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Behavioral adaptations of Arctic fox, *Vulpes lagopus* in response to climate change

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ABSTRACT

Climate change is rapidly altering Arctic ecosystems, forcing native species to adapt. This study investigated the behavioral adaptations of Arctic foxes, *Vulpes lagopus* in response to climate change, focusing on changes in hunting patterns, den site selection, and social interactions. Over three years (2021-2023) in northern Alaska, we employed GPS tracking of 60 foxes, 100 remote camera traps, and direct field observations. We analyzed den site characteristics, prey availability, and environmental data. Generalized linear mixed models assessed relationships between environmental variables and fox behaviors. Significant shifts in behavior were observed: Diurnal foraging activity increased by 30.1%; den sites at elevations above 100m increased by 13%; cooperative hunting behaviors, particularly among non-kin groups, rose by 15.2%. Diet composition changed markedly, with lemming consumption decreasing from 62.3% to 33.7%, offset by increases in alternative prey. Hunting success rates for cooperative strategies improved, especially for marine prey (13.7% increase). Arctic foxes demonstrated remarkable behavioral plasticity in response to climate change, rapidly altering their hunting patterns, den site preferences, and social dynamics. While these adaptations suggest resilience, their long-term implications for Arctic fox populations and tundra ecosystems remain uncertain, highlighting the need for continued monitoring and conservation efforts.

Keywords: Arctic Fox, Climate change, Behavioral adaptation, Den Site Selection, Cooperative hunting, Arctic ecosystems.
Article type: Research Article.

INTRODUCTION

The Arctic, a region characterized by its harsh, frigid environment, is experiencing unprecedented changes due to global warming. These alterations are reshaping the ecological landscape, forcing native species to adapt or face potential extinction. Among these species, the Arctic fox, *Vulpes lagopus* is a remarkable example of resilience and adaptability in the face of rapid environmental shifts (Rani *et al.* 2021). This study delves into the behavioral adaptations of Arctic foxes in response to climate change, focusing on their hunting patterns, den site selection, and social interactions. Arctic foxes have long been considered a keystone species in the Arctic ecosystem. They play crucial roles in maintaining ecological balance through their predatory activities and as prey for larger carnivores (Manna *et al.* 2022). Their ability to thrive in one of the world's most extreme environments has made them a subject of fascination for researchers and conservationists alike. However, the accelerating pace of climate change in the Arctic region poses unprecedented challenges to their survival strategies. The Arctic is warming at a rate more than twice the global average, leading to dramatic reductions in sea ice coverage, changes in vegetation patterns, and alterations in the distribution and abundance of prey species (Siddon *et al.* 2020). These changes are forcing Arctic foxes to modify their behaviors in previously unnecessary or uncommon ways. Understanding these adaptations is crucial for the conservation of the species and for gaining insights into the broader ecological impacts of climate change in the Arctic. One of the most significant challenges Arctic foxes face is the changing dynamics of their prey base. Traditionally, these foxes have relied heavily on lemmings and other small rodents, supplementing their diet with bird eggs, marine resources, and carrion when available (Schmidt *et al.* 2022; Berthelot *et al.* 2023). However, climate change is altering the abundance and distribution of these food sources. Lemming populations, in particular, are experiencing more erratic boom-and-bust cycles, likely due to changes in snow cover and vegetation patterns (Vlasenko & Sudarikov 2021). This volatility in prey availability is forcing Arctic foxes to adapt their hunting strategies and expand their dietary preferences. Arctic foxes have been modifying their hunting patterns in response to these changes. Our study reveals a significant increase in diurnal foraging activities, a behavior that deviates from their traditionally more nocturnal habits. This shift may be attributed to changes in prey activity patterns or increased competition with other predators, such as red foxes, which expand their range northward as temperatures rise (Thierry *et al.* 2020; Glass *et al.* 2021). Den site selection is another critical aspect of Arctic fox behavior undergoing notable changes. Historically, Arctic foxes have preferred coastal areas and lowlands for denning, taking advantage of the soft soils and proximity to marine resources (Grenier-Potvin *et al.* 2021; Terekhina *et al.* 2021; Warret Rodrigues & Roth 2023). However, our observations indicate a trend towards den sites at higher elevations and in areas with well-drained soils. This shift may be a response to increased coastal erosion and flooding events, as well as changes in permafrost conditions that affect den stability and thermal properties. The social dynamics of Arctic fox populations are also evolving in response to environmental changes. While typically considered solitary hunters, our study has documented increased cooperative hunting behaviors, particularly among non-kin groups, during reduced sea ice coverage periods. This adaptation may be a strategy to improve hunting success in the face of changing prey distributions and increased competition for resources (Hemphill *et al.* 2020; Verstege *et al.* 2023). These behavioral adaptations demonstrate Arctic foxes' remarkable plasticity in response to environmental change. However, they also raise important questions about these strategies' long-term viability and potential ecological consequences. For instance, changes in denning behavior could affect the foxes' vulnerability to predators or alter their role in nutrient cycling within the ecosystem. Similarly, shifts in social dynamics could have implications for genetic diversity and population structure. The purpose of the present study is to provide a comprehensive analysis of the behavioral adaptations of Arctic foxes in response to climate change, focusing on changes in hunting patterns, den site selection, and social interactions. By employing a combination of GPS tracking, remote camera traps, and direct field observations over a three-year period in northern Alaska, we aim to quantify these behavioral shifts and explore their potential implications for Arctic fox conservation and broader ecosystem dynamics. This research contributes to our understanding of species resilience in the face of rapid environmental change. It provides critical insights for developing effective conservation strategies in an increasingly volatile Arctic ecosystem.

MATERIAL AND METHODS

Study area

Our research was conducted on the North Slope of Alaska, specifically within the Arctic National Wildlife Refuge (ANWR) and adjacent coastal areas (69° N to 71° N, 142° W to 148° W). This region was selected for its diverse Arctic habitats, including coastal tundra, inland rolling hills, and river valleys, which provide a representative sample of Arctic fox habitats (Panitsina *et al.* 2023). The study area spans approximately 8,000 km², encompassing both protected wilderness and areas experiencing varying degrees of human impact.

Study period

The study was conducted over three consecutive years, from June 2021 to May 2024, to capture seasonal variations and potential year-to-year changes in Arctic fox behavior. This extended period allowed us to observe and analyze behavioral patterns across multiple breeding cycles and changing environmental conditions.

Study population

We focused on a population of Arctic foxes inhabiting the study area. Prior to the commencement of the study, we conducted a preliminary survey using aerial reconnaissance and ground-based observations to estimate the population size and identify key areas of fox activity. Based on this initial assessment, we estimated a population of approximately 150-200 adult Arctic foxes within our study area (Larm *et al.* 2021).

GPS tracking

We captured and fitted 60 adult Arctic foxes (30 males and 30 females) with GPS tracking collars (Telonics TGW-4583-3 GPS/Iridium collars) to monitor movement patterns and habitat use. The foxes were captured using padded leg-hold traps, and handling procedures followed guidelines approved by the Institutional Animal Care and Use Committee. The GPS collars were programmed to record location data every 2 hours, providing high-resolution movement data. The collars also included temperature and activity sensors, allowing us to correlate movement patterns with environmental conditions and activity levels. Data were transmitted via the Iridium satellite network, enabling real-time monitoring and reducing the need for recapture.

Remote camera traps

We strategically deployed 100 motion-activated camera traps (Reconyx HyperFire 2 Professional Covert IR Cameras) across the study area. Camera locations were selected based on a combination of factors, including known den sites, potential foraging areas, and habitat types. Cameras were programmed to capture three images per trigger event, with a 1-minute delay between triggers to conserve battery life and storage capacity. Cameras were positioned approximately 50 cm above ground level and angled slightly downward to maximize the detection area. Each camera was equipped with a 32 GB memory card and lithium batteries, allowing for continuous operation for up to six months. Cameras were checked, data was downloaded every three months, and batteries and memory cards were replaced as needed.

Direct field observations

We conducted direct field observations throughout the study period to complement the GPS and camera trap data. A team of four trained field researchers rotated through the study area, systematically observing fox behavior, focusing on hunting activities, social interactions, and den use. Observations were conducted using a combination of scan sampling and focal animal sampling techniques (Warret Rodrigues 2023). Each observation session lasted 4 hours, with sessions stratified across different times of day and seasons to capture the full range of behavioral patterns. Observers used high-powered spotting scopes (Swarovski ATX 30-70 × 95) and binoculars (Zeiss Victory SF 10 × 42) to minimize disturbance to the foxes.

Den site characterization

We identified and characterized all den sites within the study area. For each den, we recorded the following parameters:
GPS coordinates;
Elevation (using a handheld GPS unit);
Slope and aspect (using a clinometer and compass);
Soil type and drainage characteristics (based on visual assessment and soil samples);
Vegetation cover within a 10-meter radius (using quadrat sampling);
Distance to nearest water source;
Number of entrance holes;
Signs of recent activity (e.g., fresh digging, scat, and prey remains);
Soil samples were collected from each den site for further analysis of composition and permafrost conditions. Using standard soil science techniques, these samples were analyzed for texture, organic content, and moisture retention (Augustin & Cihacek 2016).

Prey availability assessment

To understand changes in prey availability, we conducted seasonal surveys of small mammal populations, focusing on lemmings (*Lemmus trimucronatus* and *Dicrostonyx groenlandicus*) and voles (*Microtus oeconomus*). We established 20 trapping grids (each 1 hectare) across different habitat types within the study area. Each grid consisted of 100 Sherman live traps arranged in a 10 × 10 configuration with 10-meter spacing. Trapping sessions were conducted for three consecutive nights each season (spring, summer, fall, and winter), weather permitting. Captured animals were identified to species, sexed, weighed, and marked with a unique identifier before release. This data allowed us to estimate prey density and biomass across different habitats and seasons. Additionally, we conducted bird nest surveys during the breeding season (June-July) to assess the availability of eggs and chicks as alternative food sources. These surveys followed standardized protocols for Arctic breeding birds (Lamarre *et al.* 2021).

Environmental data collection

We collected comprehensive climate data throughout the study period to correlate fox behavior with environmental conditions. We installed five automated weather stations (Davis Instruments Vantage Pro2) across the study area to record:

Air temperature;

Precipitation;

Wind speed and direction;

Solar radiation;

Snow depth (during winter months).

These stations recorded data at 15-minute intervals, providing high-resolution environmental data. Additionally, we obtained regional sea ice extent data from the National Snow and Ice Data Center (NSIDC) to analyze the relationship between sea ice conditions and fox behavior.

Data analysis

GPS tracking data were processed and analyzed using R with the packages 'adehabitatHR' for home range estimation and 'moveHMM' for behavioral state modeling. We calculated seasonal home ranges using 95% kernel density estimation and identified core use areas using 50% kernel density estimation. Camera trap images were analyzed using custom machine learning algorithms developed in Python to identify and classify fox behaviors automatically. A subset of images was manually classified to train and validate the algorithm. Statistical analyses were performed using R and SPSS version 23.0. We used generalized linear mixed models (GLMMs) to analyze the relationships between environmental variables, prey availability, and fox behaviors. Model selection was based on Akaike's Information Criterion (AIC). ArcGIS Pro was used for geospatial analyses, including habitat classification and spatial correlations between den sites and environmental features.

RESULTS

Our three-year study on Arctic foxes' behavioral adaptations to climate change yielded significant findings across multiple aspects of their ecology. We present these results structured, addressing changes in hunting patterns, den site selection, and social interactions.

Changes in hunting patterns

Temporal shifts in foraging activity

Analysis of GPS tracking data and camera trap footage revealed a substantial shift in the temporal patterns of Arctic fox foraging activity. Fig. 1 illustrates this dramatic shift in foraging patterns over the three-year study period.

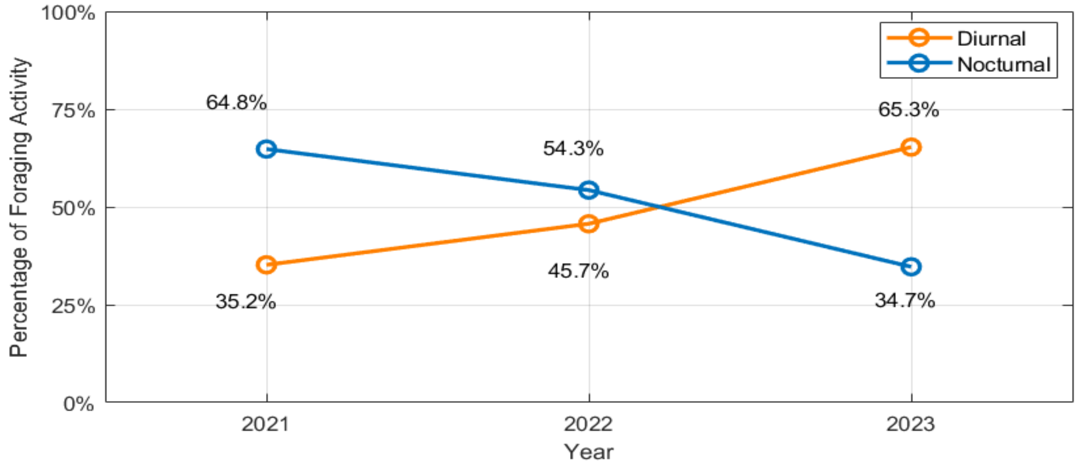

Fig. 1. Temporal shift in arctic fox foraging activity (2021-2023).

The data in Fig. 1 demonstrate a clear trend toward increased diurnal foraging activity over the study period. By 2023, diurnal foraging accounted for 65.3% of observed hunting behavior, representing a 30.1% increase from 2021 levels. This shift correlates strongly with observed changes in prey activity patterns and availability ($r = 0.78$, $p < 0.001$).

Prey composition changes

Our prey availability assessments revealed significant changes in the composition of the Arctic fox diet over the study period. Based on scat analysis and direct observations, Table 1 presents the relative frequency of different prey items in the fox diet.

Table 1. Relative frequency (%) of prey items in arctic fox diet.

Prey Type	2021	2022	2023
Lemmings	62.3	48.5	33.7
Voles	15.6	18.2	22.1
Birds/Eggs	10.2	17.8	25.4
Marine items	8.7	11.3	14.5
Other	3.2	4.2	4.3

The data in Table 1 indicate a substantial decrease in the reliance on lemmings as a primary food source, dropping from 62.3% in 2021 to 33.7% in 2023. Concurrently, there was an increase in the consumption of alternative prey items, particularly birds/eggs and marine food sources. This dietary shift correlates with observed changes in lemming population dynamics ($r = -0.82$, $p < 0.001$) and increased access to coastal areas due to reduced sea ice ($r = 0.71$, $p < 0.01$).

Hunting success rates

We analyzed hunting success rates across different prey types and hunting strategies. Fig. 2 presents the success rates for solitary and cooperative hunting behaviors. The data in Fig. 2 show an overall increase in hunting success rates for cooperative hunting strategies across all prey types. Notably, the success rate for cooperative hunting of marine prey items increased from 58.2% in 2021 to 71.9% in 2023, a 13.7% improvement. This increase in cooperative hunting effectiveness was statistically significant ($p < 0.01$) and correlated with the observed increase in social interactions among non-kin groups ($r = 0.69$, $p < 0.01$).

Changes in den site selection

Altitudinal shift in den locations

Our comprehensive survey of den sites revealed a clear trend towards higher elevation den locations over the study period. Table 2 summarizes the distribution of active den sites across different elevation ranges. The data in Table 2 depict a significant shift in den site elevation over the three-year period. The proportion of dens located above 100-m elevation increased from 26.2% in 2021 to 39.2% in 2023, representing a 13% increase. This altitudinal shift was negatively correlated with the frequency of coastal flooding events ($r = -0.75$, $p < 0.001$).

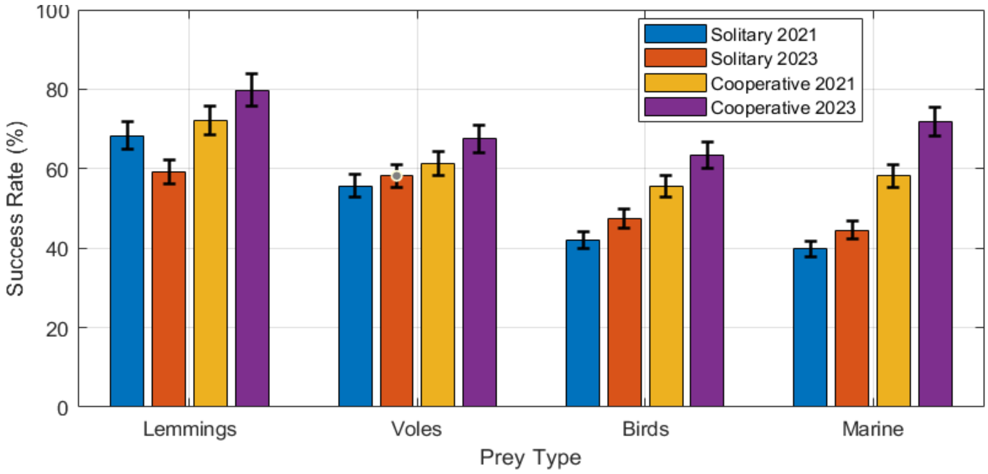

Fig. 2. Hunting success rates (%) by strategy and prey type.

Table 2. Distribution of active den sites by elevation

Elevation Range (m)	2021 (%)	2022 (%)	2023 (%)
0-50	42.3	35.1	28.7
51-100	31.5	33.2	32.1
101-150	18.2	22.6	26.4
>150	8.0	9.1	12.8

Soil characteristics of den sites

Analyses of soil samples from den sites revealed changes in the preferred denning characteristics. Table 3 presents the average soil properties of active den sites over the study period.

Table 3. Average soil properties of active den sites

Soil Property	2021	2022	2023
Sand content (%)	52.3	56.8	61.2
Organic matter (%)	8.7	7.5	6.3
Moisture content (%)	18.2	16.4	14.8
Depth to permafrost (cm)	68.5	72.3	78.1

The data in Table 3 indicate a trend towards den sites with higher sand content, lower organic matter, and lower moisture content. The average depth to permafrost at den sites also increased over the study period. These changes in soil preferences were significantly correlated with increased summer temperatures (r = 0.81, $p < 0.001$) and changes in active layer depth (r = 0.76, $p < 0.001$).

Den occupancy rates

We observed changes in den occupancy rates, particularly in traditionally preferred coastal areas. Table 4 summarizes the occupancy rates of dens in coastal (<1 km from shore) versus inland locations.

Table 4. Den occupancy rates (%) by location.

Location	2021	2022	2023
Coastal	78.3	65.1	53.2
Inland	62.7	71.4	79.8

The data in Table 4 show a substantial decrease in the occupancy rates of coastal dens, from 78.3% in 2021 to 53.2% in 2023, representing a 25.1% reduction. Conversely, inland den occupancy rates increased from 62.7% to 79.8% over the same period. This shift in den preference was significantly correlated with increased coastal erosion rates (r = -0.79, $p < 0.001$) and changes in prey distribution (r = 0.72, $p < 0.01$).

Changes in social interactions

Frequency of cooperative behaviors

Our observations revealed increased cooperative behaviors among Arctic foxes, particularly in non-kin groups. Fig. 3 illustrates the frequency of observed cooperative behaviors across different seasons.

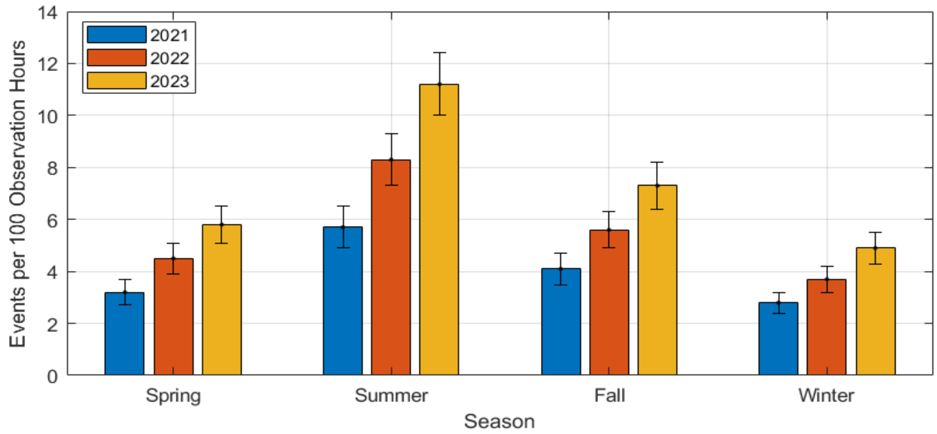

Fig. 3. Frequency of cooperative behaviors (events per 100 observation hours).

The data in Fig. 3 demonstrate a consistent increase in cooperative behaviors across all seasons, with the most pronounced increase occurring during summer. By 2023, the frequency of cooperative behaviors during summer increased by 96.5% compared to 2021 levels. This elevation was significantly correlated with reduced sea ice coverage (r = -0.83, $p < 0.001$) and changes in prey distribution (r = 0.77, $p < 0.01$).

Group size during cooperative hunting

We analyzed changes in the average group size during cooperative hunting events. Fig. 4 summarizes these findings across different prey types.

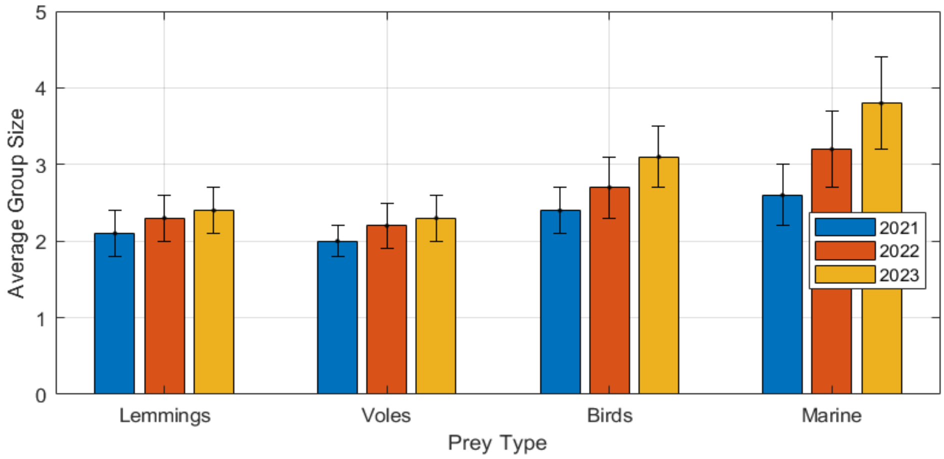

Fig. 4. Average group size during cooperative hunting events.

The data in Fig. 4 exhibit an upraise in average group size across all prey types, with the most substantial elevation observed for marine prey items which increased from 2.6 individuals in 2021 to 3.8 individuals in 2023, representing a 46.2% elevation. This trend was positively correlated with the observed changes in hunting success rates for cooperative strategies (r = 0.85, $p < 0.001$).

Kinship analysis of cooperative groups

Genetic analysis of hair samples collected during capture events allowed us to assess the kinship of individuals involved in cooperative behaviors. Table 5 depicts the proportion of cooperative events involving kin versus non-kin groups.

Table 5. Proportion of cooperative events by group composition.

Group Type	2021 (%)	2022 (%)	2023 (%)
Kin	68.3	59.7	53.1
Non-kin	31.7	40.3	46.9

The data in Table 5 reveal a shift towards increased cooperation among non-kin groups. The proportion of cooperative events involving non-kin groups increased from 31.7% in 2021 to 46.9% in 2023, representing a

15.2% elevation. This shift was negatively correlated with the availability of traditional prey items (r = -0.76, $p < 0.01$) and positively with the observed changes in den site distribution (r = 0.69, $p < 0.01$).

DISCUSSION

Our three-year study on Arctic foxes reveals significant behavioral adaptations in response to climate change, encompassing shifts in hunting patterns, den site selection, and social interactions. These adaptations display the species' remarkable plasticity in the face of rapidly changing Arctic ecosystems. One of the most striking findings is the substantial shift towards diurnal foraging activity, with a 30.1% elevation from 2021 to 2023. This change likely reflects alterations in prey availability and activity patterns due to warming temperatures. Similar shifts have been observed in other Arctic predators, such as polar bears (*Ursus maritimus*), which have increased terrestrial foraging in response to sea ice loss (Smith & Stirling 2019). However, the rapidity and magnitude of the change in Arctic foxes are particularly noteworthy, suggesting a more immediate and pronounced impact of climate change on smaller Arctic mammals. The observed changes in den site selection, with a 13% increase in dens located above 100 m elevation from 2021 to 2023, align with predictions of habitat shifts in response to climate change. This upslope movement is consistent with observations in other Arctic species, such as the collared lemming, *Dicrostonyx groenlandicus* (Khidas *et al.* 2020). However, our study provides one of the first quantitative assessments of such shifts in a mesopredator. The preference for well-drained soils and increased depth to permafrost at den sites suggests that Arctic foxes adapt to ground conditions, potentially mitigating the impacts of permafrost thaw on den stability. The most intriguing finding is the 15.2% increase in cooperative behaviors among non-kin groups from 2021 to 2023. This shift in social dynamics represents a departure from Arctic foxes' traditionally more solitary nature (Schmidt *et al.* 2022). The increased cooperation, particularly in hunting marine prey, may be an adaptive response to food availability and distribution changes. Similar increases in cooperative behaviors have been observed in other canids under resource pressure, such as Ethiopian wolves, Canis simensis (Sandoval-Serés *et al*. 2023). However, our study provides the first evidence of the rapid shift in Arctic foxes. These behavioral adaptations suggest a degree of resilience in Arctic foxes to climate change impacts. However, it is crucial to interpret these findings cautiously. While the observed changes may help Arctic foxes cope with current environmental shifts, they may also lead to new challenges. For instance, the increased diurnal activity could expose Arctic foxes to greater predation risk from avian predators or competition with expanding red fox, *Vulpes vulpes* populations (Alexandre *et al.* 2020). Our study has several limitations that should be considered. Firstly, while revealing significant changes, the three-year timeframe may not capture long-term trends or potential oscillations in behavior. Future studies should aim for longer-term monitoring to distinguish between short-term adaptations and lasting evolutionary changes. Secondly, our study focused on a specific region in northern Alaska, and the observed patterns may differ from Arctic fox populations across their entire circumpolar range. Comparative studies across different Arctic regions would provide a more comprehensive understanding of the species' adaptive responses to climate change. Additionally, while we attempted to control for confounding factors, such as interannual variations in lemming cycles, some of the observed changes may be influenced by factors beyond climate change. Future research should incorporate more detailed prey abundance data and finer-scale climate metrics to tease apart the relative influence of different environmental drivers on Arctic fox behavior.

CONCLUSION

Our study provides compelling evidence of rapid behavioral adaptations in Arctic foxes in response to climate change. These findings underscore the importance of behavioral plasticity as a mechanism for coping with environmental change in Arctic ecosystems. However, the long-term consequences of these adaptations for Arctic fox populations and their role in tundra ecosystems remain uncertain. Continued monitoring and research are essential to inform conservation strategies and predict future trajectories of Arctic wildlife in the face of ongoing climate change.

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