molecular ion (*6*) is well established, and the bound-state level energies can be calculated to 10-digit precision. The same is true for the e$\bar{p}$He system (*6, 7*) that is found to withstand a test of QED.

Third, the transition frequencies sensitively depend on the mass ratios of the constituent particles. Similarly, as in a spectroscopic determination of the proton-electron mass ratio from HD^+ spectroscopy (*8*), evaluation of the data of Hori *et al.* yields a value for the antiproton–electron mass ratio. We learn that antiprotons weigh the same as protons, up to the 10th digit.

The frontier of particle physics is commonly approached in the realm of high-energy physics, using particle accelerators like the Large Hadron Collider (LHC). The detection of the Higgs boson at the LHC marks the culmination of the standard model of physics, but the quest is on to explore new physics beyond that. Alternative approaches exist in the low-energy domain by performing extreme precision measurements on small atomic and molecular systems for which the quantum-level structure is calculable (*1*). This can be done, for example, through the search for an electric dipole moment of the electron in molecules that might reveal signatures of supersymmetry (*9*). Laser precision measurements of optical transitions in molecules constrain the existence of higher dimensions beyond the 3 + 1 (spatial and time) that we regularly observe, or the occurrence of a fifth force beyond the three forces known in the standard model plus gravity (*1*). Previous measurements on antiprotonic helium have already set limits on the strength of such a hypothetical fifth force at sub-ångström length scale (*10*); the present data constrain these phenomena even further.

This exotic atom involving antimatter seems a fortunate accident of nature. It exhibits long-lived (metastable) quantum states that can be probed with lasers, and it survives the collisional conditions needed to cool its kinetic motion, as Hori *et al.* have demonstrated. It is likely that these properties may be further exploited to reveal new physics in future experiments on this extraordinary atom-like particle. ■

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CONSERVATION

Migratory birds under threat

Habitat degradation and loss, illegal killings, and climate change threaten European migratory bird populations

By **Franz Bairlein**

The populations of migratory bird species that breed in Europe and overwinter in sub-Saharan Africa are declining considerably faster than those of non-migratory resident species or of migratory species that overwinter in Europe (*1*). Likely factors are habitat changes due to changes in land use, illegal killing and taking along the northern African coasts, and climate-induced changes in timing of migration and breeding. However, not only European trans-Saharan migrants are declining fast. This holds also for North American long-distance migrants wintering in Central and South America. To halt these declines, preservation of remaining habitats and restoration of habitats both at breeding and nonbreeding grounds is essential, as well as stopping illegal killing and taking of birds along their migration routes.

ILLEGAL KILLING AND TAKING

Every year, between 11 million and 36 million birds are killed or taken illegally in the Mediterranean region (*2*). The areas of greatest concern are in the eastern and central Mediterranean, with more than 5 million birds taken in both Egypt and Italy and an estimated 1 million each in Cyprus and Lebanon. Common migratory species such as Eurasian chaffinch, blackcap, and song thrush are most affected, but many less common migratory species are also taken in substantial numbers, including species of global conservation concern such as red kite and Eurasian curlew. On average, the annual illegal killings and takings of threatened or near-threatened migratory bird species amount to 1.0 to 3.5% of their populations (*2*)—percentages that are very likely to have considerable impacts on the fate of these species.

Illegal trapping can cause a collapse in population numbers within a short period of time. For example, the yellow-breasted bunting was abundant in its Eurasian breeding range until illegal takings in China caused an 84% population decline between 1980 and 2013 (*3*). Similarly, the passenger pigeon was once the most abundant migratory bird in North America, numbering around 3 billion to 5 billion birds in the early 19th century. Massive-scale hunting as cheap meat resulted in its extinction at the turn of the 20th century (*4*).

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HABITAT DEGRADATION AND LOSS

Many European migratory birds that overwinter in sub-Saharan Africa do not travel across those areas of the eastern Mediterranean most affected by illegal killings. Rather, they use a flyway across the western Mediterranean where illegal taking is much less intense (see the figure). Other factors must play a role in their decline.

A large number of European migratory species overwinter in the dry savannas of sub-Saharan Africa. Annual survival of many of these species correlates with rainfall in the Sahel zone (*1*). However, despite an increase in rainfall in the Sahel in recent decades, bird populations have continued to decline. Thus, factors other than rainfall must contribute to the population declines. Land-use and land-cover changes are the most important (*5*). Between 1975 and 2000, agriculture increased by 57% in sub-Saharan Africa at the expense of natural vegetation, with nearly 5 million hectares of forest and nonforest vegetation lost per year (*6*). Most affected are the Sahel and Guinea Savanna zones where the majority of the Eurasian migratory species overwinter. An analysis of breeding-bird survey trends of 26 long-distance migratory species in the United Kingdom shows that wintering habitat is the most important determinant of population trends, with specialist species that occupy either open or woodland habitats in Africa showing declines (*7*).

CLIMATE CHANGE

Climate change is another major driver for biodiversity changes, including responses of bird populations (*8*). Many migratory species, including those that overwinter in sub-Saharan Africa, now arrive earlier at their spring breeding grounds (*9*). However, different organisms do not respond to climate change at the same pace, which has led to an ecological mismatch between some consumers and their prey (*10*).

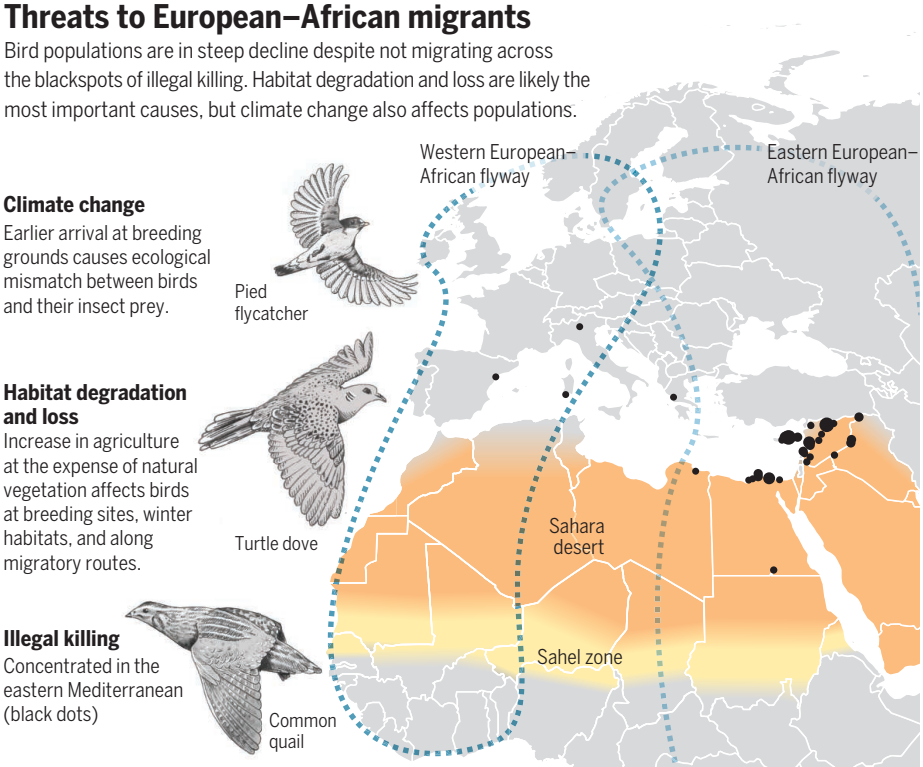
Dutch pied flycatchers, which overwinter in sub-Saharan Africa, do not arrive earlier at breeding grounds, but the populations of their insect food peak earlier as a result of warmer spring temperatures.

This mismatch between breeding and food availability has caused a decline of up to 90% in Dutch pied flycatcher population sizes (*11*).

Similarly, an analysis of 242 time series over the past five decades for 117 European migratory bird species revealed a larger population decline for species with a larger mismatch between food availability and consumer requirement (*12*). Climate change–induced changes in migratory bird populations are thus evident, but their relative contribution to population changes in long-distance migrants wintering requires further clarification.

Threats to European–African migrants

Bird populations are in steep decline despite not migrating across the blackspots of illegal killing. Habitat degradation and loss are likely the most important causes, but climate change also affects populations.



A GLOBAL ISSUE

Although I have focused on the European–African migration system, many migratory bird species are declining around the world. In North America, the Breeding Bird Survey—a roadside census throughout the United States and parts of Canada that has been running since 1966—shows that half of the migratory bird species are declining (*13*); declines in long-distance Neotropical migrants are more pronounced than those of birds that migrate short distances. As for the European–African migrants, climate mismatch is a factor, but the long-distance migrants are particularly sensitive to habitat changes (*14*). Similar patterns might be expected for migratory birds in East Asia, but large-scale and long-term breeding bird population surveys, population trends, and nonbreeding habitat assessments are largely missing for that region.

OUTLOOK

Any attempt to understand and ameliorate migratory bird losses must consider threats far away from their breeding sites. These threats could include killing and taking, human disturbance at staging sites, pesticide exposure, or collisions with human obstacles such as wind turbines and traffic. The most important drivers of population declines in migratory bird species are likely to be land-use changes and connected habitat degradation and loss, but few studies have investigated the specific impacts of land-use and land-cover changes on migratory bird populations in detail (*7*). Such studies are urgently needed to disentangle the various factors acting on populations of migratory species.

These studies must include carry-over effects, because conditions at nonbreeding grounds can affect reproductive success in the breeding season (*15*). Conversely, conditions at breeding grounds can affect nonbreeding fitness. In the red knot, climate-induced malnutrition at their Arctic breeding grounds resulted in shorter bills and reduced survival rates at their African wintering grounds (*16*).

Future studies must also consider the role of stopover sites. Most long-distance migratory species rely on considerable fueling at such stopover sites before they embark on migratory flight, particularly if they need to cross oceans or deserts with no or limited feeding opportunities. The main fuel for migratory flights is fat. Consequently, migrants must accumulate enormous amounts of fat before migratory flights, some doubling their body mass within just a few weeks. To achieve that timed fueling, suitable habitats and food must be available at stopover sites. The effect of habitat loss and degradation at stopover sites on population trends in trans-Saharan migrants remains uninvestigated.

Consequently, future studies also need to clarify where species of conservation concern stop over and overwinter, and which migration routes they take. For example, British common cuckoos migrate along two routes to the same winter destination in sub-Saharan Africa. They face a much higher en route mortality when migrating along a western route than along an easterly route (*17*). Emerging technologies for tracking individual migratory birds throughout their annual cycle (*18*) will reveal migratory routes and destinations in more detail than past bird marking, allowing more detailed and frequent assessment of the drivers of migratory species declines.

Existing data can, however, already be translated into immediate conservation actions to halt the decline of these migratory species. Wetlands can be protected from drainage; woody vegetation can be protected from grazing or even be replanted. Such efforts would not only support migratory birds but also the local biodiversity and livelihoods of local farmers and pastoralists. In addition, illegal taking and killing can be stopped. The required political instruments, such as the African–Eurasian Waterbird Agreement and the African–Eurasian Migratory Landbird Action Plan, are already in place. We just need to act, and we can if we wish. ■

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