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Animal-borne sensors as a biologically informed lens on a changing climate

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Animal-borne sensors as a biologically informed lens on fine-scale climate dynamics

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Supplementary Material 1: Examples of knowledge gaps for understanding biological responses to climate change where advances can be facilitated by ABS.

Theme	Significance	Current shortcomming	ABI provided benefit	ABI Example	ABI species	ABI Citation	Non-ABI Citation
Microclimate change	Environmental conditions experienced by animals at fine spatial grains. How animals use microclimates reflects their exposure,sensitivity, and adaptive capacity to climate change and current extreme events	Areas with heterogeneous microclimates provide opportunities for species to persist in place or connect distant ranges as stepping stones, yet are rarely incorporated in global change research. The current generation of microclimate models require validation	Quantify how microclimates buffer species from extreme temperatures. Validate microclimate models or ABI collect microclimatic measurements themselves. Coupling fine scale biological and microclimate data can improve model predictions of species distributions and habitat use	Alpine Ibex balance increasing heat with forage oportunity by moving upslope	Alpine ibex (*Capra ibex*)	1	2-4
Animal behavior under climate change	Behavioral flexibiltiy is a mechanism for coping with climate change. Species may persist in thermally heterogeneous environments by using microclimates and altering their daily activity patterns	Hard to integrate behavioral and physological responses in the wild over the lifespan of organisms	Quantifying energy expenditure and activity in the wild. Quantify the trade-off of adjusting activity budgets for thermoregulation and foraging	African wild dogs adjust their activity to warming temperatures. Alpine Ibex balance increasing heat with forage oportunity by moving upslope	African wild dog (*Lycaon pictus*), Alpine ibex (*Capra ibex*)	1,5	6-7
Increase in extreme weather events	Extreme weather events will increase in frequency and severity under climate change (i.e. heatwaves, cyclones, polar vortex)	Designing experiments to study the impact of extreme events on wildlife is challenging, yet critical for species climate vulnerability assessments. It is unknown whether animals return to original areas after extreme event or whether permanent range shift has ocurred	Species space & habitat use is collected before, during, and after extreme events. ABI may help assess how resilient species are to extreme events based on their behavior and habitat use	Deer responding to cyclones by moving to higher elevations. Seabirds navigating under extreme winds	White-tailed deer (*Odocoileus virginianus seminolus*) 18 seabird species	8-10	11-12
Increased risk of zoonosis	Zoonotic spillovers are projected to increase under climate change	Estimating infection rate and dispersal of zoonotic vectors remains challenging	Document infection and disease of wild animals in near real time. Wild animals may act as early warning sentinels	Immune response of mallads was documented in response to physiological and behavioral traits. Movements of mallards was linked to potential dispersal of avian influenza into novel areas	Mallard ducks (*Anas platichrynchos*)	13-14	15-16
Phenological shifts in a warming world	Phenological changes such as migration and reproductive timing may lead to temporal mismatches between predator & pret resource requirements. Animals may track resources to increase their energetic gains by moving in synchrony to phenological variation in space.	What is the degree of plasticity in phenological sensitivity across and within species? What is the degree of asynchrony of species interactions?	Life long tracking of individuals of species, such as predators and prey. Identify new migratory routes and breeding areas. Assess phenotypic plasticity within species	Parturition times of caribou generaly ocurrs earlier in the year during the past decades. Earlier arrival to arctic summering grounds in adult bald eagles	Caribou (*Rangifer tarandus*) Bald eagle (*Haliaeetus leucocephalus*)	17-18	19-21
Intraspecific variation to assess resonses to climate change bellow the species level	Most niche assessments are aggregated at the species level ignoring intraspecific variation; crucial to understand how variable repsonses to global change are.	Is there intraspecific variation in both diet consumed as well as climatic and landscape feature used?	Tracking multiple individuals at fine spatio-temporal resolutions across the entire geographic range of species may reveal heterogeneity in species habitat use and climate change exposure and resilience	High variability in individual niches suggests heterogeneous vulnerability to climate change	White storks (*Ciconia ciconia*) African elephants (*Loxodonta africana*)	22-23	24
Niche tracking	Animals may track resources and climatic conditions to increase their energetic gains by moving in synchrony to phenological variation in space	Does niche tracking emerges at the population or species level or through individual level behavior? Do animals track long term averages or annual peaks in productivity? Despite niche estimates imoproving when incorporating fine scale microclimate, this is rearely used.	Assess whether animals track long term averages or shorter term phenological peaks. Quantify whether animals respond stronger to micro or mesoclimatic variation. Assess how niche tracking varies with animal movement strategies across land, air, and sea	Straw-colored fruit bat migration follow sort term green up resource peaks. Long living blue whales track long term average conditions, being particularly susceptible to climate change. Niche tracking appears to occur at the individual and population level in white storks	Straw-colored fruit bat (*Eidolon helvum*) Blue whale (*Balaenoptera musculus*) White stork (*Ciconia ciconia*)	25-27	28
Species re-distribution under climate change	Range shifts are occurring faster for marine than for terrestrial species across latitudes worldwide.	Heavy focus on coarse scale range shifts based on slow but steady increases in mean temeprature. Limited accounting for organisms dispersal ability and physiological tolerances. The importance of extreme events on range shifts remains mostly unknown	Honing into range shifts bellow the species level. Assess potential range shifts after extreme events. More timely forecasts of species range shifts has important implications for management of species, particularly economic important species and zoonotic vectors	NA	NA	NA	3, 29-30
Thermal vulnerability to assess species sensitivit to climate change	Thermal vulnerability indices are used to forecast the impacts of climate change on species (primarily ectotherms)	Validation of these indices is considered a knowledge gap to improve predictions of species vulnerability to climate change. Particularly sudden changes in temperatures through extreme events, are typically not accounted for in thermal indices.	Assess how thermal vulnerability changes throughout and individuals life span, species geographic range, and climatic seasons. Quantify the sensitivity, exposure and adaptability of species through microclimate use and behvior when thermal conditions near survivable extremes	Movement performance of mojave desert tortoises was related to field based thermal performances by climatic seasons. Thermal indices collected in the wild were similar to laboratory estimates	Mojave deserte tortoise (*Gopherus agassizii*)	31	32

Supplementary Material 1 Bibliography

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