Supplementary Materials for

Mapping out a future for ungulate migrations

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Supplementary Text:

Threats to wildebeest migration in Kenya

In Kenya's Kajiado County the wildebeest population migrating between the Nairobi National Park (117 km2, 1º 20′ -1º 26′ S and 36º 50′-36º 58′ E) and the adjoining Athi-Kaputiei Plains (2200 km2) decreased by 98% from 30,000 animals by 1978 to 509 by 2014 (*1*, *2*). Migratory wildebeest in the neighbouring Amboseli ecosystem also declined by 83% from 16,292 in 1977 to 2,738 in 2011 (*3*). The collapse of both wildebeest migrations was concurrent with range contractions driven by extreme land fragmentation and transformations. Wildebeest were especially vulnerable to the anthropogenic impacts in their wet season dispersal ranges located outside the four protected areas in Kajiado County (*1*, *2*).

Materials and Methods:

Collection of wildlife movement data

Barren-ground caribou—Barren-ground caribou (*Rangifer tarandus groenlandicus*) have been monitored by the Government of the Northwest Territories (GNWT) with GPS/ARGOS satellite radio collars since 1996. Collaring takes place in late winter (usually March), primarily via helicopter net gunning; no drugs are used. The captures are under a Standard Operating Procedure (SOP) and capture permits are supervised by an Animal Care Committee that includes a wildlife veterinarian. Over the period of monitoring, the duty cycles have ranged from one per day or every 3-5 days (early satellite collars), to every hour (more recent collars). The map in Figure S2 aggregates the tracks of 937 individuals from seven major herds spanning 1996 km west to east in northern North America. The data are archived and regularly updated on Movebank (https://www.movebank.org/cms/movebank-content/arctic-animal-movement-archive#citation) and as part of the Arctic Animal Movement Archive (AAMA) (*4*). Information on existing and proposed roads in the NWT was provided by the GNWT Department of Infrastructure.

Red deer—Red deer (*Cervus elaphus*) from Switzerland (Fig. 1) were captured in autumn and winter with a dart gun from a vehicle. All individuals were fitted with an ear tag and a GPS collar (*5*). Deer were captured by official gamekeepers based on standard protocols approved by the Federal office of the environment. The single individual trajectory is archived in Movebank (https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study1469693468). The red deer in Stelvio National Park (Italy) was captured in October 2009 by free range darting from a vehicle. The female deer was marked with an ear tag and a GPS collar with reflectors, according to standard protocols approved by the National Wildlife Institute. The single individual trajectory (Fig. S2) is archived on Movebank (https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study1469680858)

African elephant— The elephant (*Loxodonta africana*) shown in Figure S2 was anesthetized by a veterinarian from the ground and equipped with a GPS collar in November 2012, under permit #15/2012 from the Zimbabwe Parks and Wildlife. Data are available on Movebank (Study ID: "African elephant (Migration) Chamaillé-Jammes Hwange NP", Animal ID: "AWT_545", https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study307786785).

Mule deer—The mule deer (*Odocoileus hemionus*) movement data shown in Figure 1 were first collected in 2011 for a study of migration tactics (*6*). The high-use corridor was delineated from movement data following the approach of Sawyer et al. (*7*). In 2016, the Wyoming Game and Fish Department designated this corridor as vital habitat according to state policy (*8*). A description of the spatial data and analyses necessary to generate the migration lines and designated corridor files are available in a 2020 report by the US Geological Survey (*9*), and the data are publically available through the USGS ScienceBase archive (*10*). These migration data are also viewable as a dynamic map at https://westernmigrations.net.

Oil and gas leasing data displayed in Figure 1 were compiled by The Wilderness Society, sourced from the Bureau of Land Management (BLM) Navigator (*11*) and EnergyNet (*12*), which is a marketplace for oil and gas transactions. In the 3rd quarter of 2019, the BLM deferred 5674 ha (14,020 acres) of oil and gas leases within this high-use mule deer corridor (*13*).

Pronghorn—The pronghorn (*Antilocapra americana*) corridor depicted in Figure 1 has been a focal point for the conservation of migration in the western U.S. for nearly two decades (*14*, *15*). The corridor delineation was included in a revision to the Bridger-Teton Forest Plan in 2008 (*16*) and is redrawn from (*17*) with permission.

Wildebeest—The wildebeest data in this article (Fig. S1, panel 1) represent a selection of animals from a long-term GPS collaring study (1999-present) managed by the Serengeti Biodiversity Program. Reproductively active female wildebeest from the Serengeti ecosystem were fitted with GPS collars (Followit, formerly 'Televilt,' GSM or Iridium transmitters). Animals were immobilized by professional wildlife veterinarians from the Tanzania Wildlife Research Institute (TAWIRI) and the Tanzania National Parks (TANAPA) using an injectable dart containing 4-6 mg of etorphine and 80–100 mg of azaperone, shot from a stationary vehicle using a CO_2 charged Tel-Inject rifle. Professional wildlife veterinarians followed the handling and animal care protocols established by TAWIRI with permissions from the Tanzania Commission of Science and Technology (permit no: 2021-033-NA-2007-034). The datasets presented in this study are available on the Movebank Data Repository (www.movebank.org, Study ID 409031855) with approval from JGC Hopcraft.

Lions—The lion data presented in this article (Fig. S1, panel 2) come from the long-term Serengeti Lion Project managed by Craig Packer. The data represent the movement of a nomadic male lion (CV37) who was GPS tracked from 16-Apr-06 to 3-Mar-07. The animal was immobilized by veterinarians from the Tanzania Wildlife Research Institute (TAWIRI) and Tanzania National Parks (TANAPA) with permission from the Tanzania Commission of Science and Technology and IACUC permit 0801A24001 from the University of Minnesota. The lion was captured using an injectable dart using a DanInject rifle from a stationary research vehicle. The collar was removed after the study using the same procedure. The data are available on Movebank (www.movebank.org, Study ID 1473348957).

Vultures—The vulture data presented in this article (Fig. S1, panel 3) come from research conducted by Corinne Kendall and Munir Virani in the Masai Mara National Reserve, Kenya. All vultures were captured at baited carcass sites using nooses by qualified animal handlers from Princeton University and the Peregrine Fund. Vultures were fitted with backpack-attached GSM-GPS transmitters providing 4-6 points per day between May 2009 and March 2011. Backpack harnesses perish over time and drop off the animal, leaving it free to live naturally. Permission for the research was granted from the Kenya National Commission for Science, Technology & Innovation (NACOSTI, permit no NCST/5/002/R/448), and received IACUC approval from Princeton University protocol no 1751. Data were previously published in Kendall et al. (*18*) and can be accessed on the Movebank Data Repository (www.movebank.org, Study ID 5465787) by request to C. Kendall.

Base Map Data— Base data for maps were sourced from Esri, Natural Earth Data, and Open Street Map. Protected area data were sourced from UNEP-WCMC and IUCN, Protected Planet: The World Database on Protected Areas (WDPA)/The Global Database on Protected Areas Management Effectiveness, Cambridge, UK. Available online at: www.protectedplanet.net.

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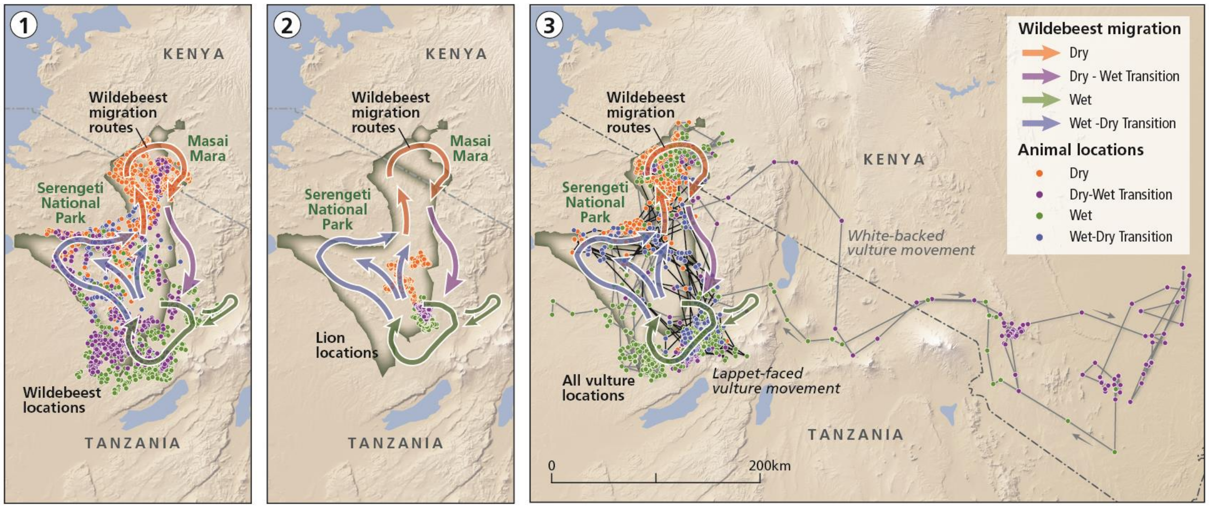
Migration underpins terrestrial ecosystems

The annual migration of 1.3 million wildebeest, plus several hundred thousand zebra, gazelle, and eland, influence ecological dynamics in the Serengeti ecosystem. This mass migration of herbivores supports a diverse predator and scavenger community that tracks their year-round movements. Migrating wildebeest routinely spill out beyond the boundaries of Serengeti and Masai Mara National Parks, which were established to protect the ecosystem.



1 Wildebeest migration
GPS locations for several wildebeest moving between the dry (orange) and wet season (green) illustrate the generalized migration route.

2 Lion movements
Despite being tied to their home ranges, lion prides follow the seasonal flux of ungulate prey (GPS locations illustrate the year-round track of one lion).

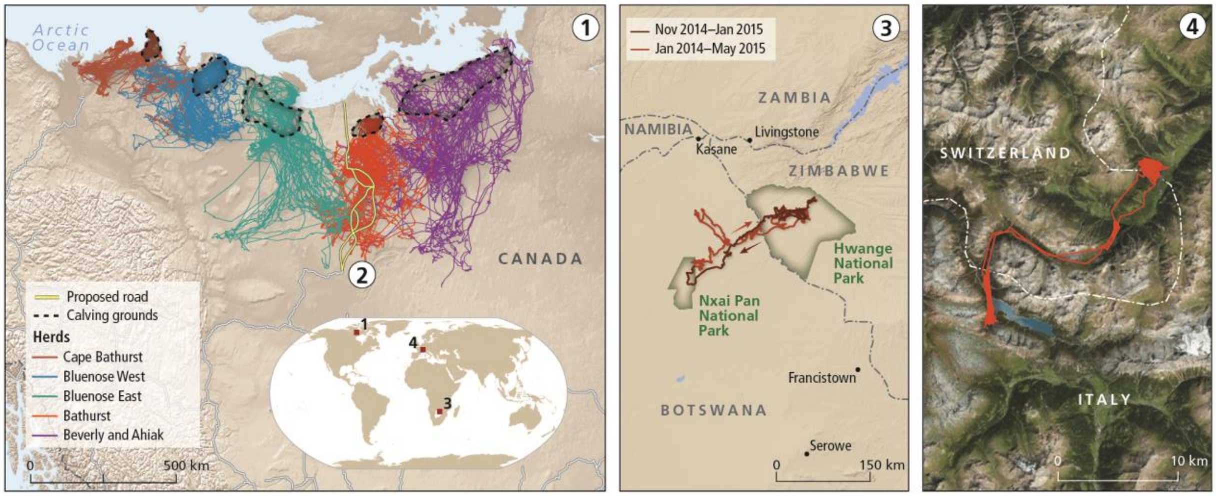
3 Vulture movements
Several species of vultures scavenge extensively on the carcasses of migratory wildebeest, synchronizing their movements to the dry season range from hundreds of kilometers away. The track of a lappet-faced vulture is shown, along with the more wide-ranging movements to the east of a white-backed vulture.

Fig. S1.

Migration underpins terrestrial ecosystems. The annual migration of 1.3 million wildebeest, plus several hundred thousand zebra, gazelle, and eland, influence ecological dynamics in the Serengeti ecosystem. This mass migration of herbivores supports a diverse predator and scavenger community that tracks their year-round movements. Migrating wildebeest routinely spill out beyond the boundaries of Serengeti National Park and Masai Mara National Reserve, which were established to protect the ecosystem.

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 migration and identify threats with precision.



1 Barren-ground caribou
In the Northwest Territories and Nunavut, caribou range over vast areas of Arctic tundra and boreal forest before converging to give birth on herd-specific calving ranges near the coast.

2 A proposed road
Migration tracking data is being used to evaluate proposed alternatives for an all-season road (yellow line) that would cut through the post-calving, summer and winter range of the Bathurst herd, which has declined 97.5% since 2000.

3 African elephants
Elephants leave Botswana and make a transboundary migration across unprotected areas to find permanent surface-water in their dry season range in Zimbabwe. A representative track of one elephant is shown.

4 Red deer, European Alps
In remote habitats, red deer are still able to fully exploit the abundance of seasonal forage by migrating across mountain ranges.

Fig. S2 *(additional panels to main map figure).*

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 migration and identify threats with precision.