The role of behavior in responses to anthropogenic changes

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Running title: Behavioral responses to anthropogenic changes

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Abstract

Environmental changes driven by human activities are exposing organisms to novel and increasingly variable selective pressures. Among many possible responses, behavior stands out as rapid and often reversible mechanisms by which individuals adjust to altered conditions. By shaping how organisms interact with their environments, behaviors can influence exposure to challenges, mediate interactions with other components of the phenotype, such as physiology, morphology, or life history, and ultimately affect ecological and evolutionary outcomes. Despite their potential importance, behavioral responses to anthropogenic change are not as well integrated across systems and disciplines. Here, we synthesize current research drawn from discussions at a symposium focused on the role behavior plays in confronting a rapidly changing world. We integrate insights across taxa and across major forms of human-driven environmental change, including sensory pollution, urbanization, wildfire, habitat modification, and climate change. Across contexts, we examine how behaviors interact with physiology, life history, ecology, and evolution, emphasizing the need to understand behavior as part of a dynamic and interconnected system in which plastic responses can buffer, redirect, or amplify the effects of environmental change. We identify common themes in how behaviors respond to different anthropogenic challenges, as well as key differences related to ecological context or biological constraint. We also highlight persistent gaps in knowledge, particularly regarding when

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behavioral flexibility is sufficient to mitigate environmental challenges, how behaviors interact with other traits over different timescales, and when behavioral flexibility may constrain or facilitate evolutionary responses. By synthesizing current knowledge and identifying priorities for future research, we advance an integrative approach to understanding the role of behavior in anthropogenic change. In doing so, we aim to promote cross-system comparisons and collaboration, while also clarifying the conditions under which behavioral plasticity plays a critical role in shaping organismal resilience in an increasingly human-altered world.

Resumen

Los cambios ambientales ocasionados por actividades humanas están exponiendo a los organismos a presiones de selección nuevas y cada vez más variables. Entre las diversas respuestas posibles, el comportamiento destaca como un mecanismo rápido y a menudo reversible mediante el cual los organismos se ajustan a diferentes condiciones. Al moldear la forma en que los organismos interactúan con su entorno, el comportamiento determina la exposición a diversos retos, media las interacciones con otros componentes del fenotipo, como fisiología, morfología, e historias de vida, y en última instancia afecta a los procesos ecológicos y evolutivos. A pesar de su importancia potencial, las respuestas conductuales a cambios antropogénicos no han sido integradas completamente a través de sistemas y disciplinas. Aquí, sintetizamos investigación actual extraída de discusiones dentro de un simposio enfocado en el papel de la conducta en un mundo que cambia rápidamente. Integramos conocimiento entre taxones y entre las formas principales de cambio antropogénico, incluyendo contaminación sensorial, urbanización, incendios forestales, modificación del hábitat, y cambio climático. A través de diferentes contextos, examinamos cómo la conducta interactúa con fisiología, historias

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de vida, ecología, y evolución, enfatizando en la necesidad de entender al comportamiento como parte de una dinámica y sistema interconectado donde las respuestas plásticas pueden amortiguar, redireccionar, o amplificar los efectos del cambio ambiental. Identificamos temas comunes en la forma en que la conducta responde a distintos desafíos antropogénicos, así como las diferencias clave relacionadas con el contexto ecológico o con restricciones biológicas. También destacamos algunas lagunas persistentes en nuestro conocimiento, especialmente en lo que respecta a cuándo la flexibilidad conductual es suficiente para mitigar los cambios ambientales, cómo las conductas interactúan con otros rasgos a través de diferentes escalas temporales, y cuándo la flexibilidad conductual puede limitar o facilitar respuestas evolutivas. Sintetizando conocimiento actual e identificando prioridades para investigación futura, promovemos un enfoque integrativo para entender el papel de la conducta en el cambio antropogénico. Con ello, pretendemos promover colaboración y comparación entre sistemas de estudio, al tiempo que aclaramos las condiciones en las que la plasticidad conductual desempeña un papel crítico al moldear la resiliencia de los organismos en un mundo cada vez más alterado por el ser humano.

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Introduction

Organisms increasingly encounter environmental change driven by human activities. Climate change is leading to more variable temperatures as well as more frequent and intense storms, droughts, and heat waves (IPCC 2023a). Habitats are being transformed for agriculture, housing, commerce, and transportation, fragmenting the landscape and reconfiguring ecological communities (Rockström et al. 2009; Laurance et al. 2014; Gaston et al. 2017; Curtis et al. 2018; IPCC 2023b). Urbanization further alters landscapes through infrastructure such as roads and buildings, which concentrate human activity, alter organismal movement and exposure to disturbance, and fragment resource distribution. Alongside these structural changes, sensory pollution introduces chemicals, noise, and artificial light into habitats. Finally, wildfire regimes are shifting, becoming more severe and affecting larger areas (Kreider et al. 2024). These environmental changes can act independently or synergistically to alter abiotic and biotic conditions and reshape selective pressures.

Behavior may be at the forefront of responses to these anthropogenic changes (Figure 1; Sih et al. 2011; Tuomainen and Candolin 2011). From thermoregulatory behaviors to movement, communication, aggression, parenting and beyond, behaviors are generally viewed as organismal traits involving action or inaction (Levitis et al. 2009). Behavioral traits are often related to – but distinct from – physiological and morphological traits, and they have long been viewed as keystone traits in shaping how environmental change affects organisms and their evolutionary trajectories (Mayr 1963; West-Eberhard 1989; Muñoz 2022; Rosvall and Derryberry this issue). Rapid and reversibly expressed, behaviors are among the first phenotypes to adjust when environmental conditions change (Sih et al. 2011). Behavioral adjustments have the potential to shield organisms from selection or expose them to new selective pressures, shaping the pace of

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evolution (Huey et al. 2003; Sih et al. 2010; Snell-Rood 2013; Muñoz 2022). However, research on behavioral responses to anthropogenic changes lags that of other fields (Buchholz et al. 2009), such as physiology and life history, limiting our ability to predict how populations and species will fare in a rapidly changing world (Fey et al. 2019).

Here, we integrate across taxa and biological scales to synthesize research on behavioral responses to five major anthropogenic stressors: climate change, habitat modification, urbanization, sensory pollution, and wildfire. These anthropogenic changes are likely to affect wild animals through several diverse but often overlapping mechanisms, including altered abiotic regimes (e.g., droughts, heatwaves, extreme weather events), built infrastructure (e.g. roads, buildings), direct human activity (e.g. recreation, traffic, agriculture), and environmental by-products (e.g. artificial light, noise, pollution). Rather than providing an exhaustive review of each stressor or cataloging case studies of resilience and decline, we focus specifically on characterizing how behavior functions as a mechanistic interface between environmental change and organismal performance. We examine how behavioral responses mediate exposure to anthropogenic stressors, when they generate novel constraints, and where trade-offs emerge. We then apply this understanding across taxa and levels of biological organization to identify key knowledge gaps and critical next steps in linking behavioral responses to ecological and evolutionary outcomes.

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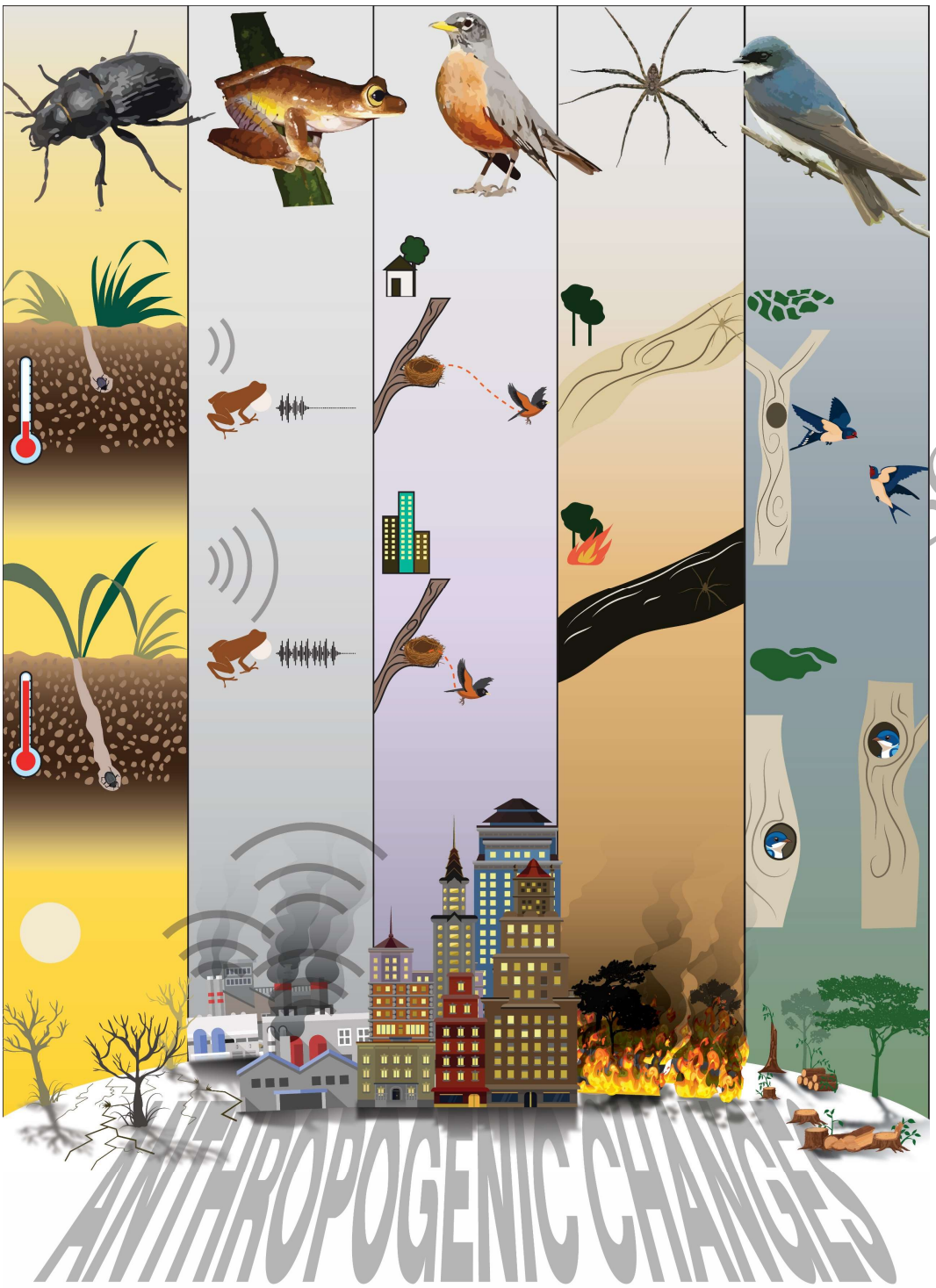

Fig. 1. Five major anthropogenic changes that modulate behavioral responses in animals. From left to right: Dung beetles (Scarabaeidae) bury brood balls deeper in warmer temperatures; Tree frogs (*Bokermannohyla hylax*) have a prolongated call when in noisy environments; American

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robins (*Turdus migratorius*) have a longer flying initiation distance in less urbanized environments; Darker spiders of the species *Syntrechalea brasilia* actively choose burned trunks after a fire; female Tree swallows (*Tachycineta bicolor*) show territorial behavior in more fragmented habitats.

Behavior and five major anthropogenic challenges

Climate change

Animals are increasingly challenged by changes to Earth's abiotic environment, including warmer temperatures, greater thermal variance, changes in wind speed, and more frequent extreme events like droughts, heat waves, cold snaps, and storms (IPCC 2023a). Organisms are not passive recipients of these changes, and behavioral responses may provide an immediate line of defense against both hydric and thermal stress (Kearney et al. 2009; Huey et al. 2012; Fey et al. 2019; Wu et al. 2025). Across endotherms and ectotherms, behavioral adjustments in activity patterns, parental care behaviors, and microhabitat use can limit exposure to thermal extremes and buffer organisms and their offspring from some physiological costs (Kearney et al. 2009; Riddell et al. 2019; Ma et al. 2021), thereby filtering how climate change is experienced (Sih et al. 2010) and maintaining fitness over a range of environmental conditions (Fey et al. 2019).

Nevertheless, the capacity for behavioral buffering is unevenly distributed across environments and the tree of life. Organisms that are sessile or in a sessile life stage cannot escape extreme temperatures (e.g., Palumbi et al. 2014) and may face energetic constraints or opportunity costs (Kearney et al. 2009). Even when mobile, individuals may be unable to behaviorally buffer themselves (Sinervo et al. 2010; Salazar et al. this issue) or their offspring from stressful conditions (Telemeco et al. 2009; Mamantov and Sheldon 2021; Lane et al. this issue). In habitats with low thermal heterogeneity or wide transit distances between suitable thermal patches, movement to cooler microclimates can reduce foraging and reproductive

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opportunities (Huey 1974; Sears and Angilletta 2015; Cunningham et al. 2021). More broadly, behaviors that buffer against heat, cold, rain or wind can impinge on investment in foraging, reproduction, social interactions, or predator avoidance (Riddell et al. 2019; Green et al. 2025; Morosinotto et al. 2025; Devereaux, 2026). In some cases, behavioral buffering fails entirely. For instance, Australian flying foxes (*Pteropus spp*) die from hyperthermia during heat waves despite cooling behaviors like panting, shade-seeking, and wing-fanning (Welbergen et al. 2008). Behavioral buffering is therefore neither universally available nor cost-free, and its contribution to persistence depends on ecological context.

Seasonal and geographic context provide further insight into how animals navigate environmental change, with behavioral shifts capable of buffering incredible climatic extremes (e.g., substrate temperatures from 0 to 60°C in a high-altitude lizard (Domínguez-Guerrero et al. 2019). High latitude and high elevation systems experience pronounced seasonal shifts in precipitation and temperature (Ghalambor et al. 2006; Sheldon et al. 2018; Giacometti et al. 2024), but among ectotherms, seasonality predicts plasticity in lower but not upper thermal limits (Gunderson and Stillman 2015). Seasonally adapted organisms therefore may tolerate cold variation but not necessarily warming. Comparable population comparisons in endotherms are more limited but suggest that geographic (Michaud et al. 2024) and seasonal (Zuluaga and Danner 2023) variation in behavioral buffering may be widespread.

Behavioral adjustments in the face of thermal challenges are generally assumed to be adaptive, yet because thermoregulation operates within a multidimensional fitness landscape (Huey 1974; Angilletta 2009), the hypothesis of adaptation is challenging to address. Behavioral thermoregulatory responses may activate early in the sequence of heat exposure (Woodruff et al. 2023), with additional physiological mechanisms activating later as temperatures continue to rise

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(Woodruff et al. 2025) and additional physiological damage ensues (Eastwood et al. 2022). However, avoiding high temperatures commonly restricts activity and foraging, limiting energy intake even as metabolic demands rise (e.g., Sinervo et al. 2010). Organisms may therefore face an ecological "catch-22," in which behavioral thermoregulation amplifies metabolic crises (Huey and Kingsolver 2019; Riddell et al. 2019). Trade-offs also arise when optimal mating sites impose greater thermal stress (Leith et al. 2022; Valencia-Esquivel et al. 2024), when behavioral thermoregulation leads to slowed growth or body mass declines (van de Ven et al. 2024; Woodruff et al. 2025), and when thermal challenges directly reduce other fitness-critical behaviors, like cognitive performance, motor performance, signal production, or choosing a high quality mate (Danner et al. 2021; Coomes and Derryberry 2021; Soravia et al. 2021). Yet, the absence of behavioral adjustment also bears fitness costs: thermoconformers living with higher thermal stress, for example, grow at slower rates (Salazar et al. this issue). In other words, neither buffering nor bearing thermal stress is cost-free. Whether behavioral adjustments are typically net positive and therefore enhance persistence depends on how these costs balance against their benefits (Huey et al. 2003; Muñoz and Losos 2018; Klinges et al. 2025).

Gaps in knowledge

Studies on behavioral responses to climate change rarely investigate climatic variance in addition to directional climatic change (but see Kirkpatrick and Sheldon 2022; Gunderson 2023; Kirkpatrick et al. 2025). Beyond the context of torpor, hibernation, or migration, behavioral research on cold buffering is also less common than that of heat (but see Domínguez-Guerrero et al. 2022; Taff et al. 2025). Because climate change alters heat and cold, as well as precipitation regimes, wind, and the frequency of extreme events, interactions among these variables may

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generate non-intuitive consequences, such as warming winters that increase rainfall relative to snowfall, altering both exposure and behavioral opportunity. Understanding how organisms behaviorally integrate multiple climatic challenges remains limited.

We also lack clear criteria for when specific behaviors buffer organisms from climate change, when behaviors expose hidden costs, and how these behavioral shifts interface with physiological adaptation. Macroevolutionary comparisons suggest that the evolution of behavior and physiology are linked (Muñoz 2022; Bodensteiner et al. 2024) and that similar climatic challenges may yield divergent behavioral and demographic outcomes (Pincebourde and Woods 2020; Klinges et al. 2025), dependent on evolutionary history, organismal physiology, and the structure of thermal landscapes. These uncertainties are compounded by a mismatch between how climatic changes are defined and how organisms experience them (Vasseur et al. 2014; Sheldon and Dillon 2016; Fredston et al. 2025; Ellis-Soto et al. this issue). For instance, heat waves are typically characterized using percentile-based historic weather thresholds, yet extremes are relative to an organism's own experiences.

Future prospects

Progress requires centering behavior as a primary interface between organisms and climatic change. Whether behavior confers resilience depends on how it alters energy balance, water balance, predation risk, and reproductive costs and opportunities as environments change. Dynamic energy budget and related mechanistic frameworks have the potential to integrate these currencies (e.g., Riddell et al. 2019), studies linking parental behaviors to offspring phenotype and survival can begin to assess fitness consequences of climate change (e.g., Lane et al. this issue), and longitudinal studies on post-exposure survival remain important (Woodruff et al.

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2025), yet research remains limited by the difficulty of collecting species-specific behavioral, physiological, and environmental data under natural conditions. Moving research beyond temperature will improve ecological relevance. As behavioral databases expand and biosensing and microclimate tools advance, we will be better positioned to interrogate how behavior mediates resilience and vulnerability under continued climate change.

Habitat fragmentation and loss

Habitat fragmentation and loss are major drivers of species declines (Haddad et al. 2015), with impacts that act through behavior. For instance, fragmentation alters biotic interactions such as the frequency and predictability of social cues and predator-prey interactions. These community effects can alter the informational context by which animals make decisions, centering behavior as a critical link between landscape reorganization and eco-evolutionary processes (Bélisle 2005). Habitat connectivity changes the risks and opportunities individuals encounter (Banks et al. 2007; Bergamini and Massolo 2026; Gonçalves-Souza 2025), leading to adjusted diet choice and patch occupancy (Haddad et al. 2015). Fragmentation can also alter mating opportunities, social group dynamics, and the potential for social learning (Laiolo and Tella 2005; Banks et al. 2007). Fragmentation therefore reorganizes the decision-making landscape that animals occupy, reshaping how individuals gather information, interact with conspecifics, and allocate effort across behavioral domains.

Independent of fragmentation, habitat loss elicits robust behavioral effects, though habitat loss was historically studied more for its population-level impacts (e.g., gene flow, minimum viable population sizes) instead of its behavioral consequences (Lima and Zollner 1997). Shifts in population density or group sizes are especially useful for examining impacts of habitat loss

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because they concentrate animals into smaller areas of habitat, with common effects on rates of aggressive interactions (e.g., Bentz et al. 2021), mating competition (e.g., Mayer and Pasinelli 2013) and cooperative behaviors, like social vigilance (e.g., Clutton-Brock et al. 1999) or collaborative offspring care (e.g., Brouwer et al. 2005).

Gaps in knowledge

Faced with habitat fragmentation or loss, animals find themselves in new spatial arrangements that shape how much they compete or cooperate, how likely they are to stay or disperse, and how they communicate. However, because most research stops short of linking these behavioral changes to demographic outcomes (Banks et al. 2007; Driscoll et al. 2014), we lack a predictive framework connecting altered behavior to long-term population viability. Addressing this gap requires evaluating the costs and benefits of behavioral modification, including those mediated by the behavioral phenotypes of other individuals in the population (Kilgour et al. 2018). Cascading effects across entire communities also shape the valence of behavioral modification, driven by co-evolutionary dynamics between predators and prey (Ryall and Fahrig 2006) or hosts and pathogens (Malagon et al. 2020), which can amplify fragmentation effects (Becker et al. 2023). Among conspecifics, social interactions mediate hormone levels and metabolic state (Wingfield et al. 1998; Romero 2004), and habitat availability and fragmentation can elevate glucocorticoid 'stress' hormones (Janin et al. 2011). Dense social environments can also elevate sex steroid hormone levels in the blood (Wingfield et al. 1990), trigger hormone-dependent maternal effects that are passed to the next generation (Bentz et al. 2016), and impart enduring methylation signatures in the brain (Bentz et al. 2021). As we seek to connect habitat fragmentation and loss to behavioral outcomes, these mechanisms must be re-evaluated

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281 explicitly in the context of anthropogenic change, filling critical gaps about how habitat change
282 alters decision-making and the limits of behavioral adjustment.
283 Integration with fitness metrics remains a persistent challenge, one that is central to
284 clarifying whether observed behaviors represent adaptive plasticity or stress-mediated limitation
285 (Sih et al. 2011). Long term cross-generational studies are rare (Sutherland et al. 2013), and we
286 need studies that flip the narrative, with behavior as a potential mediator of resilience or
287 susceptibility rather than a response variable (Sih et al. 2011; Bélisle 2005). Without these links,
288 we cannot determine when behavioral shifts confer population resilience or reduce persistence,
289 and we also cannot distinguish reversible plasticity from evolutionary change.
290
291 *Future prospects*
292 A behavior-focused lens positions habitat fragmentation and loss as behaviorally-mediated
293 ecological and evolutionary change. Now is the time to prioritize data collection near
294 fragmentation boundaries and to implement pre- and post-sampling adjacent to areas of habitat
295 loss, both of which offer powerful tests on the role of behavior as a predictive tool rather than a
296 descriptive endpoint. By combining emerging technologies that quantify movement with biotic
297 interactions and decision-making across heterogeneous landscapes, we are poised to generate
298 much needed insights on the behavior of free-living, small-bodied animals such as amphibians,
299 reptiles, and invertebrates that face high extinction risk (Bergamini and Massolo 2026) yet
300 remain understudied in their behavior in the wild. Expanding this work to multi-species,
301 community-level behavioral studies offers a powerful but underutilized approach that embraces
302 the ecological scales across which adaptation, persistence, or decline unfold, with the potential to
303 uncover conserved behavioral mechanisms. Future research should explicitly integrate

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behavioral strategies with physiological properties, sharpening our ability to predict when plasticity buffers population viability and when it accelerates organismal stress under continued fragmentation. Ultimately, this integration will move the field from documenting behavioral responses to predicting which behavioral strategies promote persistence in increasingly strained habitats.

Urbanization

Urbanization is among the most rapidly growing forms of land use change and is a major driver of ecological and evolutionary processes in both terrestrial and aquatic environments (Seto et al. 2012; Alberti 2015; Keinath et al. 2023). Urban development transforms biotic and abiotic environments by altering vegetation, surface cover, hydrology, chemical exposure, thermal regimes, and light and sound conditions (Walsh et al. 2005; Grimm et al. 2008). Simultaneously, urbanization redistributes risks and resources through habitat fragmentation, anthropogenic food supplementation (e.g., bird feeders, garbage), altered predator communities, and elevated human presence (McKinney 2002). These changes vary across neighborhoods and fluctuate with human mobility and wildlife management, generating novel and dynamic conditions to which both terrestrial and aquatic organisms must adjust (Sievers et al. 2018; Schell et al. 2021).

Behavior mediates how organisms navigate these urbanized environments. Many studies link urbanization of terrestrial and aquatic environments to behavioral shifts in boldness, territorial aggression, foraging tactics, reproductive strategies, problem solving, and responses to humans (Sih et al. 2010; Lowry et al. 2013; Sol et al. 2013; Blanchett et al. 2024; Irwin et al. 2024). Urban environments can favor individuals that tolerate human disturbance, exploit novel food resources, or adjust activity to avoid peak human activity (McKinney 2002). At the same

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time, these behavioral traits reshape exposure to risk and opportunity by altering space use, activity times, and social interactions. Individuals that express certain behavioral strategies may therefore be more likely to persist in cities, while those same strategies modify how urban environments are experienced. (Sol et al. 2024).

Gaps in knowledge

Empirical data on urban wildlife behavior remain uneven in ways that limit inference about how animals persist in cities. For instance, movement ecology is strongly biased toward wilderness and protected areas (but see e.g., Ryan et al. 2014; Gaulke et al. 2015), with relatively little tracking or telemetry conducted in dense urban landscapes (Ellis-Soto et al. 2025). This bias limits understanding of how animals move through infrastructure, respond to human activity, and allocate space in high human footprint environments. In contrast, citizen science observations are disproportionately concentrated in urban areas (Kelling et al. 2015), often clustering in wealthier neighborhoods (Estien et al. 2024). Although these datasets document biodiversity patterns in the form of species presences, they rarely capture fine-scale behavioral dynamics or within-city heterogeneity. As a result, we lack behaviorally explicit data that resolve how diverse taxa respond to the complex and heterogeneous conditions that characterize cities.

Even where behavioral data exist, they rarely capture the fine-scale environmental variation that shapes behavioral expression. Cities comprise mosaics of neighborhoods that differ in green space, size and type of aquatic habitats, temperature, noise, light, chemical pollution, and human density, which may yield unknown singular, additive, or interactive effects on behavior (Schell et al. 2020). Yet many studies treat urban and non-urban habitats as categorical contrasts, potentially obscuring meaningful variation in behavioral expression and cognitive

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performance (Stanton et al. 2023). If behavioral and cognitive traits respond flexibly to local conditions, then individuals within the same city may experience distinct selective and developmental pressures (e.g., Chow et al. 2021; Klump et al. 2021). Within-city behavioral variation therefore represents both a critical gap in knowledge and an opportunity to link behavioral plasticity to environmental heterogeneity and inequality.

Finally, few studies distinguish short-term plasticity from longer-term evolutionary divergence. Urban-rural comparisons frequently report shifts in behavior and cognition, yet evidence connecting these differences to fitness advantages remains limited (Sol et al. 2020). Disentangling plasticity from adaptive divergence requires longitudinal datasets or cross-population experiments that link behavioral variation to survival and reproduction, and such studies remain rare (Atwell et al. 2012; Lambert et al. 2021). Moreover, many behavioral traits are reversible or context dependent, complicating inference regarding selection (Sih et al. 2010). The evolutionary significance of behavioral responses to urbanization therefore remains unresolved.

Future prospects

Progress requires moving beyond simple urban-nonurban contrasts and centering behavior within the fine-scale heterogeneity that characterizes urban environments (Gelmni-Canduzo et al. 2024). Integrative, cross-scale approaches that incorporate neighborhood-level variation will clarify how animals adjust space use, activity times, and risk responses across socially and structurally distinct urban contexts. For instance, integrating high-resolution movement data and other behavioral observations collected by residents with fine-scale urban features and human mobility metrics will allow researchers to quantify how animals navigate dynamic risk-resource

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landscapes (Ellis-Soto et al. 2023; Stanton et al. 2023). Linking behavioral variation to environmentally induced physiological changes across neighborhoods (e.g., diet, pollution, disease) can further clarify the mechanisms underlying how urban animals make decisions that guide their behavior and interactions with people (Schell et al. 2020).

Longitudinal and cross-city comparisons are essential for distinguishing behavioral plasticity from adaptive evolution (Lambert et al. 2021). These designs can identify when behavioral plasticity facilitates persistence and when selection reshapes behavioral distributions across generations, including selection on plasticity itself (Caspi et al. 2022). Mechanistic insight into behavior will strengthen inferences about the evolutionary trajectories of urban wildlife. Urban heterogeneity is not only ecological, but societal. Neighborhood-level differences in green space, heat, pollution, and infrastructure shape both human and wildlife exposure to risk. Understanding how animal behavior responds to this spatial inequality provides an opportunity to link behavioral plasticity, animal health, and environmental justice (Stanton et al. 2023). Clarifying these connections can provide actionable insights for urban planning and promote human-wildlife coexistence in ways that enhance well-being for both animals and people.

Sensory pollution

How organisms perceive their environment determines how they behave, interact, and ultimately survive (Tuomainen and Candolin 2011; Musilová and Stieb 2025). Sensory pollution—including artificial light at night (ALAN), anthropogenic noise, chemical contaminants, and altered physical environments—disrupts major sensory channels (Saaristo et al. 2018; Davies et al. 2024). Because organisms integrate information across both modalities and individuals, disruption in one channel can cascade through decision-making processes and social systems.

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Behavioral consequences of sensory pollution are therefore context dependent and vary among taxa and environments (Halfwerk and Slabbekoorn 2015).

Acoustic communication provides a clear example of how sensory pollution reshapes behavior (Kight and Swaddle 2011; Swaddle et al. 2015; Shannon et al. 2016). Anthropogenic noise amplifies background sound, reducing detectability and discriminability of acoustic signals used in communication, predator avoidance, and habitat assessment (West et al. 2007). Birds often adjust song frequency, timing, and amplitude in response to noise, but the effectiveness of these adjustments depends on spectral overlap, temporal structure, and receiver perception (Derryberry and Luther 2021). Similar shifts occur in frogs exposed to traffic noise and in marine mammals navigating vessel noise, where altered calling behavior reflects both signal modification and perceptual constraints (e.g., Parks et al. 2007; Lima et al. 2022). Noise effects also extend beyond signalers and receivers: anthropogenic noise reduces tomato reproductive success by interfering with bumblebee-mediated pollination, illustrating how sensory disruption in animals cascades into plant fitness (Varga-Szilay et al. 2025).

Visual environments are likewise reshaped by anthropogenic activity. Turbidity from pollution or boat traffic, ALAN, and structural modification alter the availability and reliability of visual information. Visual systems vary widely in anatomy, photoreceptor composition, neural processing capacity, and environmental light availability (Cronin et al. 2014). ALAN disrupts nocturnal orientation, as seen in moth flight and sea turtle hatching behaviors (Fábusová et al. 2024; Gomez Isaza et al. 2025), while urban lighting and warming can shift diel activity patterns in lizards and other taxa (Taylor et al. 2022). In aquatic systems, increased turbidity alters mate choice and predator-prey interactions (Newport et al. 2021). Human activities can also reduce availability of key dietary compounds, muting coloration in fish with consequences for sexual

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signaling and mate choice (Wong et al. 2007). These examples illustrate that visual disturbance alters behavior through changes in information reliability, not just light intensity.

Most work on sensory pollution and communication systems focuses on dyadic interactions between signalers and receivers. Yet many communication systems operate as networks in which information spreads across groups and shapes collective outcomes. Vigilance spreads socially through bird flocks (Sirot 2006), prairie dogs assess neighbors' awareness via contagious displays (Hare et al. 2014), and schooling fish coordinate threat-sensitive avoidance responses (Rieucau et al. 2014). In such systems, sensory environments influence not only whether signals are detected, but how information propagates through groups. Sensory pollution may therefore fragment communication networks, alter coordination thresholds, or disrupt collective vigilance, even when individual signaling adjustments appear sufficient.

Sensory pollution also rarely acts on only one modality. Most studies examine single sensory pathways, yet natural settings are multimodal (Halfwerk and Slabbekoorn 2015). Disruption in one modality can alter how information in other modalities is perceived and acted upon. In shore crabs, for example, ship noise increases physiological stress and impairs color change, thereby compromising background matching that protects against visual predators (Carter et al. 2020), demonstrating cross-modal effects. Environmental change can also modify background information itself, as classically illustrated by industrial melanism in the peppered moth *Biston betularia* (Walton and Stevens 2018), with additional cases reported in North America (Owen 1961). Our understanding of the current prevalence, mechanisms, and persistence of such adaptations in contemporary polluted environments remains remarkably limited (de Alcantara Viana et al. this issue).

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Gaps in knowledge

A central unresolved challenge is linking changes in sensory environments to behavioral outcomes across time and context. Behavioral responses may initially buffer organisms from altered sensory conditions, but such responses can be asymmetric, trait-specific, or context dependent. Work on acoustic communication highlights that successful adjustment depends on receiver perception and local soundscape structure, not on signal modification alone (Derryberry and Luther 2021). Further, most studies stop at individuals or dyads. We know far less about how sensory disruption alters the structure and resilience of communication networks, or how changes in information flow affect collective vigilance, coordination, and reproduction. We also lack integrative, multimodal frameworks. Animals integrate information across sensory channels and across conspecifics and heterospecifics, yet predictions typically derive from single-modality experiments. Finally, longitudinal data are scarce. Distinguishing short-term flexibility from persistent phenotypic change, network reorganization, or evolutionary divergence requires tracking individuals and groups through disturbance and recovery.

Future prospects

Progress requires integrating sensory mechanisms directly into behavioral and network-level research (Halfwerk and Slabbekoorn 2015). Studies should move beyond modality-specific and dyadic approaches to quantify how disruption in one sensory channel reshapes perception, information flow, and collective decision-making. Advances in automated acoustic and visual monitoring, biologging, and experimental manipulation of sensory environments now allow measurement of how animals experience—and respond to—complex sensory landscapes in situ (e.g., Axsom et al. 2025; Rhodes et al. 2025; Kays et al. 2015).

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Equally important is extending research across temporal scales. Longitudinal studies that track individuals, groups, and populations through periods of disturbance and recovery can reveal whether behavioral responses represent short-term flexibility, reorganization of information networks, or precursors to evolutionary divergence. Embedding sensory pollution within frameworks that integrate behavior, physiology, ecology, and evolution will improve predictions of when behavior buffers organisms from selection and when it instead exposes limits to plasticity in increasingly altered sensory worlds (Swaddle et al. 2015; Derryberry and Luther 2021; Tüzün et al. 2025).

Wildfire

Fire has always been a powerful ecological process shaping biodiversity and ecosystem functioning (Pausas and Parr 2018; He et al. 2019). However, the timing, frequency, and intensity of wildfires are changing in many regions of the world (Haas et al. 2026), and behavioral responses of organisms to wildfire are likely critical for persistence. Some animals can escape or evade wildfire by fleeing or sheltering, but the success of such behavioral strategies depends on both organismal traits (e.g., size, speed, metabolic rate) and aspects of the fire or habitat (e.g., refuge availability, wind speed, fuel) (Jolly et al. 2022). The behavioral tactics available to an animal and which tactics an individual chooses can create stark differences in survival probabilities across taxa (Batista et al. 2023). These impacts extend beyond the footprint of the fire itself, with smoke impacting billions of organisms each year (David et al. 2018). Species may have evolved behavioral adaptations to cope with or minimize damage from

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wildfire smoke (Overton et al. 2022), but behavioral responses to smoke are complex and diverse (Liu et al. 2022; Sanderfoot et al. 2022).

Wildfire also impacts animal behavior through habitat modification. By creating open spaces and reducing competitive dominance, fire can facilitate coexistence and reduce competitive exclusion (Durigan et al. 2020; Brewer 2023). Fire can restructure the canopy, alter light regimes, and increase temperature fluctuations at fine spatial scales, triggering rapid shifts in species composition and resource availability (Kelly et al. 2020). Intense wildfire events can further amplify structural and microclimatic changes, disrupting colonization dynamics, elevating mortality, and darkening the visual properties of substrates (Wolf et al. 2021; de Alcantara Viana et al. 2022, 2024; Dole et al. 2023). Due to the loss of vegetation, post-fire rainfall can lead to erosion, landslides, and the movement of sediments like soil and ash into waterways, altering water chemistry and reducing water quality (Gomez Isaza et al. 2022). Such wildfire-induced changes in aquatic environments impact animal behavior, such as decreases in oviposition in amphibians (Gamradt and Kats 1997; McDonald et al. 2018) and inhibiting the activity of fish (Gonino et al. 2019) and aquatic invertebrates (Pradhan et al. 2020; Ré et al. 2020). Post-fire transformations also have profound consequences for organisms whose survival depends on sensory perception, coloration (e.g., color polymorphism and fire-induced melanism), and behavior. For example, some prey species actively select post-fire substrates that match their coloration, whereas others rely on color polymorphism to maintain camouflage against visually hunting predators (de Alcantara Viana et al. 2022, 2024). Conversely, fire and post-fire environments may attract predators to burned areas, where they exploit carcasses and exposed or smoke-disoriented prey, as documented in predatory birds in the Pantanal wetlands (Dainezi et al. 2025). Thus, wildfire imposes both immediate behavioral challenges (escape,

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sheltering, smoke avoidance) and longer-term shifts in the sensory and competitive landscape to which organisms must behaviorally adjust. Although burns can promote long-term biodiversity maintenance (Pausas and Parr 2018; Kelly et al. 2020), they also impose immediate selective pressures that organisms must navigate.

Gaps in knowledge

Basic descriptive studies of animal behavior during or immediately after fire and smoke events are few (Nimmo et al. 2018; Liu et al. 2022; Sanderfoot et al. 2022) and experimental studies are rarer still (but see Stawski et al. 2015; Nowack et al. 2018; Fyle et al. 2026). In addition, relatively few studies examine behavioral responses to fire in aquatic compared to terrestrial species (Bixby et al. 2015; Gomez Isaza et al. 2022; Ward et al. 2022). This limits our ability to predict when and in what ecosystems behavioral responses buffer organisms from mortality and when they fail under increasingly intense fire regimes. Integrating how life history strategy, habitat, annual cycle stage, physiological status, and fire dynamics each contribute to behavioral responses and, thereby, fitness outcomes will be critical for developing a deeper understanding of organismal responses to wildfire. Hypothesis-driven approaches that link specific behavioral strategies to survival probabilities during and after wildfire (e.g., Batista et al. 2023) or that examine the sensory ecology and evolution of response mechanisms to wildfire cues (e.g., Michel et al. 2023) provide promising templates. Such frameworks could guide opportunistic and coordinated case studies when wildfire affects ongoing field systems (Cornelius et al. this issue).

Further, careful attention to fire or smoke intensity, duration, and spatial heterogeneity is important for explaining complex response patterns across systems. Without linking behavioral responses directly to health outcomes, survival, or reproductive success, it remains difficult to

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533 determine whether or how observed behavioral responses reflect adaptive plasticity, constraint,
534 or maladaptive carryover effects. As fire regimes continue to change, behavioral strategies that
535 once buffered individuals from risk may no longer do so under more frequent or extreme events.
536
537 *Future prospects*
538 Research on behavioral responses to wildfire, wildfire smoke, and post-fire dynamics lag that of
539 many other important anthropogenic changes due to logistical, safety, and ethical considerations.
540 Predicting when and where wildfires might occur, gaining access to relevant study sites,
541 acquiring essential research tools, and maintaining safety present challenging hurdles to our
542 scientific understanding of wildfire-organism dynamics. Experimental approaches with
543 prescribed burns during shoulder seasons may reduce some of these barriers via lower intensity
544 wildfire contexts, though behavioral responses of species to prescribed fires during shoulder
545 seasons may be different than responses to high intensity burns during peak fire season.
546 Communication with technology developers, funding bodies, firefighting entities and
547 management practitioners will be critical to attaining a deeper understanding of how organismal
548 behavior contributes to or mitigates ecological impacts of wildfire. Integrating behavioral
549 ecology with fire science will allow us to move beyond documenting mortality and habitat
550 change toward predicting when behavioral strategies enable persistence and when escalating fire
551 regimes exceed the limits of behavioral flexibility. As wildfire becomes a defining feature of
552 anthropogenic change in many ecosystems, understanding behavior as both a first line of defense
553 and a potential constraint will be critical for forecasting resilience in an increasingly flammable
554 world.
555

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Conclusions

A growing body of research has connected diverse behaviors to diverse elements of anthropogenic change. Thermoregulatory behaviors such as panting, posture adjustment, shade use, torpor, and seasonal shifts are widely described in a variety of taxa, including insects, lizards, mammals, and birds (Kearney et al. 2009; Lahondère 2022). Similarly, within many different taxa, urban and non-urban population comparisons have provided valuable insights into cognitive and behavioral differences associated with human-altered landscapes, including those related to sensory pollution (e.g., Mohanty et al. 2021; Lane et al. 2023). Density-mediated social interactions, including competitive behaviors and parental behavior, have been explored experimentally, though less frequently in the immediate context of anthropogenic habitat modification. Behavioral responses to wildfire, including escape tactics, refuge use, altered movement patterns, and post-fire microhabitat selection, have been documented, yet remain far less studied experimentally, particularly in the context of increasingly unpredictable fire regimes. Together, this body of work provides a solid foundation for understanding behavioral responses to environmental change, while also highlighting clear limits to the current state of knowledge.

Chief among these unresolved questions is how selection acts on behavioral variation, including when behavioral responses are purely plastic, when they are heritable, and when plasticity itself evolves (Snell-Rood and Devitz 2025). It remains rare to explicitly link behavioral responses to anthropogenic changes with their multidimensional effects on physiology, demography, and fitness (but see Woodruff et al. 2025), a critical step for connecting behavior to both ecological and evolutionary outcomes. Additional uncertainty arises from how we define temporal baselines, that is, the reference environmental conditions against which change is measured. These reference conditions can be drawn from historical climate averages,

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579 recent decades, or lifetime experiences of individuals, and the specific baseline choice can
580 substantially alter estimates of frequency, timing, and intensity of environmental 'extremes'
581 (Ellis-Soto et al. this issue). This issue is particularly relevant when assessing how organisms
582 integrate past environmental conditions, how these baselines scale with longevity, and how
583 shifting baselines influence maladaptation.

584 Moreover, most past research has emphasized shifts in average conditions (i.e., more
585 heat, more sensory pollution), but shifts in variation are another major hallmark of our changing
586 world (Volodin and Yurova 2013; Sheldon and Dillon 2016; Tamarin-Brodsky et al. 2020), and
587 they are underrepresented in behavioral analyses (but see Gilbert et al. 2022; Gillies et al. 2024;
588 Kirkpatrick and Sheldon 2022; Kirkpatrick et al. 2025; Kirkpatrick and DuRant this issue). As
589 more integrative and comparative biologists collect these behavioral data, we encourage future
590 incorporation of environmental variance, extreme events, and fine-scale spatial heterogeneity,
591 each of which can fundamentally alter our basic inferences on the role of behavior in responding
592 to anthropogenic changes (Ellis-Soto et al. this issue) as well as applications to predicting species
593 distributions and vulnerability in the future (Sheldon and Dillon 2016).

594 Behavior itself also presents practical challenges. It is inherently difficult to observe,
595 quantify, and scale across populations and time, particularly in natural systems (Keith et al.
596 2023; O'Hanlon et al. 2025). These challenges are compounded due to mismatches between the
597 spatial and temporal scales of publicly available environmental data, the scales at which
598 organisms experience change (Klinges et al. 2025), and the pace of behavioral adjustment.
599 Advances in animal tracking and machine learning are fast-tracking some of this progress (Kays
600 et al. 2022; Couzin and Heins 2023), but like community-driven science, these technologies
601 remain unevenly distributed across environments and species (Fraisl et al. 2022). Combinations

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of community observations and remotely generated data can together provide breadth of spatial scale and depth of analysis for even momentary events (Tucker et al. 2023; Aguilar et al. 2025); this complementarity of data is key to mitigating some of the logistical challenges associated with wildfire (Sanderfoot et al. 2024) and other immediately threatening elements of anthropogenic change. Critically, long-term ecological research remains a key behavioral tool (Knapp et al. 2012; Hope et al. 2026), particularly paired with standardized 'behavioral transects' to collect systematic behavioral data – now – so that these data can be leveraged by our colleagues in the future.

We also highlight several common assumptions that limit progress in this field. These include the ideas that behavior is easy to measure, infinitely flexible, or inherently capable of buffering organisms from environmental change. We caution against extrapolating from single populations to entire species, equating presence with persistence, or assuming that anthropogenic change is uniformly detrimental. Compelling narratives can persist even when empirical support is limited, reinforcing the need for careful interpretation and explicit testing of assumptions. Challenging these assumptions will be essential for developing more realistic, mechanistic, and predictive frameworks for understanding the role of behavior in a rapidly changing world.

A final, recurring theme from our literature review is that organisms do not experience different elements of anthropogenic change as isolated drivers acting independently. Urbanization and deforestation can directly modify the visual properties of environments through changes in habitat structure, water turbidity, and background coloration thereby impairing camouflage and signal contrast in animals, while climate-driven changes can indirectly modify sensory conditions across seasons and years (Delhey and Peters 2017; Spaniol et al. 2020). Reduced snow cover associated with rising temperatures can generate visual mismatch in

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seasonally color-changing species, increasing predation risk and altering predator–prey interactions (Stokes et al. 2025), while perceived predation risk feeds back to limit thermoregulatory behaviors in lizards and birds (Herczeg et al. 2008; Villén-Pérez et al. 2013). Across these examples and many more, behavioral responses emerge from interactions between physiological context and multiple, co-occurring environmental perturbations. Thus, while behavior may provide an immediate and flexible response to climate change, its effectiveness is shaped by numerous interacting pressures that demand further investigation. Importantly, this complexity is not merely an analytical challenge, but rather a reflection of the biological reality that organisms navigate through context-dependent behavioral strategies.

Author contributions

Samuel J. Lane: Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Olivia T. White:** Conceptualization, Methodology, Validation, Investigation.

Kimberly S. Sheldon: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing–Original Draft, Writing–Review & Editing; **Martha M. Muñoz:** Conceptualization, Project administration, Resources, Writing–Original Draft, Writing–Review & Editing; **Kimberly A. Rosvall**: Writing–Original Draft, Writing–Review & Editing; **João Vitor de Alcantara Viana**: Writing–Original Draft, Writing–Review & Editing; **Jamie Cornelius**: Writing–Original Draft, Writing–Review & Editing; **Saúl F. Domínguez-Guerrero**: Writing–Original Draft, Writing–Review & Editing; **Diego Ellis-Soto**: Writing–Original Draft, Writing–Review & Editing; **William H. Kirkpatrick**: Writing–Original

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Draft, Writing–Review & Editing; **Lauren O'Connell**: Writing–Original Draft, Writing–Review & Editing; **Raoni Rebouças**: Visualization, Writing – Review & Editing; Lauren A. Stanton: Writing–Original Draft, Writing–Review & Editing; **Elizabeth P. Derryberry**: Conceptualization, Project administration, Resources, Visualization, Writing – Original Draft, Writing – Review & Editing

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Conflict of interest

The authors declare no competing interests.

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672 **Data Availability**

673 Data sharing is not applicable to this article as no data were created or analyzed.

674

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