup>3)</sup>\*, 小松 守<sup>4)</sup>\*, 前田 琢<sup>5)</sup>\*, Anna MEREDITH<sup>1,6)</sup>\*, 三浦匡哉<sup>4)</sup>\*, 夏川遼生<sup>7)</sup>\*, 大沼 学<sup>8)</sup>\*, 長船裕紀<sup>9)</sup>\*, 齊藤慶輔<sup>10)</sup>\*, 佐藤 悠<sup>11)</sup>\*, Des THOMPSON<sup>12)</sup>\*, 村山美穂<sup>11)</sup>\*,\*\*

- 1) Royal (Dick) School of Veterinary Studies and the Roslin Institute, Easter Bush Campus, University of Edinburgh, Midlothian EH25 9RG, UK
- 2) 岩手大学総合科学研究科 〒020-8551 岩手県盛岡市上田 4-3-5
- 3) 兵庫県立人と自然の博物館 〒669-1546 兵庫県三田市弥生が丘 6
- 4) 秋田市大森山動物園 〒010-1654 秋田県秋田市浜田潟端 154
- 5) 岩手県環境保健研究センター 〒020-0857 岩手県盛岡市北飯岡 1-11-16
- 6) Faculty of Veterinary and Agricultural Sciences, University of Melbourne, Corner Flemington Rd and Park Dr, Parkville, Victoria 3052, Australia
- 7) 横浜国立大学大学院環境情報学府 〒240-8501 神奈川県横浜市保土ヶ谷区常盤台 79-7
- 8) 国立環境研究所 〒305-8506 茨城県つくば市小野川 16-2
- 9) 環境省猛禽類保護センター 〒999-8207 山形県酒田市草津字湯ノ台 71-1
- 10) 猛禽類医学研究所 〒084-0922 北海道釧路市北斗 2-2101
- 11) 京都大学野生動物研究センター 〒606-8203 京都府京都市左京区田中関田町 2-24
- 12) Scottish Natural Heritage, Silvan House, 231 Corstorphine Road, Edinburgh EH12 7AT, UK

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要 約

イヌワシの一亜種であるニホンイヌワシ (*Aquila chrysaetos japonica*) は、個体数と繁殖状況の現状調査に基づいて、環境省版レッドリストの絶滅危惧種に指定されている。現在、国による保全活動が行われているものの、個体数減少の原因とその改善方法に関する知見は、十分とはいえない。この数十年の間に、日本を含む世界各地において、イヌワシの種の回復に関する多分野にわたる科学的な研究が行われ、本種の保全計画に必要な情報が集められつつある。しかしながら、これらの研究は個別に進められており、学際的なアプローチが充分になされていない。本稿では、生態学、遺伝学、獣医学的健康管理、生息地管理などの、ニホンイヌワシの保全に関する諸研究を総合して概観した。野生および飼育下個体群の現状と傾向を分析し、現在および将来の保全管理の活動を報告し、ニホンイヌワシの生息域内保全および生息域外保全に向けた対策について、統合的な見地から議論した。この総説では、イヌワシの生物学や健康科学に関する国内および海外の専門家グループが、学術的な情報と実用的な解決策の両方を提示した。本稿によって、ニホンイヌワシの数の減少をくいとめるのに必要な情報と技術を提供し、日本における長期的な本種の保全に応用するための枠組みを示すことを目指す。

キーワード：イヌワシ, 生息域外保全, 生息域内保全, 保全管理

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\*ニホンイヌワシ保全研究グループ

\*\*責任著者：村山美穂 (E-mail: mmurayama@wrc.kyoto-u.ac.jp)