nature climate change

PERSPECTIVE

https://doi.org/10.1038/s41558-019-0526-5

Persecuting, protecting or ignoring biodiversity under climate change

Brett R. Scheffers[1*] and Gretta Pecl[2,3]

A climate-driven global redistribution of species is currently underway. As species alter their geographical distributions under climate change, many will not only cross into new habitats but also new geopolitical areas. In this Perspective, we discuss the historical archetypes of managing species redistribution—persecution, protection or ignorance—which points to diverse decisions and outcomes based on a balance of societal and ecological valuation. We build the case for increasing transboundary monitoring and management of species, and for shared governance agreements that are global in scope, consisting of legally binding and biologically defensible contracts among partner countries, in what would be a critical step for the future conservation of all species.

Climate change has already impacted all aspects of life on Earth, from genes to communities, across freshwater, marine and terrestrial ecosystems[1]. Perhaps the most pervasive response across the suite of observed impacts is species redistribution[2]. Where entire communities or groups of taxa in one region have been assessed, estimates suggest between 18 to 80% of species (amounting to thousands) have already shifted their ranges[3–6]. Species are moving up mountainsides and deeper in the oceans, but also shifting polewards across land and seascapes with latitude and longitude, as they try to keep pace with temperature and precipitation regimes that once defined their historic ranges. As species move, many will cross not only into new habitats, but also new geopolitical areas[7]. This begs the question: how will we manage them?

The answer to this question is complex and will likely be determined by what ecological roles these species serve relative to socioeconomic values (for example, is it a commercially valuable or charismatic species?). On one hand, the new arrival of a species, and its subsequent establishment as a reproducing and persisting population, indicates successful range extension[8]; a response that is generally welcomed by conservation biologists as some species will not be able to keep pace with climate change[9,10]. However, on the other hand, these 'successful' species might also represent invaders (sometimes referred to as native or climate invaders) that compete with or predate on historically extant species, or incur societal costs such as the case of agricultural pests or species that may disrupt economically important fisheries[11–13]. The current global redistribution of terrestrial, freshwater and marine species demands a discussion on how we manage and/or protect redistributed species—both those occupying historic ranges and those that shift into new ones—under climate change (Fig. 1)[14].

Here, we discuss past management of species that have shifted and/or expanded their ranges due to non-climate-change-related drivers, and the complexity of the motivators behind these decisions—namely the balance between the ecological roles that species fill and the way that society and culture often determine the value of a species regardless of its origin. Moreover, this ecological versus cultural balance may have considerable influence on when and how species are managed during the initial arrival stages of their redistribution. By corollary, we conclude that without detailed, transparent and consistent policies for managing newly arrived climate-driven species, our current management and conservation protocols may fail to protect species responding to climate change.

Species valuation based on ecology and society

The 'valuation' of species is dependent on ecological function (benefits or costs to the environment) relative to societal value (benefits or costs to society)[15,16] (Fig. 2). Ecological functions that help maintain healthy ecosystems can be diverse, ranging from pollination to predator-driven top-down regulation of prey. Societal values are influenced by a variety of factors ranging from cultural memory (whether or not society is familiar with the plant or animal), whether the species has recreational or industry value, or if it has costs associated with becoming an agricultural pest, for example. In some cases, native species become 'native invaders' when they move outside of their historical range, achieve extreme abundances and exert pressure (competitive or predatory) on other native species[11].

Although conservation management aims to protect native species as well as maintain the ecological function of ecosystems, past management of redistributed species—those that have expanded or shifted their ranges either naturally or in response to human modified landscapes (herein excluding species that were physically moved by humans) and not directly from climate change—has yielded mixed actions and results due to conflicting goals of diverse human interests. Ecological and societal valuations of species 'new' to a system either align or are opposed to one another, with direct implications for species management resulting in some that are persecuted, protected or ignored (Fig. 2).

Three archetypes for managing redistributed species

A fundamental tenant in ecology is that the distribution of plant and animal communities change in space and time. Consequently, managers will need to act over different spatial and temporal scales, and the current emphasis on historical species assemblages and ranges may shift towards prioritizing future ecosystem processes[17]. But what established principles or frameworks will we use to help define what an acceptable, future ecosystem looks like? The three primary archetypes of the approaches taken historically to manage species redistribution, may shed light on this question.

[1]Department of Wildlife Ecology and Conservation, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL, USA. [2]Institute for Marine and Antarctic Studies, Hobart, Tasmania, Australia. [3]Centre for Marine Socioecology, University of Tasmania, Hobart, Tasmania, Australia. *e-mail: brett.scheffers@ufl.edu

Fig. 1 | Species are not waiting for policy makers to shift their distributions. Credit: Bas Köhler

The persecuted. These are species that expand their ranges but are not welcomed additions to existing plant and animal communities. New species have the potential to out-compete[18], hybridize with[19] or predate on[20,21] historically native species[11].

Examples of species expanding their ranges (often due to mechanisms not related to climate) are abundant, with dozens of examples from North America alone (Fig. 2). For example, the barred owl *Strix varia* shifted its distribution westward in the United States and began to out compete the endangered spotted owl, *Strix occidentalis*[18]; the coyote *Canis latrans* shifted its distribution to the east and hybridized with the red wolf *Canis rufus*, as well as outcompeted and predated on small mammals (such as the grey fox *Urocyon cinereoargenteus*)[19,22]; and the brown cowbird *Molothrus ater* shifted its range eastward and parasitized the nests of eastern songbird species (for example, warblers)[23–25]. In each of these examples, management targeted the 'native invader' because of its ecological and societal costs (such as impacts on endangered species), despite each scenario representing a 'natural' redistribution[26] (Fig. 2).

The use of terms like 'invasive' species in the context of native redistributed species can promote a militaristic attitude towards nature[27]. In some instances, management that persecutes expanding species is based on the decision that the range expansions were assisted or facilitated through indirect human actions, such as agriculture expansion, and thus the redistribution is not 'natural'. For example, the expansion of the barred owl is often referred to as an 'invasion'[28], and the nine-banded armadillo is referred to as an 'invasive predator'[20], yet both species expanded their range as a result of human-caused habitat fragmentation. Changes in fire regimes can also earn species the native invasive title. For example, the red cedar *Juniperus virginiana* has become a native invasive species of the United States central plains due to fire suppression by humans[29]. But will perception and management outcomes of species that redistribute under human-caused climate change be akin to those that do for human-caused habitat change? Continued discussion and consideration around the semantics of these parallel mechanisms for redistribution is required. One clear distinction may be whether a redistributing species is expanding in one area while contracting in another, rather than just expanding (that is, 'invading'). The distinction here is blurred by extinction lags within the historical ranges of species[8], but also by governance issues if the contracting range is in one country while the expanding range is located in another. For example, the quiver tree *Aloidendron dichotomum* is a transboundary species between Namibia and South Africa, and is threatened by climate change[30]. This species has shrinking ranges within Namibia but has maintained healthy populations in South Africa. To this end, for a newly colonized species with small population size, at what point, if at all, should a country establish a monitoring and management plan (Fig. 3)?

The protected. These are commonly species with protected-status that expand their range with immediate, mandated protection in their new range area due to federal or state law. For example, the Kirtland's warbler (*Dendroica kirtlandii*), an endangered migrant bird species of the USA, has recently expanded its population from northern Michigan into Wisconsin, Michigan's Upper Peninsula and central Canada[31,32]. It received protection within its new geopolitical boundary because of its listing on the Endangered Species Act, in the USA, and the Species at Risk Act, in Canada. Such rapid responses were mandated by established government policy[33] that was aligned with ecological and societal values and, importantly, aligned across geopolitical borders (Fig. 2).

Protection of species in new range areas is predicated on those species being detected and reported in that area. However, monitoring and management generally only occurs for species declining in abundance, or for those species with economic or game/recreational value, regardless of their population status (Fig. 3). For these select species, pro-active management is more likely to be implemented to help species keep pace with climate change. For example, tropical fishes are redistributing into temperate waters at a global scale[2,34]. In response to the arrival of new species, natural resource managers in the Australian island state of Tasmania have created proactive management policies to limit catch of several 'new' species through the introduction of bag limits for recreational fishers (www.tas.gov.au), to allow new fish populations to become established. But what protections will be afforded to newly established species without clear game or recreation value?

The overlooked or ignored. Not all species have obvious societal or ecological benefits/costs to demand management. As species redistribute, populations established in new areas will initially be small in numbers, so the likelihood for many redistributed species to be overlooked by resource managers is high. So, at what point in time will these species be integrated into government species action plans? There are dozens of examples of rare or vagrant species showing up in new regions outside their historical range. For example, each year, bird watchers travel long distances to observe rare bird species that arrive unannounced (for example, see www.ebird.com). These vagrancies outside species' normal range are not unique to birds but occur across most taxa; the latter simply do not have the same intensity of citizen-science monitoring to detect rare occurrences (but, see www.redmap.org.au for marine citizen-science monitoring around Australia). However, under climate change, as species start to move into new territory, vagrancy and rarity in any given location is likely to become increasingly important in future planning scenarios. For example, vagrant animals—individuals of a species that disperse farther than 90% of the population—may portend species distribution in a climate-changed world as vagrants become pioneers[35,36]. Thus, monitoring and management will be important at the arrival stage of redistribution (Fig. 3), as well as careful review of species records to differentiate a rare species occurrence, or historically present but previously unrecorded species, from an early-stage range redistribution[37].

Ecological/societal conflicts and redistribution

Management of species redistribution, particularly in those countries that have established monitoring and management programs, occurs when new species negatively impact a historically 'native' species, when they are economically or recreationally valued, or if species have mandated protection due to their historical population declines. This begs the question: when do we begin monitoring

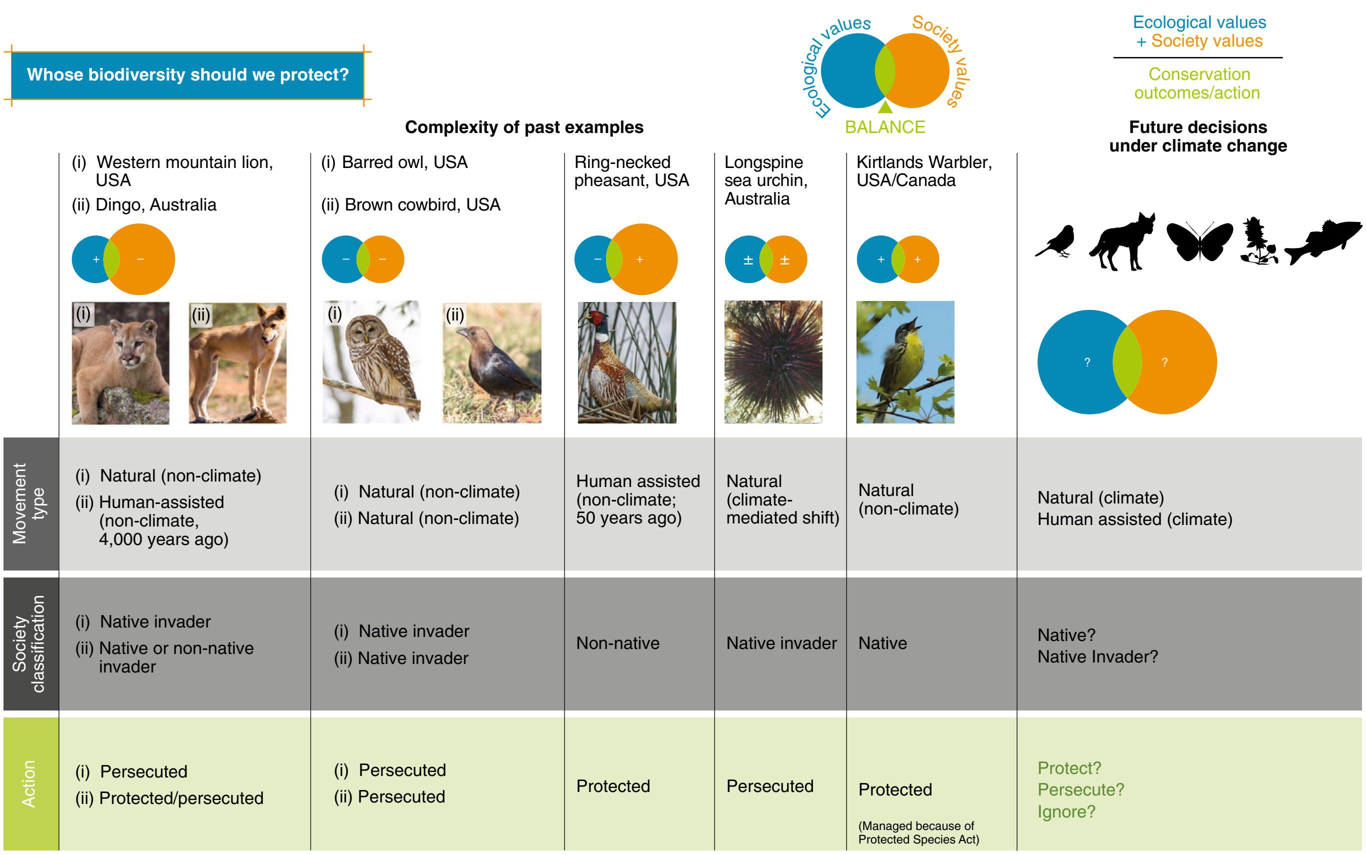

Fig. 2 | High uncertainty in future management of biodiversity. Whose biodiversity do we protect under climate change will be determined by a balance between ecological and societal values. Based on past examples of species redistribution, species will be persecuted, protected or ignored, which creates high levels of uncertainty as to the fate of the Earth's biodiversity under a global climate-driven redistribution. Image courtesy of UF/IFAS. Credit: moose henderson/iStock/Getty Images Plus/Getty (Mountain lion); FiledIMAGE/iStock/Getty Images Plus/Getty (Dingo); Fyn Kynd (Barred owl); yhelfman/iStock/Getty Images Plus/Getty (Brown cowbird); Becky Matsubara (Ringed-neck pheasant); Javier Cooper (Longspine urchin); Jim Hidgins/USFWS (Kirtlands warbler)

and managing species under climate change (Fig. 3), and how will this responsibility be shared across geopolitical borders? The global redistribution of species will largely comprise species with limited economic or recreation value. A pro-redistribution approach under future climate change would require monitoring to detect recently arrived and establishing species, and management at an intensity that is comparable to species with high value to society.

Separating winners from losers. The ecological and societal valuation of species is a complex balance and may differ from one geopolitical region to the next. For example, regime shifts, where one ecosystem shifts to another state following a disturbance, have already been observed under climate change. Widespread bleaching and subsequent coral death has occurred in the tropical waters of north-eastern Australia[38]. Concomitantly, tropical fish and corals quickly invaded the temperate waters of southern Australia following the decline of kelp forests from ocean warming[13]. Tropical species shifting poleward towards temperate waters is a positive sign of ecosystem adaptation. Yet, society may end up gridlocked in their valuation of tropical species shifting across geopolitical space, whereby the spread of tropical species poleward is viewed positively by society at low-latitudes and negatively by society at high-latitudes (or vice versa).

Human-assisted migrations. Humans have been intentionally moving species outside their geographic range for millennia, often resulting in conflicts between societal and ecological valuations. There are many examples of truly exotic species being intentionally introduced and subsequently managed for recreational purposes, despite their negative impacts on ecological systems (for example, wild horses in North America and Australia; the introduced western North American rainbow trout *Oncorhynchus mykiss* and the Asian Ring-necked pheasant *Phasianus colchicus* in the eastern and central United States, introduced for fishing and hunting, respectively). Additionally, resource managers are increasingly moving non-game/non-recreational species to new habitats, often outside of their historical ranges, in order to safeguard populations from human disturbances such as climate change and habitat loss[39]. Assisted migration of native species outside historical ranges has sparked considerable debate over the role society plays in engineering and shaping the ecological systems of the future. Under climate change, a discussion is needed to identify legitimate versus illegitimate uses of assisted migration and to promote transnational diplomacy that might help eliminate hurdles when countries are reluctant to assist the migration of their biota abroad (for example, concerns over biopiracy and tourism concerns related to charismatic species)[40].

The examples of human-assisted migrations given here showcase how both ecological and societal values will likely impact management decisions related to species redistribution. This mixed bag of outcomes begs questions as to how society could or should manage species that are undergoing redistribution as a function of anthropogenic climate change, and the degree to which managers should shape or create future ecosystems. The overwhelming influence of societal valuation on management makes it clear that natural-resource

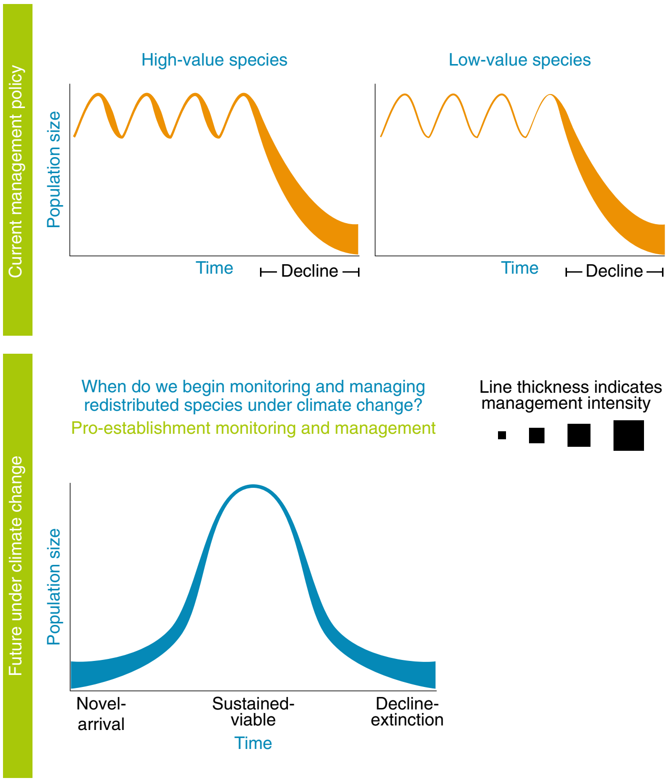

Fig. 3 | Species on the move will require pro-establishment monitoring and management practices. The intensity of species management is high when species have high societal value. A pro-establishment approach requires management at the arrival- and establishment-end of redistribution, with management intensities comparable to species with high societal value. Image courtesy of UF/IFAS.

managers need established and transparent processes, policies and guidelines for decision-making under climate change. But what should these policies look like considering that species redistribution is occurring across geopolitical boundaries at a global scale, and that some flexibility needs to be retained?

Each example noted here also resulted in different decisions on how best to manage redistributed species. Such flexibility in deriving diverse management practices is essential for successful species conservation and will be critical in future management scenarios under climate change[17]. One key issue, however, is that to successfully implement a management plan, in many cases, sufficient baseline data is required for informed decision making. This highlights the essential need for ecological monitoring to serve as the foundation for conservation of species on the move[41].

Conservation of biodiversity under climate change

If species adapt, we are destined for a world comprising of newly arrived species by the end of the twenty-first century[2,42]. Potential management complications resulting from thousands to hundreds of thousands of newly arrived species over the next century may be at least partially reconciled with clear management frameworks. Current adaptation-based management under climate change includes facilitation of movement either by building corridors that increase landscape permeability, creation of buffer zones around protected areas, or increased study of genetic diversity and viability of populations[43]. Adaptation-based management may be achieved through increasing interstate and international cooperation and future transnational treaties.

A first step is to develop 'management agreements' with legally and biologically defensible contracts that would provide for continuity in conservation management following species establishment (similar to 'recovery management agreements'[44]). Here, the ultimate focus of managing redistributed species is to achieve self-sustaining wild populations[44]. Indeed, future conservation of redistributed species is going to require unprecedented flexibility in objective, data-driven conservation priorities combined with transnational agreements for species management. Similarly, to avoid socio-political conflict over newly shared marine resources, management of commercial marine stocks will also require proactive transboundary agreements[7].

Species monitoring and prioritization at local, regional and transnational scales will entail active monitoring and prioritization of endangered/threatened species (those assessed by the International Union for Conservation of Nature Red List; www.iucnredlist.org); systems of early detection, such as Redmap (www.redmap.org.au) that may facilitate identification of shifting species, and therefore early identification of costs and benefits of redistribution; and a framework/decision tree process to establish clear and definable values (a balance of ecological function with societal values) relative to risk (potential damage). In the latter scenario, where newly arrived species are beneficial to society (for example, a commercial fishery), a consistent framework can help delineate future quotas and accessibility within the new range of the commercial species. This does require careful consideration as, traditionally, quotas are commonly based on historical catches, which may not be applicable to newly redistributed populations with no prior baseline in the new location. Lastly, policy will need to address the minimum viable population sizes of a given target species relative to its expanding and contracting range edges, especially when their distribution extends across multiple political boundaries (Fig. 3). For example, asymmetries in cross-border protection of species are widespread in North America[45]—a pattern that is likely applicable to other geographic regions.

Shared governance to tackle global redistribution

Ultimately, agreements will need to match the scale of climate change, which means global partnerships are required. There are active treaties in place that dictate the current ownership of, and responsibility for, species. For example, the Nagoya Protocol on Access and Benefit Sharing under the Convention on Biological Diversity, guides the equitable sharing of benefits arising from the utilization of genetic resources from nature. Borrowing from this, we discuss two options for shared governance of biodiversity under species redistribution: (1) a Climate Change Redistribution Treaty and/or (2) modification of existing transboundary treaties—both of which have complications in their establishment and execution.

A Climate Change Redistribution Treaty should acknowledge the transnational redistribution of all species from climate change and establish shared governance agreements for their establishment, ownership, protection, exploitation and/or management. Sharing a resource or ecosystem is not in itself sufficient rationale for transboundary management. There has to be an apparent need for the countries involved to consider devolving power towards a transboundary regime, as there are occasions where there is little net gain from collaboration[46]. For example, for a country where natural resource and species management is currently absent, these inadequacies can rarely be overcome by 'going transboundary'.

Importantly, a new treaty is likely to take considerable time for implementation; yet, climate change and its impacts on nature are rapidly accelerating. How long will such an agreement take to implement? To address this question, we reviewed nine international agreements (for example, the United Nations Fish Stocks Agreement and agreements under the Convention of Migratory Species of Wild Animals) that protect migratory species, and examined the relationship between the number of signatory countries and the number

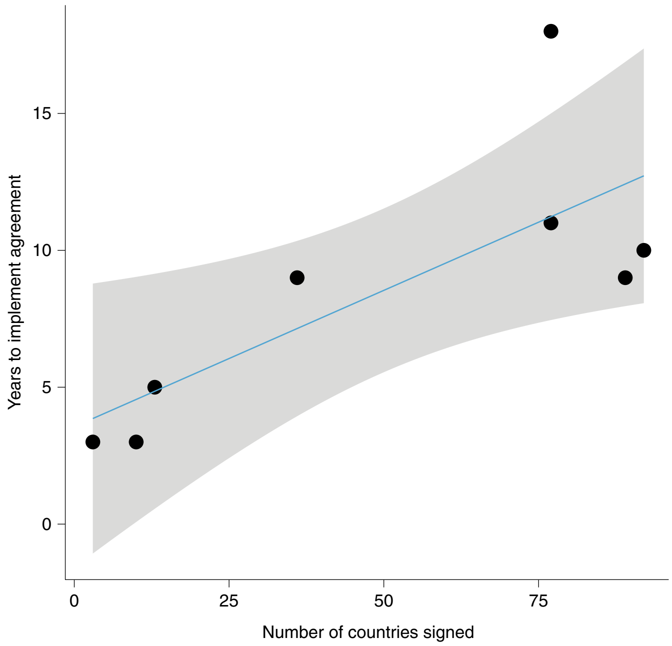

Fig. 4 | Number of years to implement transboundary agreements. The relationship between the number of signatories and the years required to implement the agreement for governing migratory species across geopolitical boundaries.

of years it took from first proposal to enforcement of each treaty. We modelled this relationship and found a strong positive correlation between the number of signatories and the number of years to implementation of an agreement (linear regression: adjusted $R^2 = 0.52$, $P < 0.027$; Fig. 4). Using this relationship to predict the timeframe for an agreement that tackles climate change redistribution, we show that a treaty that is of equal scope to the 21st Conference of the Parties Paris Agreement on carbon emissions, which includes 195 signatories, would require approximately 23 years (lower and upper 95% confidence intervals = 10 to 36 years, respectively) for full implementation. Therefore, under a typical scenario and if policy makers start now, we might implement such a treaty by 2041. By this time, based on the Intergovernmental Panel on Climate Change Special Report on the impacts of global warming, we would have already experienced 1.5 °C of warming. Further to this point, climate change will likely complicate existing agreements as migratory species shift to new territories.

Thus, policy makers must act now, and act fast, if countries intend to be prepared for a global redistribution. Fortunately, there are already established treaties in place that society can borrow from to help guide the development of future agreements. For example, the Agreed Measures for the Conservation of Antarctica Fauna and Flora guides the protection, scientific study and rational use of the fauna and flora of Antarctica. Here, the measures state that a 'native' animal or plant is defined as any member, at any stage of its life cycle, of any species that is indigenous to the Antarctic or occurring there through natural agencies of dispersal. Interestingly, this agreement calls to question the very issue and complexity of climate change redistribution, in that defining and characterizing 'natural agencies of dispersal' and 'indigenous' under anthropogenic climate change is unclear. Some policies explicitly target mobile species, such as the Migratory Bird Treaty Act for the Americas, which is a transnational treaty established to protect birds that migrate across political boundaries[47]. Several other treaties, similar in design, goals and outcomes, exist for African birds migrating to and from Europe[48], as well as birds moving to and from Australia and Asia (there are numerous bilateral agreements for these species, such as the East Asian–Australasian Flyway Partnership, which protects migrating birds[49]). These bilateral and multilateral agreements were implemented, and are guided by, existing platforms under the Bonn Convention or the Convention of the Conservation of Migratory Species of Wild Animals, both of which operate under the aegis of the United Nations Environment Program. These initiatives, however, provide a global platform for the conservation of mostly migratory animals and their habitats. Therefore, migratory agreements would need to be broadened to include non-migratory species that redistribute their ranges. Other avenues for species conservation under climate change include the Convention on Biological Diversity (CBD). For example, under Goal 1.3 of the CBD's Programme of Work on Protected Areas agreement, Parties are requested to establish and strengthen regional networks, transboundary protected areas, and collaboration across national boundaries. Here, there are positive signs of increasing transboundary partnerships, with a steady increase to over 200 transboundary conservation areas worldwide over the past 30 years (www.tbpa.net). Adaptation and modification of these platforms, combined with clear systematic frameworks for guiding the management and protection of establishing populations (Fig. 3), will ensure that conservation practitioners have the tools and political support necessary to safeguard biodiversity as it redistributes under climate change.

The ability of natural ecosystems to deliver services and to support sustainable development is already being challenged by the largest climate-driven global redistribution of species since the Last Glacial Maximum 20,000 years ago[1,2]. A transformation in the way we manage biodiversity, that extends across geopolitical boundaries, is required to address the long-term sustainability challenges of the Anthropocene. Indeed, the very definition of 'sustainability' needs revisiting under climate change. The future of global biodiversity underpins societal capacity for economic development, livelihoods, food security, human well-being and the climate system itself, and we cannot leave the fate of biodiversity critical to human survival to be randomly persecuted, protected or ignored.

Received: 19 September 2018; Accepted: 5 June 2019;
Published online: 08 July 2019

References

1. Scheffers, B. R. et al. The broad footprint of climate change from genes to biomes to people. *Science* **354**, aaf7671 (2016).
A comprehensive review showing that over 80% of ecological processes considered in terrestrial, marine, and freshwater ecosystems as well as human systems have evidence of observed impact from climate change.
2. Pecl, G. T. et al. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* **355**, eaai9214 (2017).
A comprehensive review showing that impacts of species redistribution extends from nature to society.
3. Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B. & Thomas, C. D. Rapid range shifts of species associated with high levels of climate warming. *Science* **333**, 1024–1026 (2011).
4. Parmesan, C. & Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**, 37–42 (2003).
5. Poloczanska, E. S. et al. Responses of marine organisms to climate change across oceans. *Front. Marine Sci.* **3**, 1–61 (2016).
6. Sunday, J. M., Bates, A. E. & Dulvy, N. K. Thermal tolerance and the global redistribution of animals. *Nat. Clim. Change* **2**, 686–690 (2012).
7. Pinsky, M. L. et al. Preparing ocean governance for species on the move. *Science* **360**, 1189–1191 (2018).
A paper highlighting the complexity of future governance of marine ecosystems under climate change.
8. Lenoir, J. & Svenning, J. C. Climate-related range shifts – a global multidimensional synthesis and new research directions. *Ecography* **38**, 15–28 (2015).
9. Both, C., Van Asch, M., Bijlsma, R. G., Van Den Burg, A. B. & Visser, M. E. Climate change and unequal phenological changes across four trophic levels: constraints or adaptations? *J. Animal Ecol.* **78**, 73–83 (2009).
10. Corlett, R. T. & Westcott, D. A. Will plant movements keep up with climate change? *Trend. Ecol. Evol.* **28**, 482–488 (2013).

11. Carey, M. P., Sanderson, B. L., Barnas, K. A. & Olden, J. D. Native invaders – challenges for science, management, policy, and society. *Front. Ecol. Environ.* **10**, 373–381 (2012).
12. Ling, S. D. Range expansion of a habitat-modifying species leads to loss of taxonomic diversity: a new and impoverished reef state. *Oecologia* **156**, 883–894 (2008).
13. Wernberg, T. et al. Climate-driven regime shift of a temperate marine ecosystem. *Science* **353**, 169–172 (2016).
14. Webber, B. L. & Scott, J. K. Rapid global change: implications for defining natives and aliens. *Glob. Ecol. Biogeo.* **21**, 305–311 (2012).
15. Schlaepfer, M. A., Sax, D. F. & Olden, J. D. The potential conservation value of non-native species. *Conserv. Biol.* **25**, 428–437 (2011).
16. Shine, R. & Doody, J. S. Invasive species control: understanding conflicts between researchers and the general community. *Front. Ecol. Environ.* **9**, 400–406 (2011).
17. Lawler, J. J. Climate change adaptation strategies for resource management and conservation planning. *Ann. NY Acad. Sci.* **1162**, 79–98 (2009).
18. Kelly, E. G., Forsman, E. D. & Anthony, R. G. Are barred owls displacing Spotted Owls? *Condor* **105**, 45–53 (2003).
19. Wayne, R. K. & Jenks, S. M. Mitochondrial DNA analysis implying extensive hybridization of the endangered red wolf *Canis rufus*. *Nature* **351**, 565–568 (1991).
20. Crane, A. L., McGrane, C. E. & Mathis, A. Behavioral and physiological responses of Ozark zigzag salamanders to stimuli from an invasive predator: the armadillo. *Int. J. Ecol.* **2012**, 1–7 (2011).
21. Fitch, H. S., Goodrum, P. & Newman, C. The armadillo in the Southeastern United States. *J. Mammal.* **33**, 21–37 (1952).
22. Gompper, M. E. Top carnivores in the suburbs? Ecological and conservation issues raised by colonization of North-eastern North America by Coyotes. *Bioscience* **52**, 185–190 (2002).
23. Brittingham, M. C. & Temple, S. A. Have cowbirds caused forest songbirds to decline? *BioScience* **33**, 31–35 (1983).
24. Mayfield, H. The Brown-headed Cowbird, with old and new hosts. *Living Bird* **4**, 13–28 (1965).
25. Rothstein, S. I. The cowbird's invasion of the far west: history, causes and consequences experienced by host species. *Stud. Avian Biol.* **15**, 301–315 (1994).
26. Siegle, R. & Ahlers, D. *Brown-headed cowbird management techniques manual* (US Department of the Interior, 2004).
27. Head, L. The social dimensions of invasive plants. *Nat. Plants* **3**, 17075 (2017).
28. Peterson, A. T. & Robins, C. R. Using ecological-niche modeling to predict Barred Owl invasions with implications for Spotted Owl Conservation. *Conserv. Biol.* **17**, 1161–1165 (2003).
29. Zhang, D. & Hiziroglu, S. Impact assessment and utilization of eastern red cedar. *Am. J. Appl. Sci.* **7**, 1032–1037 (2010).
30. Guo, D., Arnolds, J. L., Midgley, G. F. & Foden, W. B. Conservation of Quiver trees in Namibia and South Africa under a changing climate. *J. Geosci. Environ. Prot.* **4**, 1–8 (2016).
31. Probst, J. R., Donner, D. M., Bocetti, C. I. & Sjogren, S. Population increase in Kirtland's warbler and summer range expansion to Wisconsin and Michigan's Upper Peninsula, USA. *Oryx* **37**, 365–373 (2003).
32. Richard, T. Confirmed occurrence and nesting of the Kirtland's Warbler at CFB Petawawa, Ontario: a first for Canada. *Ont. Birds* **26**, 2–15 (2008).
33. Harris, J. B. C. et al. Conserving imperiled species: a comparison of the IUCN Red List and U.S. Endangered Species Act. *Conserv. Lett.* **5**, 64–72 (2012).
34. Poloczanska, E. S. et al. Global imprint of climate change on marine life. *Nat. Clim. Change* **3**, 919–925 (2013).
35. Fogarty, H. E., Burrows, M. T., Pecl, G. T., Robinson, L. M. & Poloczanska, E. S. Are fish outside their usual ranges early indicators of climate-driven range shifts? *Glob. Change Biol.* **23**, 2047–2057 (2017).
36. Veit, R. R. Vagrants as the expanding fringe of a growing population. *The Auk* **117**, 242–246 (2000).
37. Robinson, L. M. et al. Rapid assessment of an ocean warming hotspot reveals "high" confidence in potential species' range extensions. *Glob. Environ. Change* **31**, 28–37 (2015).
38. Hughes, T. P. et al. Global warming and recurrent mass bleaching of corals. *Nature* **543**, 373–377 (2017).
39. Hoegh-Guldberg, O. et al. Assisted colonization and rapidclimate change. *Science* **321**, 345–346 (2008).
40. Lawler, J. J. & Olden, J. D. Reframing the debate over assisted colonization. *Front. Ecol. Environ.* **9**, 569–574 (2011).
41. Bonebrake, T. C. et al. Managing consequences of climate-driven species redistribution requires integration of ecology, conservation and social science. *Biol. Rev.* **93**, 284–305 (2018).
A comprehensive review on complex management scenarios when considering species redistribution.
42. VanDerWal, J. et al. Focus on poleward shifts in species' distribution underestimates the fingerprint of climate change. *Nat. Clim. Change* **3**, 239–243 (2012).
43. Heller, N. E. & Zavaleta, E. S. Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biol. Conserv.* **142**, 14–32 (2009).
44. Scott, J. M. et al. Recovery of imperiled species under the Endangered Species Act: the need for a new approach. *Front. Ecol. Environ.* **3**, 383–389 (2005).
45. Thornton, D. H. et al. Asymmetric cross-border protection of peripheral transboundary species. *Conserv. Lett.* **11**, e12430 (2018).
46. Petursson, J. G., Vedeld, P. & Vatn, A. Going transboundary? An institutional analysis of transboundary protected area management challenges at Mt Elgon, East Africa. *Ecol. Soc.* **18**, 28 (2013).
47. Yong, D. L. et al. Challenges and opportunities for transboundary conservation of migratory birds in the East Asian-Australasian flyway. *Conserv. Biol.* **32**, 740–743 (2018).
48. Kirby, J. S. et al. Key conservation issues for migratory land- and waterbird species on the world's major flyways. *Bird Conserv. Int.* **18**, 49–73 (2008).
49. Yong, D. L. et al. Migratory songbirds in the East Asian-Australasian Flyway: a review from a conservation perspective. *Bird Conserv. Int.* **25**, 1–37 (2015).

Acknowledgements

We are grateful to A. Abolhassani and B. Haas for researching information for Fig. 4. T. Bryant was instrumental in creation of the other figures. G.P. was supported by an ARC Future Fellowship; and B.R.S. thanks Oak Ridge Associate Universities for their support via the Ralph E. Powe Junior Faculty Enhancement Award.

Author contributions

B.R.S. conceived the study, G.P. and B.R.S. collected data, B.R.S. analysed data, B.R.S. wrote the manuscript with development and revision from G.P.

Additional information

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence should be addressed to B.R.S.

Peer review information: *Nature Climate Change* thanks Chrystal Mantyka-Pringle, Morgan Tingley and other, anonymous, reviewer(s) for their contribution to the peer review of this work.