INSIGHTS

POLICY FORUM

CONSERVATION

Mapping out a future for ungulate migrations

Limited mapping of migrations hampers conservation

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Migration of ungulates (hooved mammals) is a fundamental ecological process that promotes abundant herds, whose effects cascade up and down terrestrial food webs. Migratory ungulates provide the prey base that maintains large carnivore and scavenger populations and underpins terrestrial biodiversity (fig. S1). When ungulates move in large aggregations, their hooves, feces, and urine create conditions that facilitate distinct biotic communities. The migrations of ungulates have sustained humans for thousands of years, forming tight cultural links among Indigenous people and local communities. Yet ungulate migrations are disappearing at an alarming rate (*1*). Efforts by wildlife managers and conservationists are thwarted by a singular challenge: Most ungulate migrations have never been mapped in sufficient detail to guide effective conservation. Without a strategic and collaborative effort, many of the world's great migrations will continue to be truncated, severed, or lost in the coming decades. Fortunately, a combination of animal tracking datasets, historical records, and local and In-

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Over 1,300,000 blue wildebeest migrate in a 600-km circuit every year between the Serengeti plains in Tanzania and the Masai Mara in Kenya searching for food and water. Such seasonal movements are becoming more difficult as the human footprint expands.

digenous knowledge can form the basis for a global atlas of migrations, designed to support conservation action and policy at local, national, and international levels.

NEW TECHNOLOGY, NEW DISCOVERIES

New technologies have enabled precise mapping of long-distance migrations and are revealing that the movements of ungulates across the globe are more diverse and behaviorally complex than previously recognized. When animal tracks are overlaid on dynamic maps of seasonal resources, they reveal diverse migration patterns, from long-distance movements across climatic gradients, to shorter elevational movements to access alpine habitats. Recent discoveries span several continents (see the figure). In 2014, a zebra migration was discovered that stretches 500 km across Namibia and Botswana, a new record for the species (*2*). On the Mongolian Steppe, gazelle were found to explore an area roughly the size of Hungary (100,000 km^2) over their lifetimes (*3*). In Ethiopia's Gambella National Park, researchers discovered that white-eared kob migrate in an 860-km circuit connecting to the Boma-Bandingilo migration in South Sudan, extending the species' known migratory range (*4*).

Detailed movement data are also leading to new ecological discoveries. A key finding suggests that in some species, migratory behavior is a type of animal culture that must be learned and transmitted between generations. In North America, bighorn sheep and moose failed to migrate when first translocated into new landscapes. Over multiple generations, however, individual populations gained knowledge to move seasonally and find forage at broader scales, and they became more migratory (*5*). This reliance on culture carries a stark warning for conservation—namely, that the persistence of a migration corridor may depend on the survival of individuals that possess the knowledge to travel along it.

MIGRATIONS IN DANGER

Historical accounts describe numerous migrations that have been lost. The millions of Cape springbok that once traversed the Karoo landscape of South Africa were eradicated by fencing, disease, and hunting at the end of the 19th century. In Kenya's Kajiado County, migrations of wildebeest, zebra, and Thomson's gazelle have collapsed owing to competition with livestock and massive land conversion. When the tens of millions of bison that roamed North America were slaughtered, the abundance necessary to promote migration was also lost. The Yellowstone population is one of just a few bison herds that still migrate.

Barriers have long restricted the free movement of migratory herds. Today, nomadic movements of Mongolian gazelles and khulan are constrained by railroads and border fences (*3*). In Botswana, veterinary fences built in the 1950s caused the death of hundreds of thousands of wildebeest. In Russia's Kola Peninsula, the construction of a railroad divided the wild reindeer population and eliminated the longest of the region's migrations. In Europe, red deer must now navigate a landscape shaped by millennia of human infrastructure and habitat fragmentation, exploiting seasonal cycles of forage only where their routes are not disrupted (see the figure). Recent estimates project that 25 million km of new roads will be built across the globe by 2050 (*6*), which will constrain and sever seasonal migrations even further.

Climate change poses an additional threat. Many ungulates time their migrations to exploit patterns of plant green-up and other key weather events. Droughts are becoming commonplace, making it more difficult for animals to move in synchrony with green-up and access the best forage (*7*). In southern Africa, zebra, blue wildebeest, and African elephant migrations are driven by water availability, which is changing as rainfall patterns shift, leading to population declines of some species (*8*). In the Arctic, barren-ground caribou (fig. S2) have shifted migration and calving dates by up to 0.5 days per year over the last three decades in response to climate change (*9*). Preliminary tracking data indicate that wild reindeer in the Taimyr-Evenk population of Russia are showing similar effects in response to Arctic warming of 4°C over the past 40 years. An extreme example has been observed in endangered Dolphin and Union caribou in the Canadian Arctic Archipelago, which experience mass mortality when they break through thin ice caused by delayed fall freeze-up (*10*). Migratory ungulates are thus doubly challenged by changes in climate that alter snow, forage, and water distribution, combined with barriers that prevent them from adapting their movement tactics as conditions change.

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EXISTING CONSERVATION AND POLICY

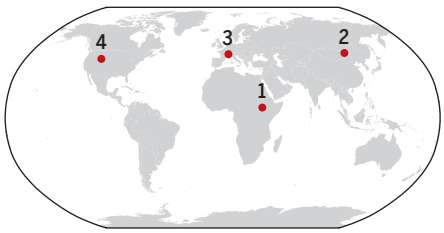
The Convention on Migratory Species (CMS) advanced conservation by formally recognizing animal migrations in 1979. Yet, tracking data were not available in sufficient detail to map ungulate migrations until recently, preventing Parties to the Convention from developing concrete policies to protect migrations. New technologies and methods now allow corridors to be mapped in detail from tracking data (*11*). When migration paths are overlaid on landscapes within a geographic information system, barriers and other threats can be identified, pointing towards effective conservation solutions.

Globally, policies to protect ungulate migrations typically require migration maps or animal tracking data. In 2008, the Path of the Pronghorn in Wyoming (USA) became the first federally protected corridor, when a map based on telemetered animals was included in the Bridger-Teton National Forest Plan, which required that forest managers consider impacts to the corridor (see the figure). In 2018, the Tanzania Wildlife Conservation Regulations were signed, establishing a means to designate wildlife corridors between the country's protected areas. In 2011, Angola, Botswana, Namibia, Zambia, and Zimbabwe signed an international treaty creating the Kavango-Zambezi Transfrontier Conservation Area (KAZA). The KAZA aims to facilitate a network of protected areas linked by dispersal corridors and migratory routes delineated from tracking data of species like blue wildebeest, African buffalo, zebra, and elephant. In Kazakhstan, the Yrgyz-Torgai-Zhylanshyk "ecological corridor"—the first of its kind for the country—was created to allow migration of the Betpakdala saiga population between protected areas. Ungulate tracking data have also facilitated the expansion of protected areas. In Mongolia, the movements of khulan beyond the border of Great Gobi B Strictly Protected Area during the extreme winter of 2009–2010 prompted a doubling of the protected area in 2019.

For classic back-and-forth migrations, corridors delineated from empirical tracking data are capable of identifying even more targeted conservation solutions. In Wyoming (USA), for example, GPS mapping of a high-use mule deer corridor (*11*) allowed researchers to identify a 400-m bottleneck used by ~5000 deer (see the figure). When this land was threatened with subdivision, The Conservation Fund raised funding to purchase and protect it as a Wildlife Habitat Management Area. Enumerating the threats to this corridor also prompted the State of Wyoming to "designate" migration corridors and manage them for "no net loss of function." In the first quarter of 2019, the US ad-

Ungulate migrations around the world

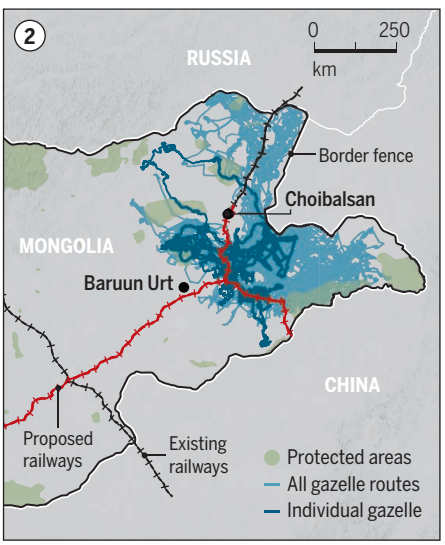
Animal tracking studies are being conducted around the world, facilitating discovery of previously unknown movements and making it possible to map migrations and identify threats with precision.



White-eared kob

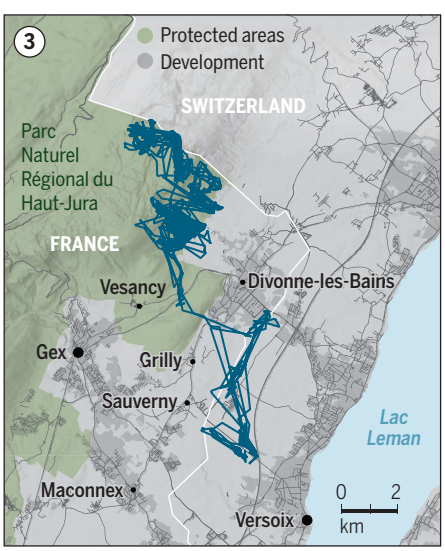
In 2018, white-eared kob were discovered to make an 860-km migratory circuit between Ethiopia and South Sudan, extending the known migratory range. The herds traverse working landscapes consisting of oil and gas concessions, hotspots of armed conflict, and commercial agricultural developments in the Boma-Gambella landscape.

Mongolian gazelle



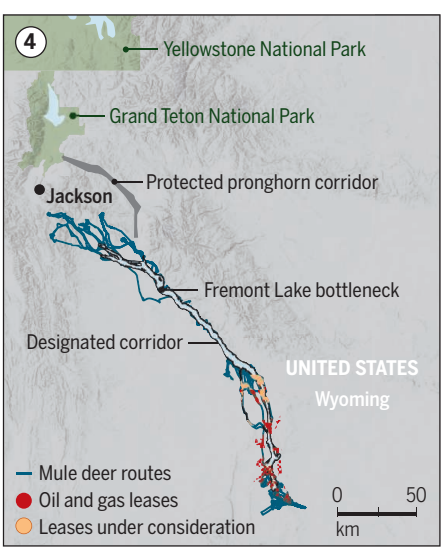
On the Eastern Steppe, the nomadic movements of Mongolian gazelle are an order of magnitude larger than the region's protected areas despite being bound by impermeable border fences with Russia and China. A proposed railroad threatens to further constrain their wide-ranging movements.

Red deer



Ungulates living in human-dominated landscapes may try to maintain migration, but their movements are often constrained and truncated by human settlements and associated infrastructure. Red deer at the Swiss-French border navigate a semi-urban landscape using remaining forest patches interrupted by highways and fences.

Mule deer



In 2014, a 242-km mule deer migration was discovered in Wyoming (U.S.) and analyzed to delineate the high-use corridor. The corridor was formally "designated" by state officials in 2016, prompting protection of the Fremont Lake bottleneck and deferral of oil and gas leases that would have put the migration at risk.

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ministration deferred 5674 ha of oil and gas leases on federal land because drilling was deemed too risky to the functioning of the corridor.

Lost migrations also need to be inventoried and mapped by leveraging Indigenous, local, and expert knowledge. Although there are only a few examples where an ungulate migration has been restored, mapping historical migrations provides an important baseline to evaluate changes and potential future conservation opportunities. In some South American rangelands, for example, conservationists are hopeful that ranch abandonment will create opportunities to restore lost migrations of guanacos and globally threatened huemul deer.

BETTER POLICIES THROUGH BETTER MAPS

The next decade is likely to witness a massive global effort to combat the twin crises of biodiversity loss and climate change, and maps of the world's ungulate migrations can inform these efforts. We therefore propose a global atlas of ungulate migration, built from tracking studies and traditional knowledge. We envision a digital archive that translates migration data into actionable migration maps that are standardized, in a central database, and publicly available. Together with new guidelines for conserving ecological connectivity (*12*), this global atlas will provide the migration maps that planners and policy-makers need to develop corridor and connectivity plans at national and regional scales, review impacts of potential developments, and consider new policies to conserve migrations.

Most of the world's governments have signed on to the Convention on Biological Diversity (CBD; 193 parties) and the CMS (132 parties). To adhere to these conventions, governments need reliable information on where biodiversity and ecological processes like migrations occur. Under the CBD, the Conference of the Parties will meet in 2021 to establish the Post-2020 Global Biodiversity Framework, which many entities hope will target at least 30% of Earth's surface for some form of protection by 2030. Signatories to the CBD are encouraged to update National Biodiversity Strategy and Action Plans, nearly 90% of which lack plans for maintaining connectivity or conserving migrations (*13*). A global migration atlas can help define the areas to be targeted by these new efforts.

Internationally funded development projects are accelerating across Asia and Africa (*6*), driven in part by China's Belt and Road Initiative. Long-distance migrations are highly susceptible to cumulative impacts, such as those that span hundreds of kilometers or cross international boundaries. Although international financing institutions are developing new policies that aim to reduce impacts to wildlife connectivity, adequate migration maps are lacking. A detailed atlas would allow these institutions to fund smart and proactive actions, such as project relocation or redesign, to reduce impacts to existing migrations across international boundaries.

Data on protected areas, Key Biodiversity Areas, and the distribution of threatened species are provided to the public and investors through the Integrated Biodiversity Assessment Tool (www.ibat-alliance.org). These data allow projects to identify environmental concerns early, avoid impacts to biodiversity, and reduce financial risks. Key Biodiversity Areas can be used to identify migratory stopover or bottleneck sites, but standardized and publicly available maps of migration pathways are also required to inform policies to maintain connectivity.

Mapping the world's ungulate migrations will also make clear that numerous stakeholders work the lands that underpin these migrations or benefit from the herds directly. The cultural traditions and identity of the Inuit and Tlicho, for example, are based on livelihoods that depend on migratory caribou (*14*). Whether for mule deer in Wyoming, caribou in the Arctic, or gazelle across the Mongolian steppe, migration mapping highlights that such journeys traverse habitats that have been stewarded for generations by local communities and private landowners. Expansive migrations across working landscapes thus demonstrate the need for sustainable conservation grounded in a social-ecological systems approach that considers the costs and benefits to people whose lands are essential for sustaining connectivity (*15*).

Developing a global atlas of ungulate migrations will require unprecedented collaboration to assemble the required knowledge, data, and analytical tools. Fortunately, tracking datasets are growing each year, and existing data can be used to map many known migrations. Unmapped migrations can be targeted for new field studies, and historical knowledge can be digitally archived. To coordinate this effort, we have created the Global Initiative for Ungulate Migration (GIUM). Under the auspices of CMS, and in partnership with the Convention's secretariat, the GIUM brings together scientists, conservationists, and wildlife managers worldwide to create a collaborative knowledge base, develop a global atlas, and catalyze new conservation actions and policies.

Many efforts, from regional regulations to national legislation and international treaties, seek to sustain the world's biodiversity. A new global atlas on ungulate migration will help target action under all existing frameworks. First, migration maps will be derived from empirical data, using established analytical methods, and the resulting maps will be peer-reviewed and centrally curated at the CMS (https://www.cms.int/gium). The recent collaborative effort by the US Geological Survey and state wildlife agencies to map ungulate migrations of the western US is a timely example of this approach (see supplementary materials). Second, empirical migration maps depict the actual movements animals make on an annual basis. Thus, the footprint of migration maps can be readily integrated into existing spatial conservation planning. For example, the recent International Union for Conservation of Nature Connectivity Guidelines (*12*) establish criteria for "ecological corridors," some of which could be delineated by mapped migration corridors. Finally, the GIUM itself is composed of both scientists and conservationists working together to compile disparate migration data in one place and explore the best means to incorporate migration maps into existing conservation frameworks.

Like much of the world's biodiversity, migrations need to be mapped and archived before they are lost. Such an ambitious effort could guide the locations of new roads, fences, and other infrastructure and identify the habitats that should remain undeveloped to safeguard the seasonal movement of ungulates, the ecosystems they sustain, and the diverse benefits they provide to humanity. ■

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science.sciencemag.org/content/372/6542/566/suppl/DC1

10.1126/science.abf0998

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Science **372** (6542), 566-569.
DOI: 10.1126/science.abf0998

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