

Beyond Site-Specific Criteria: Conservation of Migratory Birds and Their Habitats from a Network Perspective

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Supplementary Text S1: Functional aspects of the consequences of decreasing connectivity in bird movement networks

S1.1: Information diffusion

Information transmission among individuals critically affects animal population sustainability, e.g. in terms of the efficiency of foraging behaviour and the suitability of migration strategies [62]. For instance, a majority of European bee-eaters (*Merops apiaster*) stay together in groups during their 14,000-km migration using coordinated migration and foraging strategies [77]. Individual barnacle geese (*Branta leucopsis*) who rely on social information acquire food more frequently, compared to those that ignore the information [78]. Similarly, Aplin et al. [79] found that food-related social information was rapidly diffused by individual great tits (*Parus major*), and this allowed foraging innovations to persist over generations. The movement of individuals across the landscape is one of the key factors facilitating social transmission of information among birds [41]. Indeed, the ability of individuals to move between sites within a population shapes its social structure [80], and consequently any changes which affect movements may also influence the effectivity and efficiency of information transmission. Further research is needed to improve understanding of the extent to which decreasing connectivity in bird movement networks may impede information spread among and within wild bird populations.

S1.2: Predator effect

Survival and reproduction success of bird species are strongly affected by their predators [81–83]. For instance, greylag geese (*Anser anser*) utilized suboptimal foraging patches and constrained their home ranges during moulting to avoid high predator risks [84]. Voelkl et al. [83] experimentally found that a single nonlethal ‘attack’ by a model sparrow hawk (*Accipiter nisus*) triggered an instantaneous and extensive turnover in flock composition of great tits and blue tits (*Cyanistes caeruleus*). A fragmented landscape affects animal movements, and disturbance to particular areas may cause individuals to make non-optimal anti-predatory decisions [85], e.g., with higher social mixing and suboptimal habitat use. In highly fragmented landscapes, even human-induced predator management strategies cannot mitigate the population declines of prey species under predator attacks [85]. On the other hand, a fragmented movement network of a prey species can also be suboptimal for a predator species [86,87], and may thereby decrease the predation risk for a prey species. Despite various studies covering effects of habitat configuration on predator-prey interactions, few studies have tested this specific aspect explicitly and empirically [88]. The mechanism by which connectivity loss in predatory bird movement networks affects population dynamics of prey species remains unclear.

S1.3: Disease transmission

Many bird species are competent hosts for infectious pathogens [89–91], such as Usutu virus, West Nile virus, and avian influenza virus. Because of their high mobility, birds are important agents for large-scale dispersal of viruses [7] and pathogenic bacteria, including strains resistant to antibiotics. Although bird movements may be impeded through habitat disturbance, reducing network efficiency, this can also facilitate pathogen transmission if infected birds move to novel areas in response to a perturbation event [92]. This effect was observed among badgers (*Meles meles*) and red foxes (*Vulpes vulpes*), which expanded their home ranges and invaded novel regions in response to culling operation for Bovine tuberculosis [92] and rabies [93]. Recent incidents of site loss in bird migration networks may increase the probability that birds from different flyways co-occur more intensively at their crossroads [94], thereby increasing the probability of disease transmission between these birds, also by restricting their movements in smaller spatial ranges [95], potentially causing infections to ‘jump flyways’. However, habitat perturbations and partial network collapse can also lead to reduced population sizes, which can have a negative effect on disease spread and pathogen infection probabilities. Therefore, knowledge about how habitat perturbations affect movement networks is pivotal for better understanding of global disease spread.

S1.4: Propagule dispersal

Many waterbird species, e.g., Anatidae or shorebirds, are herbivorous or omnivorous, and feed on plants and their seeds. Seeds and other propagules of a broad range of plants can survive during gut passages in waterbirds [96–99], and thus the short and long distance movements of birds are amongst the primary agents for seed dispersal between isolated habitat patches [100]. For instance, geese can be key vectors for seed dispersal within island networks [101]. Mallards (*Anas platyrhynchos*) can disperse seeds farther when using fragmented movement networks [8] because less connected habitat patches may force them to move farther for foraging and resting. In contrast, a higher diversity of plant seeds can be transported in well-connected mallard movement networks, because different plants are ingested at different sites [98], and because the egestion rates of seeds significantly decrease when travelling over long distances [8]. Therefore, long-distance dispersal (LDD) of seeds may be favoured by connectivity loss in movement networks if it forces birds to move over longer distances, but LDD rates also depend on bird population size, which may decline under reduced connectivity. In addition, LDD rates may also be reduced by short-stopping, such as in the case of declines in the proportion of greylag geese populations undertaking migration to southern Europe [102]. Waterbirds are also vital for dispersal of aquatic invertebrates within networks of wetlands [103], and may even be responsible for the dispersal of some fish species [104].

S1.5: Biovectoring of nutrients or contaminants

Birds can also transport nutrients and contaminants via their movements. Migratory seabirds are an important agent moving nutrients and contaminations from ocean to land in the Arctic and Antarctic via their guano [105,106]. Migratory scarlet ibises (*Eudocemus ruber*) transported mercury to soils of red mangrove forests in South America via their toxin-accumulated moulted feathers [107]. Gulls feeding in landfills transport nutrients and heavy metals into lakes and reservoirs used as roost sites, causing eutrophication. Thus, connectivity changes in bird movement networks affect the distribution of nutrients and contaminants in the environment, potentially triggering cascading effects [108].

S1.6: Gene flow

Changes in bird movement networks may affect population genetic structures and subsequently influence genetic evolution in birds [109]. For instance, shifted migratory patterns in response to environmental change induce a higher mixing rate between different populations of barnacle geese. Thus, an increased chance of genetic exchange was observed between these populations [110]. Moreover, the probability of avian hybridizations may be altered [111], because inter-species mixing based on structures of movement networks is a prerequisite for mating with a different species. Black stilts (*Himantopus novaezelandiae*), a critically endangered native species in New Zealand, are threatened by hybridization with pied stilt (*Himantopus leucocephalus*) since the latter spread from Australia to New Zealand, probably in response to habitat changes [111]. Hybridization between the speckled teal (*Anas flavirostris*) and yellow-billed pintail (*A. georgica*) probably provided the latter with genes that allowed it to colonize high altitudes in the Andes [113]. Thus, linking spatial-temporal movement patterns with phylogenetic networks of birds [114] may facilitate better understanding of hybridization and evolution in birds.

S1.7: Cascading effects

Loss of connectivity of bird movement networks may lead to population declines, local extinctions, and cascading changes in ecosystems. Extensive habitat loss resulting from wetland conversion to croplands may be the major cause of the dramatic decline of slender-billed curlews (*Numenius tenuirostris*) [115] and extirpation of pink-headed ducks (*Rhodonessa caryophyllacea*) [116]. We observed a population decline in waterfowl species with decreasing connectivity in their migration networks [14]. Meanwhile, Studds et al. [10] found that habitat loss in a keystone site, i.e., Yellow Sea intertidal mudflats, induced rapid population declines in migratory shorebirds. This can also be explained by a simulation study that showed that losing the coastal sites in Bohai Bay in the Yellow Sea leads to the collapse of stork migration networks, and completely disables their migration success [13]. Losing a site often results in the isolation of other sites from the movement networks (secondary loss), thus, the consequence of habitat loss for migratory/dispersive species are often magnified [15].

Different functional aspects may interact. For instance, decreasing connectivity in a movement network may impede social information spread among birds, which can induce a reduced feeding efficiency. Reduced energy intake rate in turn may result in reduced condition and flight ability resulting in poorer predator escape ability [117]. Subsequently, a stronger impact of predators on prey species can turn over their social structure [83], which, in turn, through feedback, impedes information spread, leading to lower feeding efficiency and higher predation risk. Moreover, an increased mixing may facilitate disease transmission.

Table S1: Sources of the reviewed criteria:

Name of designation/network (Abbreviation)	Source
Ramsar Sites (Ramsar)	https://www.ramsar.org/sites/default/files/documents/library/ramsarsites_criteria_eng.pdf
Emerald Network of Areas of Special Conservation Interest (ASCI)	https://www.eea.europa.eu/help/glossary/eea-glossary/emerald-network#:~:text=The%20Emerald%20network%20is%20a,and%20the%20EU%20Member%20States
Natura 2000: Special Protection Areas (SPA)	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:01992L0043-20130701
Critical Site Network (CSN)	http://wow.wetlands.org/en
Western/Central Asian Site Network for Siberian Cranes and Other Waterbirds (WCASN)	https://www.cms.int/siberian-crane/sites/default/files/uploads/SiberianCrane/02-Criteria.pdf
Western Hemisphere Shorebird Reserve Network (WHSRN)	https://whsrn.org/why-whsrn/is-my-site-eligible/
East Asian - Australasian Flyway Site Network (EAAFSN)	https://eaa-flyway.net/wp-content/uploads/2018/01/EAAFP_Information_Brochure_2017_English1123_final.compressed.pdf
Global Important Bird Areas (IBA)*	http://datazone.birdlife.org/userfiles/images/Guidelines%20for%20the%20application%20of%20the%20IBA%20criteria_final%20approved%20version_July2020.pdf

* This has now been expanded within the Key Biodiversity Area (KBA)

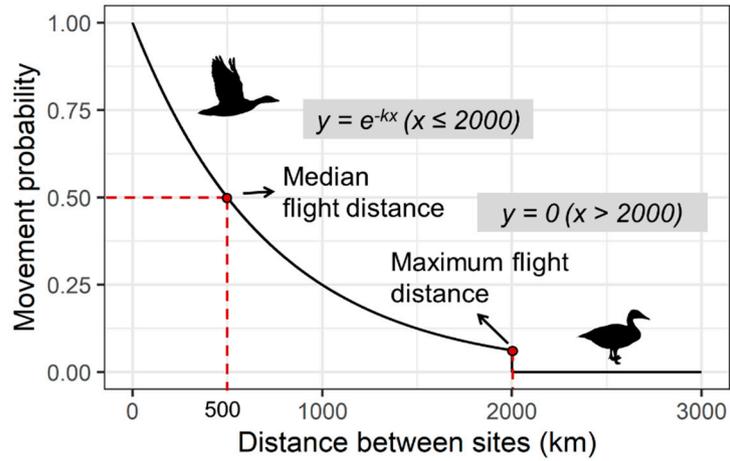


Figure S1 Quantifying the probability of dispersal from one site to another by a decreasing exponential function of distances [42]. The probability is fixed to be zero when the distance between sites exceeds the birds' maximum flight ability (e.g., 2000 km). k is a constant calculated by assuming the probability is 50% when the distance between sites equals the birds' median flight distance (e.g., 500 km), e.g., $k = -\ln(0.5)/500 = -0.001386294$.

Supplementary Text S2: Examples of management practices for keystone sites defined by the proposed framework

Putting this quantitative framework into practice in bird conservation will require actions at the intergovernmental levels by working with biodiversity and climate conventions as well as flyway agreements and framework, as well as at a national level. At national level, this includes applying the framework in a wide range of plans such as National Biodiversity Strategies and Action Plans (NBSAPs) of parties, and mainstreaming these within other development planning, climate change adaptation and mitigation frameworks. Habitat conservation and habitat creation/restoration may then be prioritised for those sites identified as important by this network-based framework.

Habitat conservation/management measures can prevent or reverse habitat loss after designating a site as a protected area. Designating protected areas through conservation legislation is the most widely used conservation approach to mitigate anthropogenic modification and disturbance of natural habitats, and can be accompanied by other measures such as hunting restrictions and regular surveys [118]. Management plans may reduce the development of barriers (e.g., linear infrastructure, roads, highways, canals, pipelines affecting water movement, power lines) to bird movements, which helps to reduce mortality rates due e.g. to solar and wind farms, and power lines placed in critical migration locations and network sites. Although habitat modification (e.g., for farming or by logging) and climate change effects (including responses to climate change) are the most common threats for birds (birdlife.org), there are other threats that can be efficiently and effectively addressed through management plans, e.g., through the control of hunting. Legal and illegal hunting are major threats to many endangered species such as spoon-billed sandpiper (*Calidris pygmeus*) [119], so hunting control may immediately reduce pressure on their populations. However, the effectiveness of protected areas for bird conservation depends on effective governance [120], and site designation is not enough. It is the management that counts. For example, only a limited proportion of waterbirds are effectively protected by Ramsar sites in the Mediterranean Basin [121], though those in Moroccan Ramsar sites showed positive population trends [122].

Another approach is habitat or landscape creation/restoration, i.e., by creating new habitats or restoring degraded or polluted habitats. Reflooding of previously drained habitats can be effective for waterbirds, e.g., winter flooding of rice fields in Japan and Europe provided habitats for waterfowl [123,124]. Invasive predator removal programs restore natural habitats for prey species, which have also been shown to be effective for species-specific protection for bird populations [125]. Artificial habitat creation like construction of ponds or reservoirs in keystone areas can be another important technical solution for some species [126], especially when an additional site is needed for increasing the connectivity of movement networks. However, natural habitat restoration (e.g., removing wetland drainage systems, reducing nutrient inputs, controlling alien cyprinids), can provide higher-quality habitats for many bird species, and may be more effective for connectivity conservation than artificial habitat creation in the same general area [127].

Supplementary Text S3: Examples of data sources for constructing bird movement networks

Animal tracking data are available from Movebank (movebank.org), which holds more than 2.2 billion tracking points covering 971 taxa. Bird ringing/banding-recapture data such as from the Bird Banding Laboratory of the United States Geological Survey (usgs.gov), the Bird Banding Office of the Canadian Wildlife Service (canada.ca), the Australian Bird and Bat Banding Scheme (environment.gov.au), EURING (euring.org), and Geese.org (geese.org) involve long-term, continental-scale, full-species observations, which are suitable for investigating the dynamics of bird movement networks. Citizen science data like eBird (ebird.org), Observado (Observation.org), the International Waterbird Census (www.wetlands.org/IWC) and the Global Biodiversity Information Facility (gbif.org) may be alternative valuable data sources; however, they require considerable modelling efforts involving plausible assumptions for decision-making underlying bird movements. Precise monitoring of environmental variables may also assist model development.

Supplementary Text S4: References for the contents in Supporting Information [77–127]

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