ECOLOGICAL MONITORING

Ecological insights from three decades of animal movement tracking across a changing Arctic

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The Arctic is entering a new ecological state, with alarming consequences for humanity. Animal-borne sensors offer a window into these changes. Although substantial animal tracking data from the Arctic and subarctic exist, most are difficult to discover and access. Here, we present the new Arctic Animal Movement Archive (AAMA), a growing collection of more than 200 standardized terrestrial and marine animal tracking studies from 1991 to the present. The AAMA supports public data discovery, preserves fundamental baseline data for the future, and facilitates efficient, collaborative data analysis. With AAMA-based case studies, we document climatic influences on the migration phenology of eagles, geographic differences in the adaptive response of caribou reproductive phenology to climate change, and species-specific changes in terrestrial mammal movement rates in response to increasing temperature.

The Arctic and adjacent regions are experiencing the most rapid climate and environmental changes on Earth, caused primarily by anthropogenic greenhouse gas emissions (*1*). Notable trends include warming winter temperatures, ice loss, and earlier spring snowmelt. These changes profoundly affect conditions experienced by animals, including food availability, interspecific competition, predation, and increased human disturbances (*2*). Impacts of climate change on Arctic vertebrates include rapid poleward range shifts (*3*, *4*); phenological trophic mismatches (*5*); and changes in migration (*6*), foraging, and predator–prey dynamics (*7*). Because rapid environmental change in the Arctic challenges the ability of the region's fauna to adapt, a primary response will likely occur through phenotypic plasticity in the patterns, locations, and timing of their movements (*2*). Documenting and understanding these changes requires multidecadal, pan-Arctic data at multiple trophic levels.

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We demonstrate the ecological utility of the Arctic Animal Movement Archive (AAMA), an active, collaborative collection of animal tracking datasets (supplementary materials). Marine ecology archives, such as IOOS-ATN, IMOS, OBIS-SEAMAP, and RAATD (*8*), provide insight regarding space use, movement, and connectivity (*9*–*11*). Terrestrial animal movement archives are rare and tend to have a regional or taxonomic focus (*12*). AAMA is the first Arctic-focused archive with both terrestrial and marine data and is hosted on the global Movebank database. The geographic scope of the AAMA (Fig. 1) includes the Arctic, Arctic marine, and subarctic "boreal forests/taiga" regions defined elsewhere (*13*, *14*) (see also supplementary materials). Currently, the archive contains more than 15,000,000 occurrences of 8000 individuals representing 86 species, from 1991 to the present (figs. S1 and S2 and tables S1 to S4). Combining data from multiple AAMA studies, we show evidence of (i) climate drivers of golden eagle migration phenology, (ii) climate adaptation of parturition by caribou, and (iii) consequences of increased temperature and precipitation on movements of mammalian predators and herbivores.

Behavioral flexibility enables migrants to optimize energy expenditure during migration and adjust arrival at summering grounds (*15*, *16*). We used tracking data from 103 individuals during 1993 to 2017 [supplementary materials (case study 1) and table S5] to examine arrival timing to breeding grounds of northward-migrating golden eagles ("summering"), modeling it with predictors for age, sex, summering onset latitude, year, and the preceding winter's mean Pacific decadal oscillation index (PDO).

Mean summering date changed slowly over 25 years (–0.5 days/year). The long-term trend differed among age classes, with adults arriving earliest, then subadults, and then juveniles, and it was influenced by winter climate (PDO) (Fig. 2 and tables S8 and S9). Eagles of all age classes began summering later at northern latitudes (1.08 days/degree). The significant interaction of year and previous "warm-phase" PDO explains earlier summering dates for subadults and juveniles, highlighting their known responsiveness to environmental conditions (*16*). These warm-phase winters cause a warmer and drier climate with reduced snowpack and an earlier snow-free date. Earlier adult arrival to summering grounds should result from selection and competition for territories, yet local climatic variables affect eagle condition before, and energy expenditure during, northward migration (*16*). For subadults sampled after 2011, the direct effect of PDO is significant (–8.27 days), whereas the full subadult dataset does not show a significant effect of winter PDO (Fig. 2). This period-related difference in inference of climatic drivers highlights the importance of compiling long-term, multigenerational observations. Given the importance of the winter PDO and known impacts of global climate change, golden eagles could face age-specific challenges during migration and at their warming Arctic summering grounds.

The timing of parturition is a key to the demography of wildlife populations and can be an adaptive response to climate shifts (*17*). For many mammals, the period from late pregnancy through weaning has the highest energetic demands and thus is timed to occur when vegetation productivity is highest (*18*). Caribou occur in five different ecotypes (Fig. 3) across boreal and Arctic North America and are facing global declines (*19*). On the basis of data from 917 individuals during 2000 to 2017 in northern Canada, we used characteristic patterns of low movement during the calving season to estimate 1630 parturition dates in five populations of barren-ground, northern and southern boreal woodland, and northern and southern mountain woodland caribou [supplementary materials (case study 2) and table S6].

We found differences in parturition timing and trends among the five populations. The southern and northern boreal populations calved earliest, followed by northern and southern mountain populations (table S10). Barren-ground caribou calved later despite occupying a similar latitudinal range as the northern boreal caribou (Fig. 3). Most importantly, barren-ground and northern woodland caribou, but not southern woodland caribou, exhibited significant trends toward earlier parturition [0.4 to 1.1 days/year (table S10)]. This is the first continental-scale retrospective evidence of potential adaptive responses to climate trends by caribou.

Animals conserve energy by modifying their behavior in response to weather conditions, with important implications for individual fitness and species resilience under climate change (*20*). We tested for effects of temperature and precipitation on seasonal movement rates (in meters per minute) using records from 1720 individuals of two herbivore and three predator species (black bear, grizzly bear, caribou, moose, and wolf) during 1998 to 2019 [supplementary materials (case study 3) and table S7]. We predicted that winter movement rates would decline relative to summer, when energetic costs of self-maintenance would be highest. Rate would also decline within seasons, during weather conditions that increase the energetic cost of movement (e.g., snow that increases energy requirements for movement or higher ambient temperatures during the summer that accelerate metabolism).

All species exhibited lower movement rates during winter relative to summer (Fig. 4). As

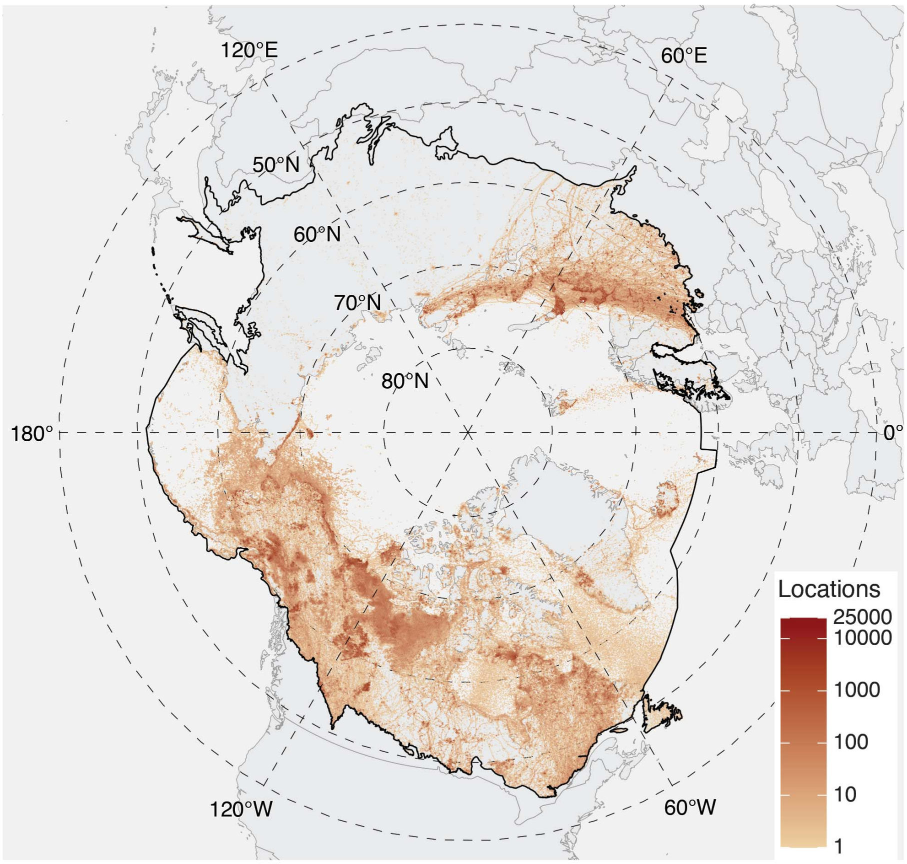

Fig. 1. Map of the AAMA boundary and data. Density of animal locations (number of observations per ~100 km^2) at logarithmic scale characterizes data availability, not animal density or utilization.

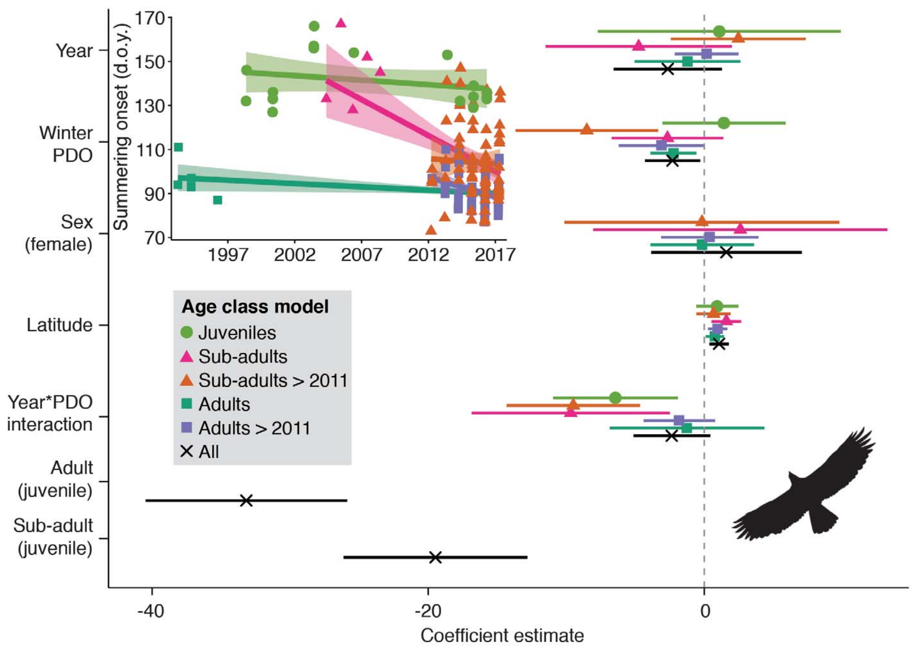

Fig. 2. Changes in the onset date of golden eagles' summering. Coefficient estimates (±95% confidence intervals) reflecting age-specific changes in response to year, previous winter PDO, sex (reference: females), latitude, interaction of year and PDO, and age class [reference: juveniles (tables S8 and S9)]. (**Inset**) Time series of model-estimated summering. d.o.y., day of year.

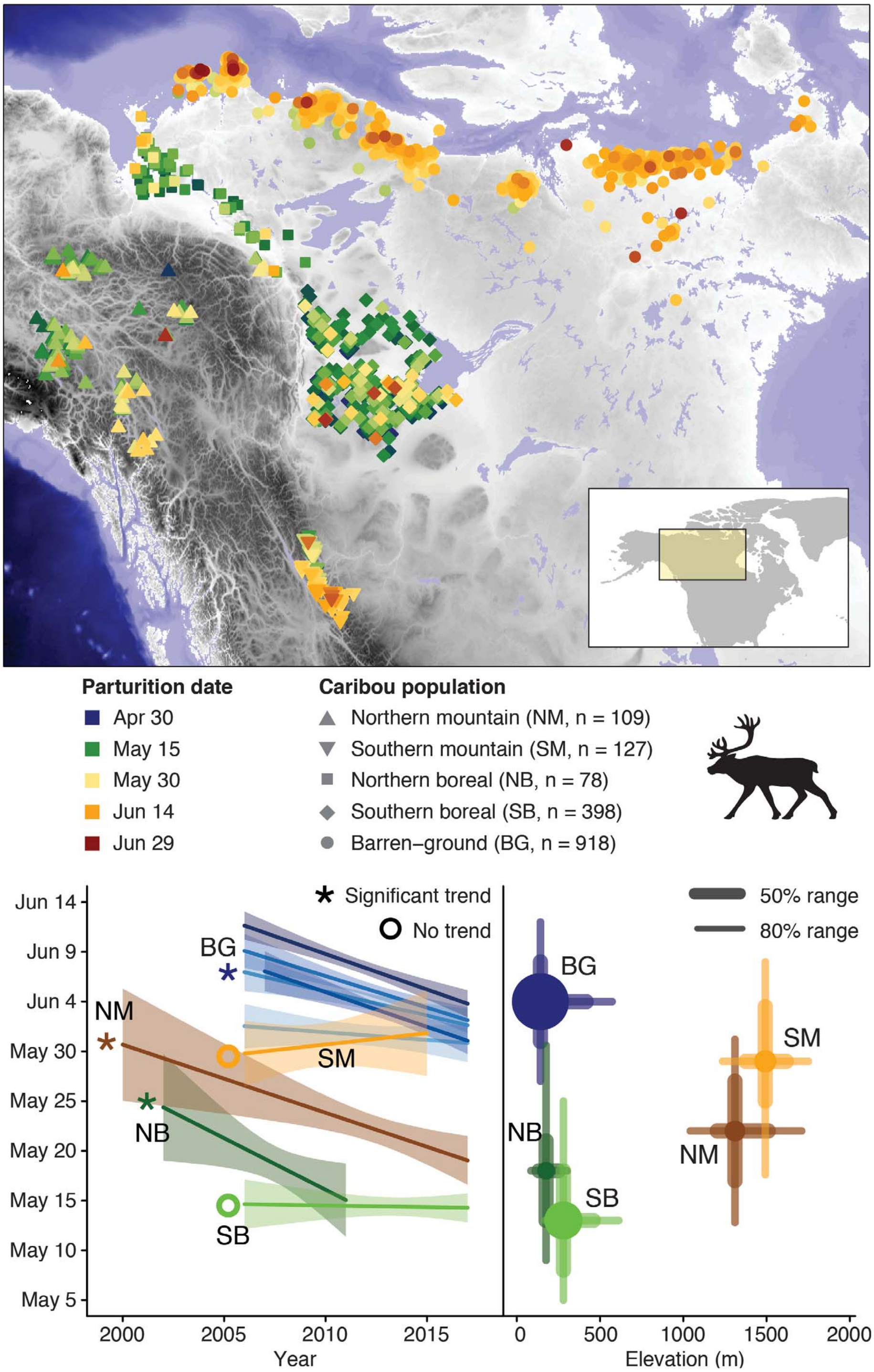

Fig. 3. Climate change adaptation of parturition times (PT) of caribou. (**Top**) PT by population. (**Bottom left**) PT trends by population, including five barren-ground subpopulations. (**Bottom right**) PT dates by elevation.

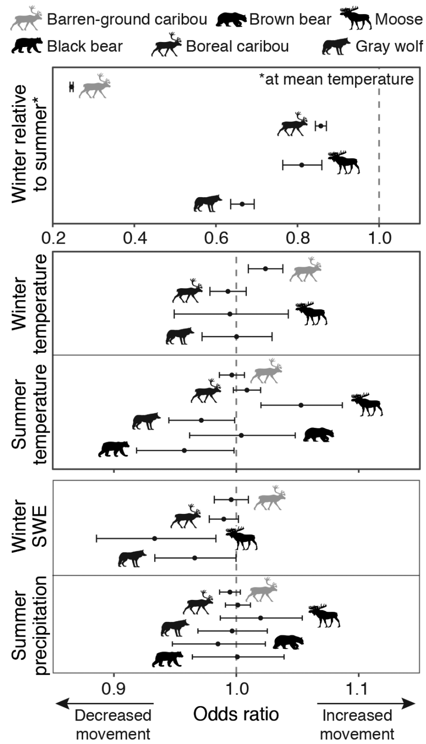

Fig. 4. Changes in species-specific movement rates in response to daily maximum temperature, summer precipitation, and winter snow–water equivalent (SWE). Odds ratios for continuous covariates represent the positive or negative change in movement rates per one unit change in temperature or precipitation, respectively. Ratios were identified as neutral if credible intervals overlapped with 1.0.

temperatures increased in summer, wolves and black bears slowed their movement rates, whereas moose increased their movement rates. In winter, only barren-ground caribou increased movement rates as temperature increased. Snow impeded wolves, boreal caribou, and moose, whereas all species were generally insensitive to summer precipitation. These patterns may reflect asynchronous responses to climate change within and across trophic levels. Climate-driven variation in animal activity is likely to affect species interactions, altering energy expenditure, encounter rates, and foraging success with demographic implications for both predators and prey.

As we demonstrate, the AAMA provides a solution to Arctic data collection and sharing challenges. It serves as a critical baseline and resource to identify early signals of local or large-scale changes in animal distribution, movement responses, and adaptive traits. Continued shifts in phenology in the Arctic pose challenges to migratory species that encounter changing seasonal fluctuations along migration routes and at Arctic summering and southern wintering grounds (*21*). Key drivers of population responses, such as migration, parturition, and foraging movement, are undergoing rapid changes, suggesting that climate change is affecting animals in ways that will shape the future of the Arctic.

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ACKNOWLEDGMENTS

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service, NSF, or NASA. This manuscript has been peer reviewed and approved for publication consistent with USGS Fundamental Science Practices. All tagging studies were performed in accordance with regulations regarding animal-involved research (table S3). **Funding:** NASA NNX15AT91A, NNX15AW71A, NNX15AV92A, NNX15AT89A, NNX15AU20A; NSF 1564380, 1823498, 1560727, 1853465, 1915347. Funding for studies participating in the AAMA are listed in table S4. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. or Canadian state, province, territory, or federal governments. **Author contributions:** S.C.D. and G.B. conceived and drafted the manuscript. N.T.B., J.U.H.E., M.T.H., L.R.P., and L.A.V. managed AAMA data-sharing agreements. S.C.D. organized and curated the AAMA on Movebank, with assistance from M.W. R.K. produced fig. S2. S.L., E.G., and P.J.M. developed the case studies. M.T.H., L.R.P., J.J., E.G., O.C., A.P.K., A.J.H.M., and R.Y.O. assisted with data interpretation. Other authors (listed alphabetically) contributed data to AAMA. All authors contributed to the writing of the manuscript. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** Data supporting the analysis in this manuscript are available through Dryad (*22*). Alaska moose and wolf GPS locations may be made available from K.J. under an agreement with the National Park Service. Links to studies participating in the AAMA (table S1) and instructions for data access are at www.movebank.org/cms/movebank-content/arctic-animal-movement-archive.

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SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/370/6517/712/suppl/DC1
Materials and Methods
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12 March 2020; resubmitted 16 March 2020
Accepted 15 September 2020
10.1126/science.abb7080

Science

Ecological insights from three decades of animal movement tracking across a changing Arctic

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Science **370** (6517), 712-715.
DOI: 10.1126/science.abb7080

Ecological "big data"

Human activities are rapidly altering the natural world. Nowhere is this more evident, perhaps, than in the Arctic, yet this region remains one of the most remote and difficult to study. Researchers have increasingly relied on animal tracking data in these regions to understand individual species' responses, but if we want to understand larger-scale change, we need to integrate our understanding across species. Davidson *et al.* introduce an open-source data archive that currently hosts more than 15 million location data points across 96 species and use it to show distinct climate change responses across species. Such ecological "big data" can lead to a wider understanding of change.

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Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.