

PERSPECTIVE OPEN ACCESS

The Neglected Role of Sex-Biased Dispersal in Range-Shift Prediction Under Climate Change

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ABSTRACT

Studies aimed at estimating species response to climate change generally employ correlative species distribution models (SDMs) coupled with dispersal scenarios. However, dispersal distances are generally lacking or nonrepresentative, so researchers typically estimate dispersal distance from allometric relationships. Yet, these estimates ignore the role of sex bias in dispersal—where one sex disperses more than the other—leading to important prediction errors. We collected sex-specific dispersal data for 47 mammal species characterised by different levels of sex bias and projected their distribution under future climate scenarios, either considering or disregarding sex-biased dispersal. Results reveal discrepancies that can be substantial for species with marked sex bias. Given the paucity of sex-specific dispersal data, climate forecasting efforts should cautiously use a range of dispersal scenarios, favouring partial dispersal scenarios that are likely to encompass true species' range shifting abilities. Further research and data collection are crucial for refining predictions and understanding the ecological drivers of sex bias in dispersal across taxa.

Dispersal is a fundamental biological phenomenon that enables species to prevent inbreeding, maintain genetic flow among interconnected populations and colonise new areas (Macdonald and Johnson 2001). In the context of global environmental changes, dispersal plays a pivotal role in determining species' ability to adapt to changing climate. As environmental conditions change, the potential distribution of a species can change accordingly if previously unoccupied areas are colonised through dispersal events (Travis et al. 2013; Santini et al. 2016). Predicting species range shifts in response to climate change is a widespread practice in ecology and conservation biology, most often employing species distribution models (SDMs) (Bateman et al. 2013).

SDMs estimate a species' associations to environmental conditions, therefore allowing one to predict changes in environmental

suitability under future scenarios of change. Such predictions are typically binarised to infer the potential species' geographic distribution (Guisan and Thuiller 2005; Santini et al. 2021). By intersecting present and future predictions, researchers can identify (a) areas that are suitable at present but likely to become unsuitable under future conditions, (b) areas expected to remain suitable over time and (c) areas that are currently unoccupied but are expected to become climatically suitable in future and might be colonised by dispersing individuals (Figure 1a). Typically, researchers predict a species' ability to colonise newly suitable areas by considering 'dispersal scenarios' (Bateman et al. 2013), where the species' dispersal distance is multiplied by number of dispersal events expected within the time frame considered (e.g., assuming one event per each generation). For instance, a species with an average generation time of 10 years and average

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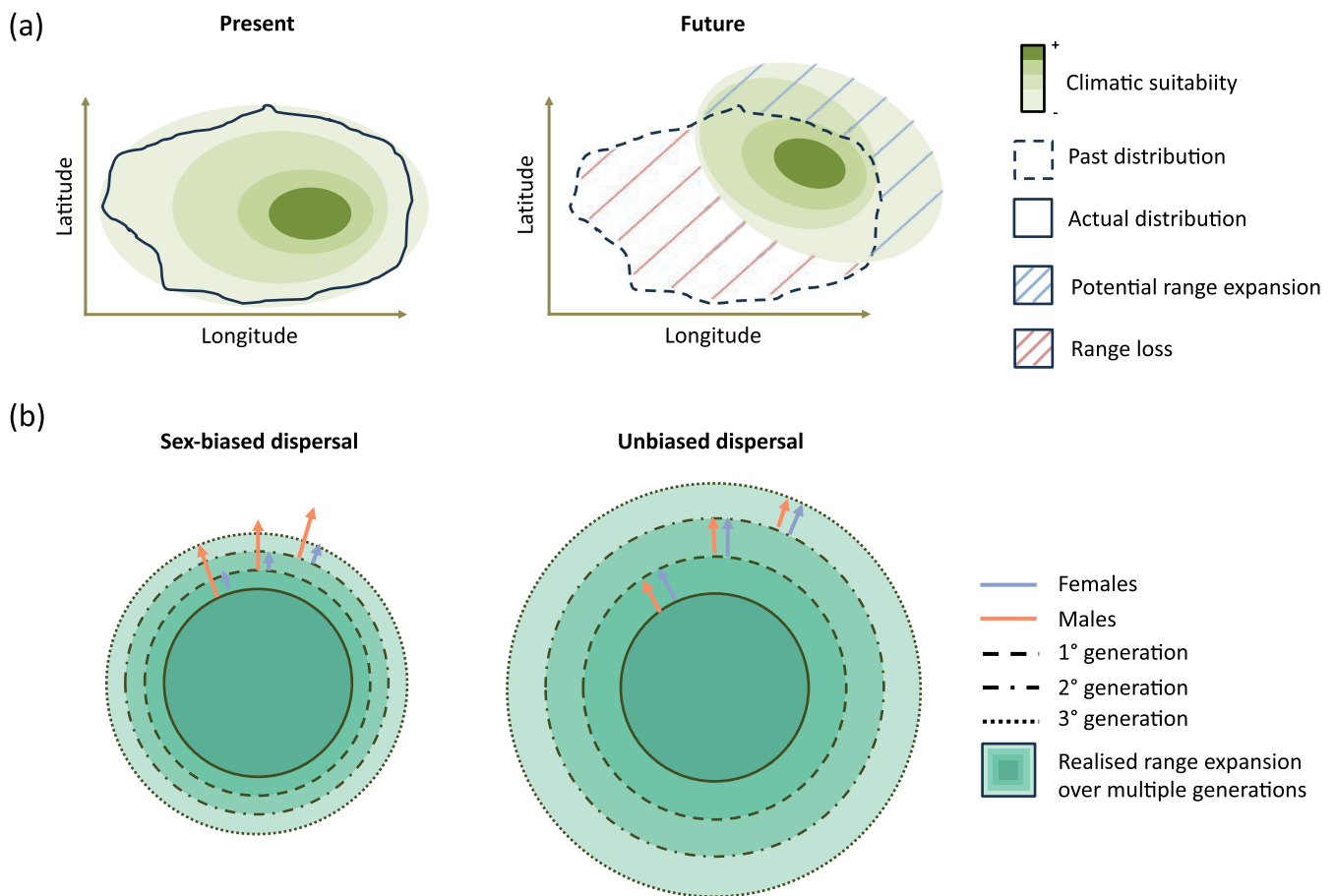


FIGURE 1 | Schematic illustration of (a) potential niche shift due to climate change, and (b) effect of sex-biased dispersal on range expansion potential of the species. (a) Potential niche shift due to climate change leads to regional extinction (range loss area) but make unoccupied areas suitable and potentially colonisable (potential range expansion areas). The future actual distribution of a species will depend on its realised range shift. (b) The effect of sex-biased dispersal on range expansion is depicted as a series of concentric regions that are colonised over multiple generations (represented by different line types and colour shadings). The arrows represent individual dispersal for the two sexes under two scenarios (sex-biased and unbiased dispersal). Under the sex-biased dispersal, the arrows of the sex that disperses the most exceed the realised range expansion boundary, meaning that individuals of one sex can reach more distant areas but the species cannot eventually colonise these areas and grow locally; new generations of dispersers can only occur where both sexes are present.

dispersal of 10 km is expected to shift its range by 30 km within a 30-year period (e.g., Schloss, Nuñez, and Lawler 2012; Visconti et al. 2016). Typically, accounting for dispersal in climate projection can mitigate substantially the risks of climate change (e.g., Warren et al. 2018; Mancini et al. 2024).

Despite its pivotal role in ecology and conservation, dispersal remains one of the most poorly known behaviours in the natural world, thus dispersal data are severely lacking. Gathering dispersal data in wild populations presents numerous challenges, and knowledge about species' dispersal abilities is at best limited (Macdonald and Johnson 2001; Driscoll et al. 2014). For example, at present, average dispersal distances are available for only approximately 150 species of mammals (approximately <3% of known mammal species; Whitmee and Orme 2012; Santini et al. 2013) and 114 of bird species (approximately ~1% of known bird species; Weeks et al. 2022). Even less is known about dispersal in less-studied vertebrates such as amphibians and reptiles (e.g., Smith and Green 2005), and virtually nothing is known for most invertebrates with few exceptions (e.g.,

Lepidoptera; Stevens et al. 2014). When possible, researchers have tackled this issue by establishing allometric relationships between observed dispersal distances and available trait data (e.g., Sutherland et al. 2000; Bowman, Jaeger, and Fahrig 2002; Whitmee and Orme 2012; Santini et al. 2013; Weeks et al. 2022). For instance, dispersal distance is known to correlate well with the home range area in mammals (Bowman, Jaeger, and Fahrig 2002; Santini et al. 2013) and wing morphology in birds (Weeks et al. 2022), among other traits.

Besides being poorly recorded, dispersal distance poses additional challenges in its prediction, since it shows high intra-specific variability, with many individuals dispersing short distances and few dispersing long distances (Trakhtenbrot et al. 2005). Second, dispersal is age-biased, that is, distance and frequency can vary with age (Morris 1982). Finally, dispersal is typically sex-biased, since there is an unequal frequency and distance of dispersal events between individuals of the two sexes (Pusey 1987; Trochet et al. 2016; Li and Kokko 2019). The extent of this latter bias varies considerably across species, ranging

from cases where one sex disperses longer distances on average to instances where only one of the two sex disperses at all. In cases of strong sexual bias, the species' ability to expand or shift its range is essentially constrained by the dispersal capabilities of the less mobile sex, which limits the shifts to gradual establishments of new home range areas adjacent to the parental habitat (Figure 1b). Notable exceptions may be secondary dispersal events by fertilised females laying eggs/giving birth in the newly colonised areas, but—in the absence of new colonisers—leading to inbreeding events.

Despite intraspecific differences, researchers have primarily focussed on species' average ability to disperse, for example, mixing males and females data to obtain mean dispersal distances to establish predictive allometric equations (Sutherland et al. 2000; Whitmee and Orme 2012; Santini et al. 2013; Weeks et al. 2022). As a consequence, the use of these equations to predict dispersal ability can lead to grossly overestimate a species' capacity to adapt to climate change.

Here, we demonstrate that accounting for sex bias can significantly alter predictions of range shifts under future climate change. We collected sex-specific dispersal estimates from 98 studies for a total of 47 mammal species with available sex-specific dispersal values (Appendix S1, Table S1), and derived sex-specific averages weighted by sample size (Table S2). This species selection was essentially limited by the availability of sex-specific dispersal estimates and is not representative of mammal species globally. It is mostly consists of medium to large-size mammals of temperate regions due to major bias in research efforts (Driscoll et al. 2014). However, our sample includes species with minor differences among sexes (e.g., *Meles*

meles) and others with marked differences (e.g., *Ursus americanus*), thus allowing us to test the influence of various degrees of sex bias in climate-induced range shifts predictions.

We then modelled species distribution and projected these under a commonly used future climate scenario using maxnet algorithm (Time horizon: 2041–2070; GCM: GFDL-ESM4; Scenario: SSP370) and applied partial dispersal scenarios (sensu Bateman et al. 2013) using the dispersal distance for both the most and least dispersing sex, and compare the range change predictions. We provide a detailed description of the modelling approach in Appendixes S2 and S3. This modelling is not meant to provide a representative assessment of future risk by climate change for mammals, which would require a more representative set of species, and a wider selection algorithms and scenarios; rather, it is meant to simply highlight the effect of sex-biased dispersal on future projections.

Results show that ignoring sex-biased dispersal results in range change estimates differing by > 50% for 19% of the species, and > 200% for 4% of the species (Figure 2a). Differences are more extreme when focussing on range expansion only, with 34% of the species exhibiting differences > 100% and 14% of the species differences > 200% (Figure 2b). Since dispersal scenarios are often based on allometric relationships taking the average of the two sexes, marked sex bias can result in either under- or overestimates of species ability to cope with climate change. Species-specific results are provided in Table S3.

Sex bias is pronounced in some species, while barely noticeable in others. This diversity in sex bias may introduce a taxonomic bias in large-scale analyses of species' responses to climate

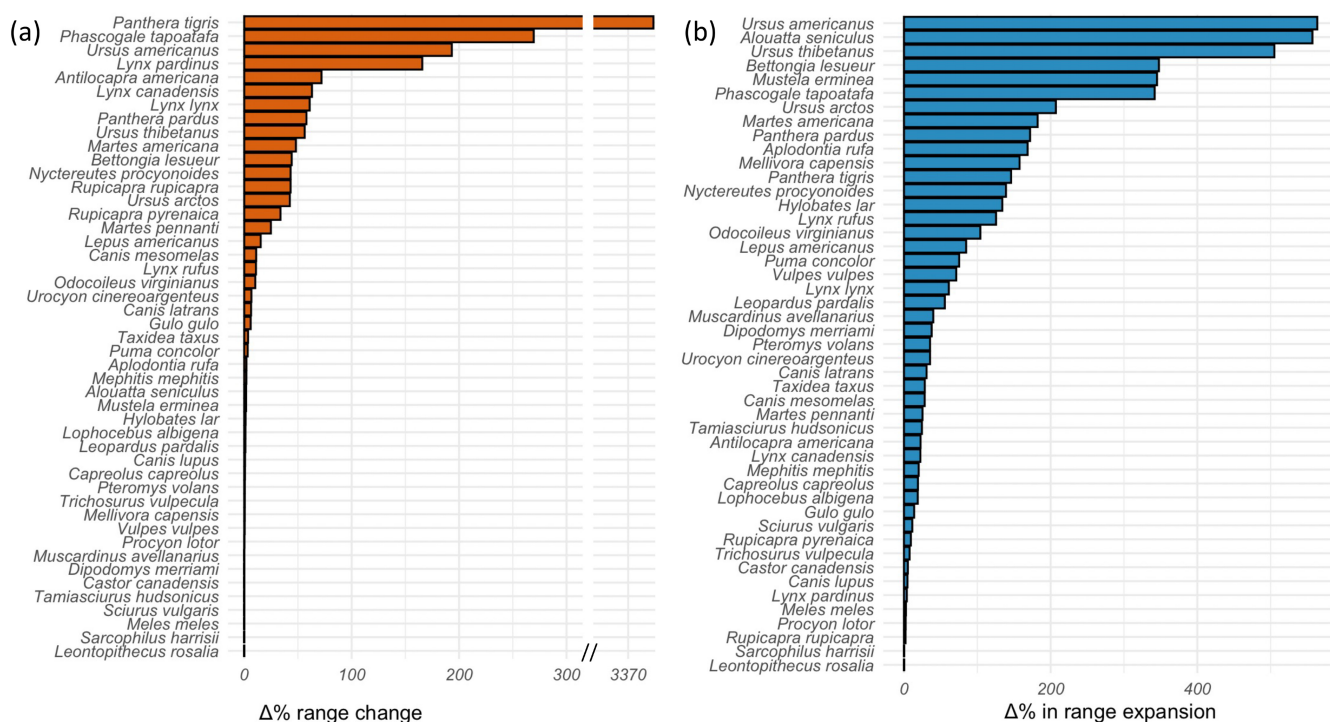


FIGURE 2 | Sex-biased dispersal leads to large differences in range change predictions when using males' or females' estimates. (a) Difference in the percentage of projected range change when using the dispersal of males and females. (b) Percentage increase in range expansion when using the dispersal estimate of the most dispersing sex.

change. While dispersal estimates for the most dispersing sex might be appropriate for connectivity analyses, dispersal estimates of the least dispersing sex should be used for climate projections. However, the available data on sex-specific dispersal are limited to only few species, which hinders our ability to generalise this information even within well-studied taxonomic groups such as birds and mammals. Biological proxies of sex-biased dispersal might help to identify species where this issue might result in important differences; however, our knowledge on the biological and ecological drivers of sex bias is still limited with several existing hypotheses (Li and Kokko 2019). For example, it has been hypothesised a connection between sex bias and species mating system. Mabry et al. (2013) found that monogamous species tend to be more female-biased and polygynous or promiscuous species tend to be more male-biased in mammals. However, this conclusion was drawn from a small data set with significant outliers and violation of statistical assumptions; a re-analysis of the data does not support their findings (Appendix S4).

Given these limitations, we recommend that conservationists take a cautious approach in using dispersal data for projecting species distribution shift. We recommend disregarding 'unlimited dispersal' scenarios where species are assumed to be capable of reaching any new climatically suitable area. We emphasise the use of partial dispersal scenarios as upper boundary estimates, by calculating range shifts in terms of average dispersal distance multiplied by the expected number of generations during the time period considered. We also suggest considering a lower boundary prediction based on home range diameter, that is, assuming the least dispersing sex can only shift the home range gradually with population growth at the range margin. While home range data may be lacking for many species, they are becoming more and more common through open databases (e.g., Broekman et al. 2022) or allometric relationships (Tamburello, Côté, and Dulvy 2015). These two latter assumptions are likely to encompass a species' ability to disperse under climate change. In the meantime, dispersal remains a crucial parameter that requires further investigation through field studies. Gathering more data may help clarify the correlates of sex bias across species, thereby contributing to a broader understanding that can be applied to a wider range of taxonomic groups.

Author Contributions

L.S. conceived the original idea with contributions from M.D.M. M.F. collected the data. G.M. ran the analyses. L.S. drafted the initial version of the paper, and all authors contributed to its revision.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data to develop the species distribution models are all freely accessible: IUCN range polygons are available from the IUCN database and climate data from the CHELSA database (Karger et al. 2017). Sex-specific dispersal estimates with respective references are provided in Table S1, and sex-specific dispersal-weighted averages used for the dispersal scenarios are provided in Table S2.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.