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 15,000,000 occurrences of 8600 individuals representing 86 species, from 1991 to the present (figs. S1 and S2 and table S1 to S4). Combining data from multiple AAMA studies, we show evidence of (1) climate drivers of golden eagle migration phenology, (ii) climate adaptation of predator-precy dynamics (7), 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) 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 S5 and S6). Geese 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). Feeders sampled after 2011, the direct effect of PDO is insignificant (~827 days), whereas the full subadult dataset does not show a

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 strategies, 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

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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 (77). 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 (78). Caribou occur in five different ecotypes (Fig. 3) across boreal and Arctic North America and are facing global declines (79). 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 1930 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 S1O)]. 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 (80). 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).
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.

REFERENCES AND NOTES
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