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Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being

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Abstract

Distributions of Earth's species are changing at accelerating rates, increasingly driven by human-mediated climate change. Such changes are already altering the composition of ecological communities, but beyond conservation of natural systems, how and why does this matter? We review evidence that climate-driven species redistribution at regional to global scales affects ecosystem functioning, human well-being, and the dynamics of climate change itself. Production of natural resources required for food security, patterns of disease transmission, and processes of carbon sequestration are all altered by changes in species distribution. Consideration of these effects of biodiversity redistribution is critical yet lacking in most mitigation and adaptation strategies, including the United Nation's Sustainable Development Goals.

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Review summary:

Biodiversity redistribution under climate change: impacts on ecosystems and human well-being

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Figure caption: As the global climate changes, human well-being, ecosystem function, and even climate itself are increasingly impacted by the shifting geography of life. Climate-driven changes in species distributions, or “range shifts,” affect human well-being both directly (for example, through emerging diseases and changes in food supply) and indirectly, by degrading ecosystem health. Some range shifts even create feedbacks (positive or negative) on the climate system, altering the pace of climate change.

BACKGROUND: The success of human societies depends intimately on the living components of natural and managed systems. Although the geographical range limits of species are dynamic and fluctuate over time, climate change is impelling a universal redistribution of life on Earth. For marine, freshwater, and terrestrial species alike, the first response to changing climate is often a shift in location, to stay within preferred environmental conditions. At the cooler extremes of their distributions, species are moving polewards, while range limits are contracting at the warmer range edge, where temperatures are no longer tolerable. On land, species are also moving to cooler, higher elevations, and, in the ocean, to colder water at greater depths. Because different species respond at different rates and to different degrees, key interactions among species are often disrupted, and new interactions develop. These idiosyncrasies can result in novel biotic communities and rapid changes in ecosystem functioning, with pervasive and sometimes unexpected consequences that propagate through and impact both biological and human communities.

ADVANCES: At a time when the world is anticipating unprecedented increases in human population growth and demands, the ability of natural ecosystems to deliver ecosystem services is being challenged by the largest climate-driven global redistribution of species since the last glacial maximum. We demonstrate the serious consequences of this species redistribution for economic

development, livelihoods, food security, human health, and culture, and we document feedbacks on climate itself. As with other impacts of climate change, species range shifts will leave “winners” and “losers” in their wake, radically re-shaping the pattern of human well-being between regions and different sectors and potentially leading to substantial conflict. The pervasive impacts of changes in species distribution transcend single systems or dimensions, with feedbacks and linkages between multiple interacting scales and through whole ecosystems, inclusive of humans. We argue that the negative effects of climate change cannot be adequately anticipated or prepared for unless species responses are explicitly included in decision-making and global strategic frameworks.

OUTLOOK: Despite mounting evidence for the pervasive and significant impacts of a climate-driven redistribution of Earth’s species, current global goals, policies, and international agreements fail to take account of these impacts. With the predicted intensification of species movements and their diverse societal and environmental impacts, awareness of ‘species on the move’ should be incorporated into local, regional and global assessments as standard practice. This will raise hope that future targets can be achievable, whether they be global sustainability goals, plans for regional biodiversity maintenance, or local fishing or forestry harvest strategies. and that society is prepared for a world of universal ecological change. Human society has yet to appreciate the implications of unprecedented species redistribution for life on earth, including for human lives. Even if greenhouse gas emissions stopped today, the responses required in human systems to adapt to the most serious of impacts of climate-driven species redistribution would be massive. Meeting these challenges requires governance that can anticipate and adapt to changing conditions, and minimize negative consequences.

Title: Biodiversity redistribution under climate change: impacts on ecosystems and human well-being

One Sentence Summary: Climate-driven species redistribution significantly impacts human well-being, ecosystem function, and even climate itself.

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Abstract: Distributions of the Earth's species are changing at accelerating rates, increasingly driven by human-mediated climate change. Such changes are already altering the composition of ecological communities, but beyond conservation of natural systems, how and why does this matter? We review evidence that climate-driven species redistribution at regional to global scales is impacting ecosystem functioning, human well-being, and the dynamics of climate change itself. Production of natural resources required for food security, patterns of disease transmission, and processes of carbon sequestration are all altered by changes in species distribution. Consideration of these effects of biodiversity redistribution is critical, yet lacking in most mitigation and adaptation strategies, including the United Nation's Sustainable Development Goals.

Main Text:

The history of life on Earth is closely associated with environmental change on multiple spatial and temporal scales ([1](#)). A critical component of this association is the capacity for species to shift their distributions in response to tectonic, oceanographic, or climatic events ([2](#)). Observed and projected climatic changes for the 21st-century, most notably global warming, are comparable in magnitude to the largest global changes in the past 65 million years ([3](#), [4](#)). The combined rate and magnitude of climate change is already resulting in a global-scale biological response. Marine, freshwater, and terrestrial organisms are altering distributions to stay within their preferred environmental conditions ([5-8](#)), and species are likely changing distributions more rapidly than they have in the past ([9](#)). Unlike the introduction of non-native species, which tends to be remarkably idiosyncratic and usually depends upon human-mediated transport, climate-driven redistribution is ubiquitous, follows repeated patterns, and is poised to influence a greater proportion of the Earth's biota. This redistribution of the planet's living organisms is a substantial challenge for human society.

Despite agreements to curb greenhouse gas emissions, the climate will continue to change for at least the next several hundred years given the inertia of the oceanic and atmospheric circulation systems ([10](#)), and species will continue to respond, often with unpredictable consequences. Since 1880 there has been an average warming of 0.85°C globally ([10](#)), resulting in well-documented shifts in species distributions with far-reaching implications to human societies, yet governments have agreed to accept more than double this amount of warming in the future (i.e., the Paris COP 21 2°C target). Moreover, current global commitments will only limit warming to 2.7-3.7°C,

more than 3-4 times the warming already experienced ([11](#)). To date, all key international discussions and agreements regarding climate change have focused on the direct socio-economic implications of emissions and on funding mechanisms; shifting natural ecosystems have not yet been considered.

Here, we review the consequences of climate-driven species redistribution for economic development and the provision of ecosystem services, including livelihoods, food security, and culture, as well as for feedbacks on the climate itself (Fig. 1, Table S1). We start by examining the impacts of climate-driven species redistribution on ecosystem health, human well-being, and the climate system, before highlighting the governance challenges these impacts individually and collectively create. Critically, the pervasive impacts of changes in species distribution transcend single systems or dimensions, with feedbacks and linkages among multiple interacting spatial and temporal scales and through entire ecosystems, inclusive of humans (Figs 2 & 3). We conclude by considering species redistribution in the context of earth systems and sustainable development. Our review suggests that the negative effects of climate change cannot be adequately mitigated or minimized unless species responses are explicitly included in decision-making and strategic frameworks.

Biological responses and ecosystem health

Species are impacted by climate in many ways, including range shifts, changes in relative abundance within species ranges, and subtler changes in activity timing and microhabitat use ([12](#), [13](#)). The geographic distribution of any species depends upon its environmental tolerance,

dispersal constraints, and biological interactions with other species (14). As climate changes, species must either tolerate the change, move, adapt, or face extinction (15). Surviving species may thus have increased capacity to live in new locations or decreased ability to persist where they are currently situated (e.g., 13).

Shifts in species distributions across latitude, elevation, and with depth in the ocean have been extensively documented (Fig. 1). Meta-analyses show terrestrial taxa, on average, moving polewards by 17 km per decade (5), and marine taxa by 72 km per decade (6, 16). Just as terrestrial species on mountainsides are moving upslope to escape warming lowlands (e.g., 17), some fish species are driven deeper as the sea surface warms (e.g., 18).

The distributional responses of some species lag behind climate change (6). Such lags can arise from a range of factors, including species-specific physiological, behavioural, ecological, and evolutionary responses (12). Lack of adequate habitat connectivity and access to microhabitats and associated microclimates are expected to be critical in increasing exposure to macroclimatic warming and extreme heat events, thus delaying shifts of some species (19). Furthermore, distribution shifts are often heterogeneous across geographic gradients when factors other than temperature drive species redistribution. For example, precipitation changes or interspecific interactions can cause downward elevation shifts as climate warms (20). Although species may adapt to changing climates, either through phenotypic plasticity or natural selection (e.g., 21), all species have limits to their capacity for adaptive response to changing environments (12) and these limits are unlikely to increase for species already experiencing warm temperatures close to their tolerance limits (22).

The idiosyncrasies of species responses to climate change can result in discordant range shifts, leading to novel biotic communities as species separate or come into contact in new ways (23). In turn, altered biotic interactions hinder or facilitate further range shifts, often with cascading effects (24). Changes in predation dynamics, herbivory, host-plant associations, competition, and mutualisms can all have substantial impacts at the community level (16, 25). A case in point involves the expected impacts of crabs invading the continental shelf habitat of Antarctic sea-floor echinoderms and mollusks—species that have evolved in the absence of skeleton-crushing predators (26). The community impacts of shifting species can be of the same or greater magnitude as the introduction of non-native species (16), itself recognized as one of the primary drivers of biodiversity loss (27).

When species range shifts occur in foundation or habitat-forming species, they can have pervasive effects that propagate through entire communities (28). In some cases, impacts are so severe that species redistribution alters ecosystem productivity and carbon storage. For example, climate-driven range expansion of mangroves worldwide, at the expense of saltmarsh habitat, is changing local rates of carbon sequestration (29). The loss of kelp-forest ecosystems in Australia and their replacement by seaweed turfs has been linked to increases in herbivory by the influx of tropical fishes, exacerbated by increases in water temperature beyond the kelp's physiological tolerance limits (30, 31). Diverse disruptions from the redistribution of species include effects on terrestrial productivity (32), impacts on marine community assembly (33), and threats to the health of freshwater systems from widespread cyanobacteria blooms (34).

The effects on ecosystem functioning and condition arising from species turnover and changes in the diversity of species within entire communities are less well understood. The redistribution of species may alter the community composition in space and time (beta diversity), number of species co-occurring at any given location (alpha diversity) and/or the number of species found within a larger region (gamma diversity) (35). The diversity and composition of functional traits within communities may also change as a result of species range shifts (36), although changes in functional traits can also occur through alterations in relative abundance or community composition, without changes in species richness. Increasingly, evidence indicates that species diversity, which underlies functional diversity, has a positive effect on the mean level and stability of ecosystem functioning at local and regional scales (37). It therefore appears likely that any changes in diversity resulting from the redistribution of species will have indirect consequences for ecosystem condition.

Extinction risk from climate change has been widely discussed and contested (38-40), and predictions of extinction risk for the 21st century are considerable (41). In some cases, upslope migration allows mountain-dwelling species to track suitable climate, but topography and range loss can sometimes trap species in isolated, eventually unsuitable, habitats (42). The American pika (*Ochotona princeps*) has been extirpated or severely diminished in some localities, signaling climate-induced extinction or at least local extirpation (43). Complicated synergistic drivers or *extinction debt*—a process in which functional extinction precedes physical extinction—may make climate-induced extinction seem a distant threat. However, the disappearance of Bramble Cay melomys (*Melomys rubicola*), an Australian rodent declared

extinct due to sea-level rise (44), shows anthropogenic climate change has already caused irreversible species loss.

Notwithstanding the rich body of evidence from the response to climate change of species and ecosystems in the fossil record (45), understanding more recent, persistent responses to climate change usually requires several decades of data to rigorously assess pre- and post-climate change trends at the level of species and ecosystems (46). Such long-term datasets for biological systems are rare, and recent trends of declining funding undermine the viability of monitoring programs required to document and respond to climate change.

Human well-being

The well-being of human societies is tied to the capacity of natural and altered ecosystems to produce a wide range of “goods and services.” Human well-being, survival, and geographical distribution have always depended upon the ability to respond to environmental change. The emergence of early humans was likely conditioned by a capacity to switch prey and diets as changing climatic conditions made new resources available (47). However, recent technological changes in agriculture, forestry, and fisheries have weakened the direct link between human migration and survival. Now, human societies rely more on technological and behavioral innovation to accommodate human demography, trade/economics, and food production to changing species distribution patterns. The redistributions of species are expected to affect the availability and distribution of goods and services for human well-being in a number of ways,

and the relative immobility of many human societies, largely imposed by jurisdictional borders, has limited capacity to respond to environmental change by migration.

Redistributions of species are likely to drive significant changes in the supply of food and other products. For example, the relative abundance of skipjack tuna in the tropical Pacific, which underpins government revenue and food security for many small island states, is expected to become progressively greater in eastern areas of the Western and Central Pacific Ocean, helping to offset the projected ubiquitous decline in the supply of fish from degraded coral reefs in that region (48). Conversely, it is estimated that an average of 34% of European forest lands, currently covered with with valuable timber trees, such as Norway spruce, will be suitable only for Mediterranean oak forest vegetation by 2100, resulting in much lower economic returns for forest owners and the timber industry (49).

The indirect effects of climate change on food webs are also expected to compound the direct effects on crops. For example, the distribution and abundance of vertebrate species that control crop pests are predicted to decline in European states, where agriculture makes important contributions to the gross domestic product (50). Shifts in the spatial distribution of agriculture will be required to counter the impact of these combined direct and indirect effects of changing climate. Geographic shifts in natural resource endowments and in systems supporting agriculture, forestry, fisheries and aquaculture, will result in winners and losers, with many of the negative effects likely to occur in developing countries (51). A prime example is the projected effect of climate change on the supply of coffee, with principal coffee growing regions expected to shift (52).

Species range-shifts are also affecting the intrinsic and economic values of recreation and tourism, in both negative and positive ways (53). The build-up of jellyfish due to warmer temperatures in a Mediterranean lagoon has had a negative effect on local economies linked to recreation, tourism, and fishing (54). In southeast Australia, a range-extending sea urchin has overgrazed macro-algae, resulting in localized loss of up to 150 associated taxa and contributing to reduced catch limits for popular recreational fisheries species dependent on large seaweed (55). Impacts have been positive in some contexts, such as the recent emergence of highly-prized species in recreational fishing areas (53).

Indirect effects from changes in species distributions that underpin society and culture can be dramatic. In the Arctic, changes in distributions of fish, wild reindeer, and caribou are impacting the food security, traditional knowledge systems, and endemic cosmologies of indigenous societies (Figs 1 & 2, 7). In partial response, the Skolt Sámi in Finland have introduced adaptation measures to aid survival of Atlantic salmon stocks faced with warming waters, and to maintain their spiritual relationship with the species. These measures include increasing the catch of pike to reduce predation pressure on salmon. In the East Siberian tundra, faced with melting permafrost, the Chukchi people are struggling to maintain their traditional nomadic reindeer herding practices (56, Fig. 2). Citizen-recording of climate-induced changes to complement assessments based on scientific sampling and remote sensing forms part of their strategy to maintain traditional practices.

Human health is also likely to be seriously affected by changes in the distribution and virulence of animal-borne pathogens, which already account for 70% of emerging infections (57, 58).

Movement of mosquitoes in response to global warming is a threat to health in many countries through predicted increases in the number of known, and potentially new, diseases (Fig. 3). The most prevalent mosquito-borne disease, malaria, has long been a risk for almost half of the world's population, with more than 200 million cases recorded in 2014 (59). Malaria is expected to reach new areas with the poleward and elevational migration of *Anopheles* mosquito vectors (60). Climate-related transmission of malaria can result in epidemics due to lack of immunity among local residents (59), and will challenge health systems at national and international scales, diverting public and private sector resources from other uses.

The winners and losers arising from the redistributions of species will re-shape patterns of human well-being among regions and sectors of industry and communities (61). Those regions with strongest climate drivers, with the most sensitive species, and where humans have least capacity to respond, will be among the most impacted. Developing nations, particularly those near the equator, are likely to experience greater climate-related local extinctions due to poleward and elevational range shifts (62) and will face greater economic constraints. In some cases, species redistribution will also lead to substantial conflict - the recent expansion of mackerel into Icelandic waters is a case in point (Fig. 1, Table S1). The mackerel fishery in Iceland increased from 1700 tonnes in 2006 to 120,000 tonnes in 2010, resulting in “mackerel wars” between Iceland and competing countries that have traditionally been allocated mackerel quotas (63). Likewise, with upslope shift of climate zones in the Italian Alps, intensified conflict is anticipated between recreation and biodiversity sectors. For example, climate-driven contractions in the most valuable habitat for high-elevation threatened bird species and for ski

trails are predicted to increase, along with an increase in the degree of overlap between the bird habitat and the areas most suitable for future ski trail construction (64).

Climate feedbacks

Species redistributions are expected to influence climate feedbacks via changes in albedo, biologically-driven sequestration of carbon from the atmosphere to the deep sea (the ‘biological pump’), and the release of greenhouse gases (65). For instance, terrestrial plants affect albedo via leaf area and color and regulate the global carbon cycle through CO₂ atmosphere-land exchanges. Similarly, CO₂ atmosphere-ocean exchanges are biologically modulated by CO₂-fixing photosynthetic phytoplankton and by the biological pump that exports carbon into deep ocean reservoirs (66).

The climate-driven shifts in species distributions most likely to affect biosphere feedbacks involve redistribution of vegetation on land (Figs 2 & 4) and phytoplankton in the ocean. Decreased albedo, arising from the combined effect of earlier snowmelt and increasing shrub density at high latitudes, already contributes to increased net radiation and atmospheric heating, amplifying high-latitude warming (67). Thus, continued warming will decrease the albedo in the Arctic not only through a decline in snow cover, but also through a northward shift of coniferous trees (Fig. 2). Pearson et al. (68) projected that by 2050, vegetation in the Arctic will mostly shift from tundra (dominated by lichens and mosses with high albedo) to boreal forest (dominated by coniferous trees with low albedo). Additionally, the greenhouse effect may be amplified by top-of-atmosphere radiative imbalance from enhanced evapotranspiration associated with the

greening of the Arctic (69). At low latitudes, ongoing plant redistribution (e.g., mangrove expansion and forest dieback; 29) potentially amplifies climate warming through carbon-cycle feedbacks (70). However, future projections in the tropics are uncertain because of a lack of close climatic analogues from which to extrapolate (71).

Species redistribution at high latitudes also affects vegetation state indirectly through pests like defoliators and bark beetles that are moving northward and upslope in boreal forests (72) (Figs 1, 2 & 4). The combined effects of increasing temperatures and droughts increase plant stress, thus contributing to the severity of pest outbreaks and tree dieback. These processes in turn increase fuel loads and fire frequency (73), ultimately driving additional feedback through massive biomass burning and CO₂ release. Finally, increased shrub canopy cover at high latitudes may locally reduce soil temperatures through a buffering effect (74), slowing the release of CO₂ from permafrost degradation, thus potentially mitigating warming (75) (Fig. 2).

Redistribution of marine phytoplankton is expected to impact the ocean's biological and carbonate pumps and the production of atmospheric aerosols. The subpolar North Atlantic, which is already highly productive and stores around 25% of the ocean's anthropogenic CO₂ (76), may experience phytoplankton changes due to retreat of the Arctic sea-ice and strengthening of ocean stratification. These changes are expected to lead, respectively, to northward movement of productive areas and suppression of the spring bloom, substantially altering CO₂ exchanges between the ocean and the atmosphere at high latitudes (77), although the net effect is uncertain. Rising temperatures may also lead to changes in the composition of different plankton functional groups (78). Expected changes in the relative dominance of diatoms

and calcareous plankton can strongly impact the biological cycling of carbon. Such a change was a possible contributor to CO₂ differences between Pleistocene glacial and interglacial periods (79). Similarly, shifts from diatom- to flagellate-dominated systems in temperate latitudes and increased microbial remineralization, both associated with warming, are expected to reduce the efficiency of the biological pump and therefore affect atmospheric CO₂ (80).

Temperature-related changes in phytoplankton distributions will also affect production of dimethyl sulfide (DMS), which contributes sulfur particles to the atmosphere and seeds cloud formation (81). These particles are expected to decrease surface temperature, but they may also act as a greenhouse gas, so the net effect on climate warming is not yet clear. There is no simple relationship between DMS production and either phytoplankton biomass, chlorophyll concentration or primary production suggesting a complex regulation of DMS production by the whole marine planktonic ecosystem and the physical environment controlling it. Hence, current climate models cannot give an estimate of the strength or even the direction? of the phytoplankton-DMS-climate feedback.

Climate-influenced links between terrestrial and marine regions may also lead to species redistribution and climate feedbacks. For example, episodic land-atmosphere-ocean deposition of iron (e.g. pulses of Sahara dust) produces phytoplankton blooms (82) and enhances carbon export via the biological pump. Changes to the phytoplankton-driven drawdown of atmospheric CO₂ may therefore arise through changes in the spatial distribution of iron deposition, which may be affected by changes in drought conditions, agricultural practices, and large-scale atmospheric circulation (83). These complex processes – not only driven by climate-induced species

redistribution, but also affecting the climate system itself - need to be incorporated into climate models to improve future projections (65).

Governance challenges

The impacts of the global redistribution of species on human welfare and ecosystem services require new governance mechanisms for biodiversity conservation and management. A dynamic and multi-level legal and policy approach is needed to address the effects of species range limits moving across local, national, and international jurisdictional boundaries. The development of international guidance where laws do not yet exist will need to account for different legal regimes, resources, and national capacities.

Shifts in species distributions will require changes in the objectives of conservation law, which have traditionally emphasised *in situ* conservation and retention of historical conditions.

Objectives should acknowledge that species will move beyond their traditional ranges, that novel ecosystems will inevitably be created and that historic ecosystems may disappear, as a consequence of such movements (84). The experience of trans-jurisdictional managed relocations (conservation introductions outside of historical ranges) may inform the development of risk assessment processes that must navigate the complex ethical challenges arising from novel interactions (85) and risks of collateral damage (86). Moreover, communication among relevant agencies throughout the new and former ranges of shifting species is essential, to avoid investing in protecting species in locations where they are no longer viable and yet failing to manage them appropriately in their new ranges.

Legal instruments are typically slow to change and often privilege the protection of property and development rights. While this inertia provides certainty and stability, it underscores the need for flexible approaches that can respond quickly to novel threats arising from species movement, or to capitalize on new opportunities. For example, the “Landscape Resilience Program” of Australia’s Queensland government identified priority locations for new protected areas that would maximize available habitat for range-shifting species (87). Some jurisdictions with well-developed land use and development processes have moved towards adaptive development approvals, and Australia’s fisheries management regime uses decision rules that automatically trigger new arrangements when pre-determined environmental conditions are reached (88). Mechanisms of this sort could be used more widely to implement adaptive management for broader conservation purposes, such as management plans with preset increases in protective strategies that are triggered, or the automatic expansion of protection for habitat outside protected areas when certain climatic indicators are observed.

The changing distribution of species within countries, between countries, and between national borders and the global commons will require increased cooperation and governance across multiple scales among new stakeholders. The EU’s Habitats Directive (EC, 1992) and Birds Directive (EC, 1979) are early examples of a cooperative approach to identifying and protecting networks of habitat across national borders. Initiatives such as the Transfrontier Conservation Areas in Southern Africa (SADC Protocol, 1999) also provide useful insights to guide future multi-scale and cross-border initiatives. Some challenges may also be addressed by increased use of dynamic management techniques. Several countries are already implementing dynamic ocean

management practices for bycatch protection ([89](#)), though equivalent applications in a terrestrial context are more limited. Collaborative initiatives with indigenous communities may also offer new opportunities for conservation of range-shifting species. Indigenous communities can provide traditional ecological knowledge that complements remote sensing and field data and provides historical context ([56](#)), and new management arrangements may incentivize conservation activities.

Earth systems and sustainable development

Human survival, for urban and rural communities, depends on other life on earth. The biological components of natural systems are “on the move,” changing local abundances and geographical distributions of species. At the same time, the ability of people and communities to track these pervasive species redistributions, and to adapt, is increasingly constrained by geo-political boundaries, institutional rigidities, and inertias at all temporal and spatial scales.

In the coming century all people and societies will face diverse challenges associated with development and sustainability, many of which will be exacerbated by the redistribution of species on the planet (Figs 2 and 3). The impacts of species redistribution will intersect with at least 11 of the United Nations’ Sustainable Development Goals (SDGs) (Table S2), and will be particularly prominent for several of these SDGs.

Zero Hunger (SDG 2) requires feeding more than nine billion people by 2050 ([90](#)). However, the ability to deliver food through agriculture will be altered through the direct effects of climate

change and as the distributions and abundances of pollinators change, and as plant pathogens and pests become more prevalent or emerge in new places as a result of global warming ([91](#), [92](#)).

Health and Well-Being (SDG 3) is made more challenging by tropical illnesses spreading to new areas ([58](#)) and changes in food security and the distribution of economic wealth on local, regional, and global scales. Moreover, human well-being is also related to many other facets of society and culture, including attachment to place ([56](#), [93](#)) and the living environment found around us. The mental health of indigenous and rural communities, in particular, may be affected as species redistribution alters the capacity for traditional practices, subsistence, or local industries. Effective *Climate Action (SDG 13)* necessitates accounting for the direct and indirect influences of shifting organisms and associated feedbacks on our biosphere, yet these processes and feedbacks are rarely accounted for in projections of future climate. Sustainable management and the conservation of *Life Below Water* and *Life on Land (SDGs 14 & 15)* are unlikely to be effective unless climate-driven alterations in species ranges and their profound ecosystem consequences are accounted for.

Managing for movement

Under extensive reshuffling of the world's biota, how should conservation goals and strategies for policy and implementation be developed that maximize long-term resilience of biodiversity and human systems? How should natural resource management across diverse, multi-use, multi-scale land and seascapes be integrated to maximize resilience of both human and natural systems? How should specific threats and stressors (including their interactions) be managed while minimizing impacts on valued ecosystem assets? For the scientific community to help develop mitigation and adaptation strategies in the face of widespread change in species

distribution and ecosystem functioning, a better understanding of the mechanisms underlying such changes is needed. Scientists also need access to real-time data streams, and to integrate this information into decision-support frameworks. Moreover, scientists and their institutions need to rapidly communicate advances and outcomes to the broader public and to policy makers.

However, the natural world responds in dynamic and unpredictable ways and the phenomenon of species redistribution is not, nor will it ever be, fully understood or completely predictable. This uncertainty necessitates flexible and dynamic governance so adaptation to changing conditions can be rapid, maximizing opportunities and minimizing negative consequences.

Underlying biological processes

Because knowledge of the biological and ecological processes underlying resilience of organisms to predicted average and extreme environmental conditions is limited, the traits on which natural/anthropogenic selection will act are uncertain. For example, specific physiological mechanisms have been hypothesized to underlie the thermal ranges of ectothermic organisms ([94](#)), yet a lack of universality in the proposed mechanisms highlights a need for novel, multidisciplinary investigations ([see 95](#)). Large-scale, multi-generational experimental research programs are required to provide a robust understanding of the adaptive responses of organisms to environmental change, and to determine the heritability of key traits, as recently has been achieved for sea turtles ([96](#)). Modeling approaches, lab and field-based experimental manipulations, and field-based monitoring programs need to be combined with more effective policy communication to understand and implement responses to species redistributions.

Monitoring programs

To best adjust to species redistributions, gaps in understanding need to be acknowledged and filled through hypothesis testing. Our understanding is weakest in poorly surveyed regions such as the tropics and Antarctica (8). As range shifts continue to unfold, there will be opportunities to refine our understanding of the process, but taking advantage of these opportunities requires access to consistent, high quality, near-real-time data on a series of environmental and biological parameters (97).

The current absence of a global, comprehensive, coordinated biodiversity monitoring system is a major obstacle to our understanding of climate change implications for natural systems. Thus far there has been extensive global cooperation and progress in terms of coordinating the collection and the distribution of physical and chemical environmental monitoring data. For example, the Global Climate Observing System (GCOS) facilitated international agreement and a global commitment towards consistent monitoring of climate variables, ultimately supporting the development of spatio-temporally explicit and uncertainty-explicit predictions about changes in our climate (98). Ongoing efforts through the Group on Earth Observation Biodiversity Observation Network (GEO BON) and the Intergovernmental Oceanographic Commission Global Ocean Observing System (IOC GOOS) are beginning to implement the use of Essential Biodiversity Variables (EBV's) (41) and ecosystem Essential Ocean Variables (eEOV's) (99) respectively, but the process is slow and under-resourced. A global, robust biodiversity monitoring system that successfully integrates field and remote sensing data could significantly

improve our ability to manage the changes to come, while potentially driving faster mitigation measures ([100](#)).

Incorporating species on the move into integrated assessment models

Understanding underlying biological processes and having access to real-time data is necessary but not sufficient for informed responses. Improved capacity to model linkages and feedbacks between species range-shifts and ecosystem functioning, food security, human health, and the climate is required. Modeling is essential to reliably project the potential impacts of alternative scenarios and policy options on human well-being, as the basis for evidence-based policy and decision support ([101](#)). One avenue forward is to incorporate species redistribution and its associated impacts into integrated assessment models ([IAMs; 102](#)), used widely within the climate science community, and now being rapidly mobilized and extended to address synergies and trade-offs between multiple SDGs ([103](#)). IAMs offer a promising approach for connecting processes, existing data, and scenarios of demographic, social, and economic change and governance. Although species distribution models are commonplace, advances are needed to connect species redistribution with ecosystem integrity ([e.g., 104](#)) and feedbacks between humans and the biosphere.

Communication for public and policy

How does the scientific community engage effectively with the public on the issue of species redistribution and its far-reaching impacts? Part of the answer could be citizen science and participatory observing approaches, in which community members are directly involved in data

collection and interpretation ([105](#)). These are tools that can help address both data gaps and communication gaps ([100](#)). When properly designed and carefully tailored to local issues, such approaches can provide quality data, cost-effectively and sustainably, while simultaneously building capacity among local constituents and prompting practical and effective management interventions ([e.g., 106](#)).

Concluding remarks

The breadth and complexity of the issues associated with the global redistribution of species driven by changing climate is creating profound challenges, with species movements already affecting societies and regional economies from the tropics to polar regions. Despite mounting evidence for these impacts, current global goals, policies, and international agreements do not sufficiently consider species range-shifts in their formulation or targets. Enhanced awareness, supported by appropriate governance, will provide the best chance of minimizing negative consequences while maximizing opportunities arising from species movements – movements that with or without effective emission reduction will continue for the foreseeable future owing to the inertia in the climate system.

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Figure legends

Fig. 1. Climate-driven changes in the distribution of life on Earth are impacting ecosystem health, human well-being, and the dynamics of climate change, challenging local and regional systems of governance. Examples of documented and predicted climate-driven changes in the distribution of species throughout marine, terrestrial, and freshwater systems of the globe in tropical, temperate, and polar regions. Details of the impacts associated with each of these changes in distribution are given in Table S1, according to the numbered key, and the links to specific Sustainable Development Goals are given in Table S2.

Fig. 2. Species on the move drive greening of the Arctic. Changes in species distribution can lead to climate feedbacks, changes in ecosystem services, and impacts on human societies, with feedbacks and linkages between each of these dimensions, illustrated here through climate-driven changes in Arctic vegetation. See Fig. 4 for a more comprehensive description of the direct and indirect climate feedbacks.

Fig. 3: Mosquito species on the move as vectors of disease. Climate change has facilitated an increase in the distribution of disease vectors, with significant human cost and associated governance challenges. The bars on the human well-being graph represent the minimum and maximum range, and the boxes depict the 25th, 50th and 75th percentile of the distribution.

Fig. 4. Climate feedbacks and processes driven by the redistribution of plant species at high latitudes. Climate affects vegetation at high latitudes directly through climatic processes, but

also indirectly through pests like defoliators and bark beetles that are moving northward and upslope in boreal forests. Some processes increase warming (blue arrows), while others may serve to decrease warming (red arrows). Increasing shrub canopy cover in the Arctic at high latitudes may reduce soil temperatures locally through a buffering effect, potentially slowing down CO₂ carbon release due to permafrost degradation, thus acting to slow climate warming. However, greening of the Arctic also decreases albedo, which accelerates warming.

Supplementary Material

Table S1: Details of the impacts associated with each of the changes in distribution documented in Figure 1, according to the numbered key.

Table S2: Influence on achieving the Global Sustainable Development Goals of observed or predicted climate-driven changes in the distribution of species.

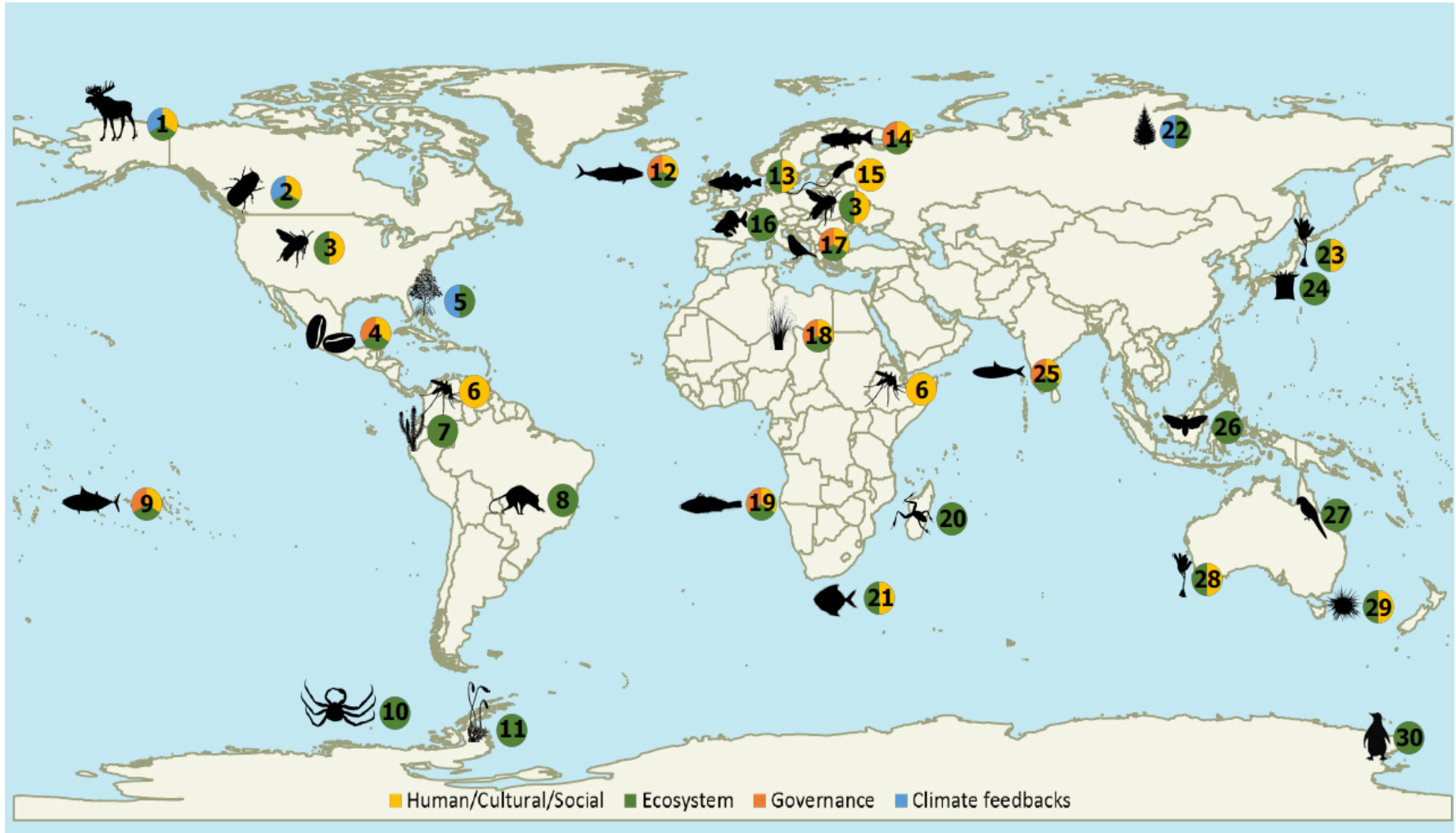


Figure 1

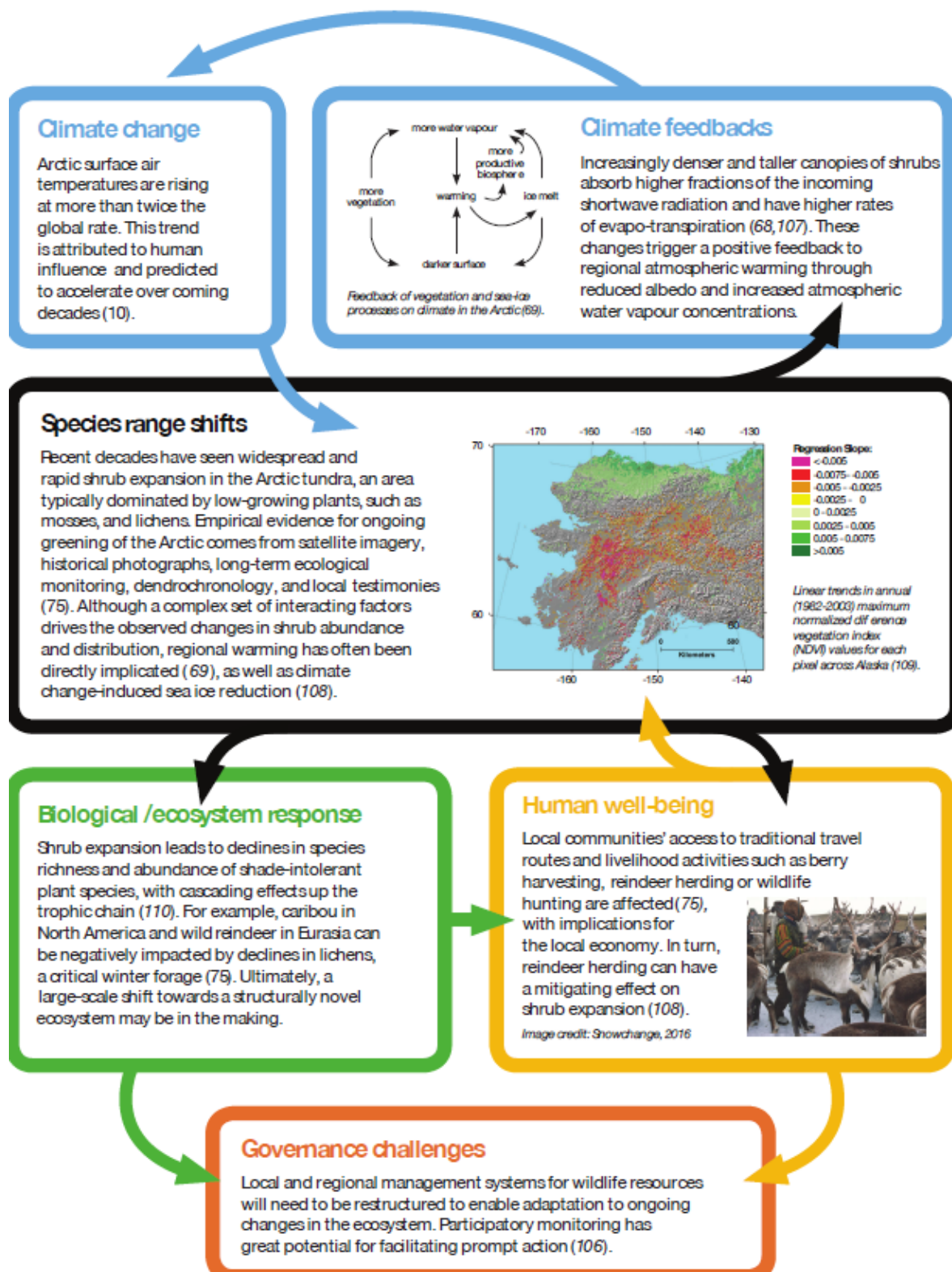


Figure 2

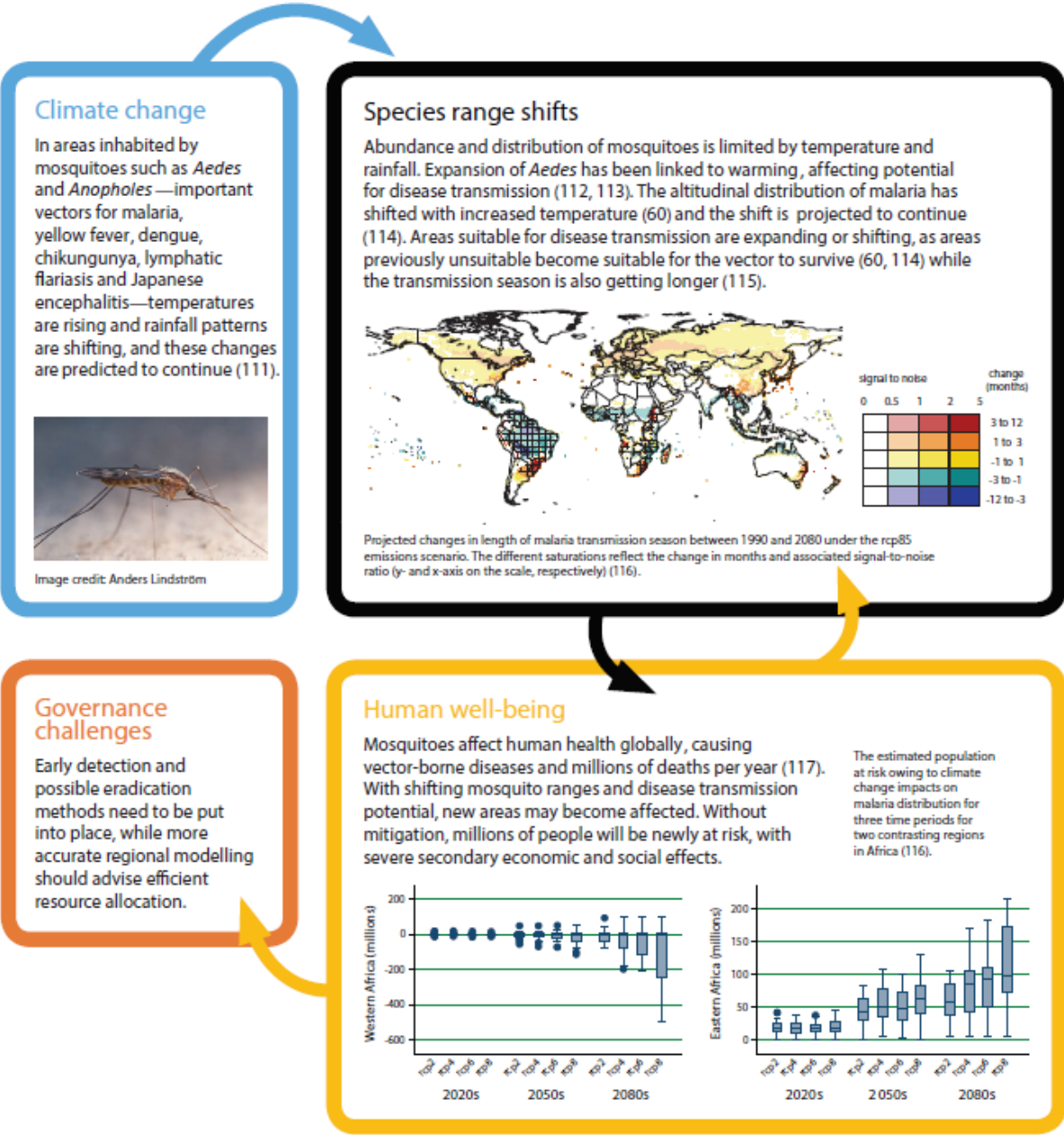


Figure 3

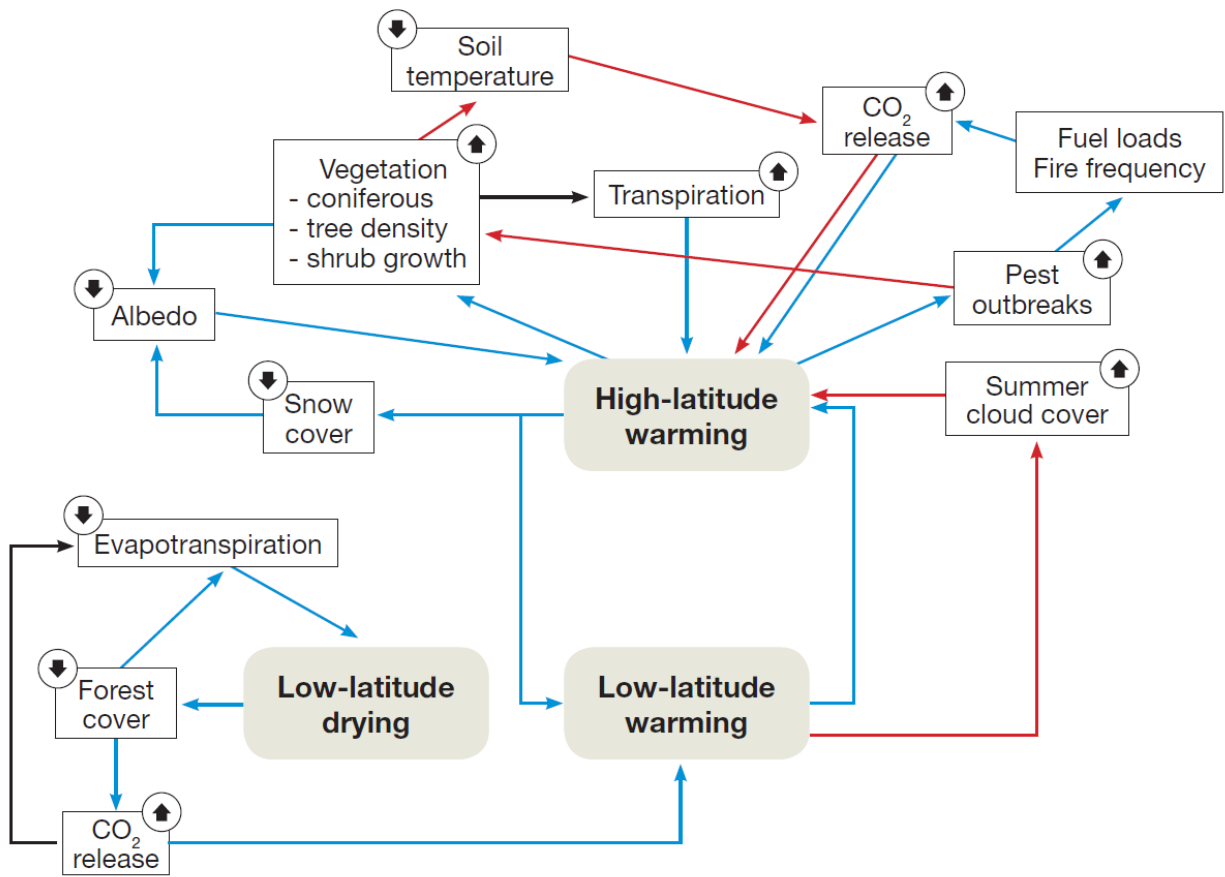


Figure 4



Supplementary Materials for

Biodiversity redistribution under climate change: impacts on ecosystems and human well-being

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This PDF file includes:

Tables S1 to S2

Table S1.

Details of the impacts associated with each of the changes in distribution documented in Figure 1, according to the numbered key.

 <p>1-Moose</p> <p>Northward expansion of Alaskan moose associated with an increase in shrub habitat and warming. Moose are likely to affect ecosystem functioning through grazing on shrubs and slowing down the greening of the Arctic, potentially impacting climate feedbacks. Hunting practices from indigenous communities and prey-predator dynamics are also affected (118).</p>	 <p>2- Bark beetles</p> <p>Northward and elevational shift of bark beetles in North America driven by warming climate. The combined effects of increasing temperatures and droughts predispose trees to defoliators and to bark beetles, thus contributing to the severity of pest outbreaks, which in turn may impact climate through increasing fuel loads and fire frequency at high latitudes (72).</p>	 <p>3- Bumblebees</p> <p>Southern range contraction and elevational shift for southern species of bumblebees in North America and Europe due to climate change. While species have experienced significant losses from equatorward range boundaries, there has been no corresponding expansion of range limits northwards for these important pollinators. Shifts to higher elevations have been restricted to southern species (119)</p>
 <p>4- Coffee</p> <p>Decrease in climate suitability for coffee cultivation in low elevation areas of Mexico, Guatemala, El Salvador, Nicaragua, and Costa Rica. New growing regions will need to be developed upslope. Local producers and rural communities that crucially depend on the coffee industry will be greatly affected, and upslope natural areas may be impacted (52).</p>	 <p>5- Mangroves</p> <p>Northward shift of mangroves in Florida, USA, correlated with less extreme cold events. The changing distribution of mangroves will affect carbon sequestration and as a consequence, climate feedbacks (29).</p>	 <p>6- Malaria</p> <p>Upslope shift in malaria distributions. The median elevation of malaria cases has increased in warmer years in both Ethiopia and western Colombia. In Ethiopia, high-elevation locations previously free of Malaria are now within the viable range for this disease. In Colombia, temperatures have fluctuated without a consistent trend of warming, and Malaria cases at high elevations have fluctuated very closely with the temperature change (60).</p>
 <p>7- Tropical plants</p> <p>Upslope shift of tropical plants in Ecuador consistent with patterns of warming. This reshaping of tropical plant distributions is consistent with Humboldt's proposal that climate has primary control on the altitudinal distribution of vegetation (120).</p>	 <p>8- Marsupials</p> <p>Range shifts under climate change scenarios for 55 marsupial species in Brazil. Projection forecasts indicate a range shift to the south east (121).</p>	 <p>9- Skipjack tuna</p> <p>Skipjack tuna is projected to become less abundant in western, and more abundant in eastern, areas of the Western and Central Pacific Ocean (WCPO). Several Pacific Island countries in the WCPO depend heavily on skipjack tuna for economic development, government revenue, and food security (48).</p>

 <p>10- King crab</p> <p>Poleward range expansion in the king crab. For millions of years cold water conditions had excluded crustaceans from the continental shelf around Antarctica. In 2010, a population of king crabs was discovered next to the continental shelf, suggesting an expansion of the range as a result of warming seas (26).</p>	 <p>11- Antarctic vegetation</p> <p>Rapid increase in moss growth rates, microbial productivity, and plant range expansion as ice melts (122).</p>	 <p>12- Mackerel</p> <p>Expanded distribution of mackerel into Icelandic waters in the recent warm period since 1996. This expansion initially supported a bycatch fishery, which then developed into a direct fishery within the Icelandic EEZ, increasing from ~1700 t in 2006 to ~120 000 t in 2009 and 2010. Negotiations over new quotas for mackerel were key to discussions of Iceland and the Faeroe Islands joining the EU (63).</p>
 <p>13- Demersal fish</p> <p>Movement to deeper water by demersal fish in the North Sea as temperatures have increased. Abundant thermal specialist fish have shifted northward, while less abundant, small southerly species have shifted southward (18).</p>	 <p>14- Atlantic salmon</p> <p>Decline in Atlantic salmon, an anadromous cold water fish, while the northern pike expanded its range in response to warmer water temperatures in Finland. The pike preys on juvenile salmon. Indigenous Skolt Sámi co-management measures have increased harvests of pike and have documented important sites (such as lost spawning beds), so that ecological restoration can provide additional habitat and increase salmon reproduction (7, 56).</p>	 <p>15- Vibrio</p> <p>Unexpected emergence of <i>Vibrio</i> infections, a bacterial waterborne disease, in northern Europe. Changes in sea surface temperature in the Baltic are thought to be responsible (123).</p>
 <p>16- Freshwater fish</p> <p>Upstream shift in freshwater fish. Since the 1980s, freshwater fish in France's river systems have moved upwards in elevation; traditionally low-reach species have moved to higher reaches. On average, these fish tracked the direction of warming, but the shifts were not as fast as climate warming (124).</p>	 <p>17- Mountain birds</p> <p>Upslope shift in suitable areas for mountain birds in Italy due to warmer temperatures. These areas are projected to overlap with suitable areas for ski-industry development, creating challenges for the conservation of these bird species (64).</p>	 <p>18- Sahel vegetation</p> <p>Changes in Sahel vegetation. Over past decades, vegetation in the Sahel region has changed, affecting the livelihood and culture of people in the region. Pastoralists have increasing difficulties finding dry-season grazing areas for their livestock and suffer from lack of security of tenure over land and resources (125).</p>
 <p>20- Reptiles & amphibians</p>		



















<p>19- Coastal fish</p> <p>Poleward range shift in the coastal fish species, <i>Argyrosomus coronus</i>, from Angola into Namibia. This shift crosses Economic Exclusive Zones, complicating fishery management, particularly in light of a lack of congruence in the fisheries policies between nations (126).</p>	<p>Upslope range shift in 30 species of reptiles and amphibians in Madagascar. These species have moved uphill from 10 to 51 meters, as climate warmed (127).</p>	<p>21- Tropical and temperate fish</p> <p>Southward shift of tropical fish and range contraction of temperate fish associated with ocean warming in South Africa. These changes in species composition and abundance have impacted the spear-fishing sector (128).</p>
<p>  22- Arctic vegetation</p> <p>Altered distribution, composition, and density of terrestrial vegetation in the Arctic, driven by climate warming, through both increasing average temperatures and a longer growing season. These changes in vegetation affect the albedo, vegetation biomass, and evapotranspiration, exacerbating climate warming (68).</p>	<p>  23- Kelp & abalone</p> <p>The loss of temperate canopy-forming macro algae in Tosa Bay, Japan, associated with recent warming. There has been local extinction of the kelp <i>Ecklonia cava</i>, loss of other temperate <i>Ecklonia</i> and <i>Sargassum</i> species, and an increase in a tropical <i>Sargassum</i>. An associated decline of commercial abalone has been attributed to the loss of <i>Ecklonia</i> (129).</p>	<p>  24- Reef coral</p> <p>Reef coral species range shifts. These species have shifted at rates up to 14 km/yr northward along the coastline of Japan, consistent with climate warming (130).</p>
<p>  25- Oil sardine</p> <p>Northward shift in the range of the oil sardine. Historically, the sardine had a restricted distribution between 8°N to 14°N, but in the past two decades, it has increased in abundance to the north: the region 14°N - 20°N now makes up 15% of the catch. The range shift of the species is a boon for coastal fishing communities in this region in India (131).</p>	<p>  26- Moths</p> <p>Upslope shift in tropical moth species. 102 montane moth species in Borneo have increased in elevation by a mean of 67 m over 42 years, driven by climate warming (17).</p>	<p>  27- Birds & possums</p> <p>Upslope shift of 13 bird and 4 ringtail possum species as a result of climate warming in the wet tropics of Australia (132).</p>
<p>  28-Kelp, fish & invertebrates</p> <p>Range contraction of 100 km in kelp forests and other habitat-forming seaweeds in Western Australia. Increases in warm-water fish and invertebrates associated with ocean warming, leading to increased herbivory, loss of kelp and replacement of by seaweed turf (eastern and western Australia). These changes in ecosystem structure could impact Australia's most valuable single-species fishery (rock lobster) (30, 31).</p>	<p>  29- Sea urchin</p> <p>Poleward range shift in the sea urchin, <i>Centrostephanus rodgersii</i>, into Tasmania, tracking the pattern of warming in this region. Through grazing this species has converted kelp forests into urchin barrens, affecting the regional lobster and abalone fisheries (55).</p>	<p>  30-Adelie penguins</p> <p>Increase in numbers and poleward range expansion in Adelie penguins. In McMurdo Sound (the Ross Sea) the breeding range of Adelie penguins has expanded 3 km southwards. The population size has also increased markedly (from 1983 to 1987) (133).</p>

Table S2.

Influence on achieving the Global Sustainable Development Goals (134) of observed or predicted climate-driven changes in the distribution of species. Secondary effects and consequences of changing distributions of species will ultimately impact most of the Sustainable Development Goals. Here, we highlight those that, based on our collective knowledge and informed by an analysis of links between Aichi Biodiversity targets and SDG's (135), will likely be most significantly and immediately affected.

	Targets likely to be impacted (134)	Rationale	Example & reference in Table S1
1. No Poverty	By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance.	<p>Access to natural resources will change as species move into or out of particular areas. Health of plants and animals that human societies depend on for food may be affected by changes in the distribution of pollinators, pathogens and parasites.</p> <p>Forests, wetlands, and coastal areas are particularly important as sources of food and income during times of stress for the most marginalized and vulnerable people living in rural areas.</p>	<p>Moose (1)</p> <p>Bumblebees (3)</p> <p>Coffee (4)</p> <p>Skipjack tuna (9)</p> <p>Atlantic salmon (14)</p> <p>Sahel vegetation (18)</p> <p>Coastal fish (19)</p> <p>Tropical and temperate fish (21)</p> <p>Oil sardine (25)</p>
2. Zero Hunger	<p>By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.</p> <p>By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production,</p>	<p>Some ecosystems may no longer support productive agriculture, aquaculture, subsistence hunting or fisheries.</p> <p>Food production systems may be subject to new pathogens, pests, or other disruptive species (e.g. jellyfish or harmful algal blooms).</p>	<p>Moose (1)</p> <p>Bumblebees (3)</p> <p>Coffee (4)</p> <p>Skipjack tuna (9)</p> <p>Atlantic salmon (14)</p> <p>Sahel vegetation (18)</p>

	<p>that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.</p> <p>By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge.</p>	<p>Poleward and elevational movement of species could result in increased production costs or jurisdictional issues, as species move across borders or decrease in abundance due to lack of suitable habitat.</p> <p>Genetic diversity could be compromised because “successful movers and colonisers” may require a specific set of traits.</p>	<p>Coastal fish (19)</p> <p>Tropical fish (21)</p> <p>Oil sardine (25)</p>
3. Good Health and Well-Being	<p>By 2030, end the epidemics of AIDS, tuberculosis, malaria and neglected tropical diseases and combat hepatitis, water-borne diseases and other communicable diseases.</p>	<p>Many diseases, such as malaria, are expected expand in distribution both in elevation and to higher latitudes.</p> <p>Mental health and well-being of farmers and fishers, and indigenous or rural communities, may be impacted as their lands or fishing grounds can no longer support the same ecosystems or traditional practices and subsistence activities. These consequences are more likely as the rate of species movements increases.</p>	<p>Malaria (6)</p> <p>Vibrio (15)</p>
5. Gender Equity	<p>Undertake reforms to give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property, financial services, inheritance and natural resources, in accordance with national laws.</p>	<p>The natural resources that women harvest may decline in abundance, be impacted by pests or pathogens, or shift to other places, creating increased tensions for women participating in the provision of adequate food or other resources.</p>	<p>Sahel vegetation (18)</p>
6. Clean water and sanitation	<p>By 2030, achieve universal and equitable access to safe and affordable drinking water for all.</p>	<p>The capacity of water-related ecosystems such as mountains, forests, wetlands, rivers, aquifers and lakes, to ensure sustainable supply of clean freshwater, is</p>	<p>Bark beetles (2)</p> <p>Mangroves (5)</p>

	<p>By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.</p> <p>By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.</p> <p>By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.</p> <p>Support and strengthen the participation of local communities in improving water and sanitation management.</p>	<p>dependent upon healthy ecosystems and therefore impacted by changes in the distribution of associated species. Ecosystem services impacted by changes in species distribution also includes the reduction or removal of pollutants. Natural ecosystems, e.g. mangrove belts, can be effective in reducing the flooding impacts of storm surges occurring during cyclones, typhoons and hurricanes on the quality of drinking water in low-lying coastal areas.</p>	<p>Vibrio (15)</p>
8. Decent work and Economic Growth	<p>Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead.</p>	<p>Sustainable production may be harder to achieve or require new methods, as the distribution and relative abundance of species changes and conditions become less suitable for common crops and forms of animal production and aquaculture.</p>	<p>Skipjack tuna (9)</p> <p>Mackerel (12)</p> <p>Atlantic salmon (14)</p> <p>Mountain birds (17)</p> <p>Sahel vegetation (18)</p> <p>Coastal fish (19)</p> <p>Kelp and abalone (23)</p> <p>Oil sardine (25)</p>
10. Reduced inequities	<p>By 2030, progressively achieve and sustain income growth of the bottom 40 per cent of the population at a rate higher than the national average.</p>	<p>Many lower-income populations are dependent on harvesting natural resources, which may no longer be supported in their regions as species abundances and distributions change.</p>	<p>Skipjack tuna (9)</p> <p>Mackerel (12)</p> <p>Mountain birds (17)</p> <p>Sahel vegetation (18)</p> <p>Coastal fish (19)</p> <p>Oil sardine (25)</p>
11. Sustainable cities and communities	<p>Strengthen efforts to protect and safeguard the world's cultural and natural heritage.</p> <p>By 2030, significantly reduce the number of deaths and the number of</p>	<p>Human culture and attachment to place can be closely associated with particular species and thus can be affected when existing species move out of a local area</p>	<p>Moose (1)</p> <p>Mangroves (5)</p> <p>Vibrio (15)</p>

	<p>people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.</p> <p>By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities.</p> <p>Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning.</p> <p>By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels.</p>	<p>and ‘new’ species move in.</p> <p>Natural ecosystems can have an important role in mitigating against disasters.</p> <p>Development planning for positive links between urban and rural areas depends upon knowledge of the distribution of natural resources.</p>	Sahel vegetation (18)
12. Responsible Consumption and Production	<p>By 2030, achieve the sustainable management and efficient use of natural resources.</p>	<p>Agriculture, fisheries and aquaculture that is currently sustainable may be unsustainable in the future as the distributions of food species, and/or pollinators, pathogens and pests shift with global warming.</p>	Bumblebees (3) and other examples involving harvesting
13. Climate Action	<p>Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.</p> <p>Integrate climate change measures into national policies, strategies and planning.</p> <p>Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning.</p>	<p>Biodiversity conservation and health strategies will require improved education to raise awareness of the impacts and implications of range-shifting species on food production. Appropriate adaptations should be incorporated into species-specific and ecosystem management plans as well as into broader national policies.</p>	<p>Moose (1)</p> <p>Bark beetles (2)</p> <p>Mangroves (5)</p> <p>Arctic vegetation (22)</p>

		Direct and indirect influences of shifting species ranges and associated feedbacks on our climate system need to be more thoroughly accounted for in projections of future climate.	
14. Life below water	<p>By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans.</p> <p>By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics.</p> <p>By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information.</p> <p>By 2030, increase the economic benefits to Small Island Developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism.</p> <p>Provide access for small-scale artisanal fishers to marine resources and markets.</p>	<p>The movement of marine species will constantly challenge management, as sustainable practices require adjustment to keep pace with alterations in the distribution and abundance of species</p> <p>Restoration of degraded marine areas may not return habitats to their original state, because colonising species may no longer be present or may be unable to become established in these habitats.</p> <p>Marine protected areas established to help conserve species may become ineffective as target species are redistributed.</p>	<p>Skipjack tuna (9)</p> <p>King crab (10)</p> <p>Mackerel (12)</p> <p>Atlantic salmon (14)</p> <p>Coastal fish (19)</p> <p>Kelp and abalone (23)</p> <p>Oil sardine (25)</p> <p>Kelp, fish and invertebrates (28)</p> <p>Sea urchin (29)</p> <p>Adelie penguins (30)</p>
15. Life on land	<p>By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements.</p> <p>By 2020, promote the implementation of sustainable management of all</p>	<p>The restoration of forests, wetlands, mountains and drylands may be compromised by changes in the species that are able to colonise and live in these habitats.</p>	<p>Moose (1)</p> <p>Bark beetles (2)</p> <p>Bumblebees (3)</p> <p>Tropical plants (7)</p>

	<p>types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally.</p> <p>By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world.</p> <p>By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development.</p> <p>Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.</p>	<p>Range expansions of pathogens, pests and disease vectors will reduce the potential to protect biodiversity.</p> <p>As species ranges shift (e.g., up mountains), their habitats may become more fragmented, resulting in increased genetic isolation. For some moving species, there may not be sufficient habitat at the poleward or upslope margins of their distributions to prevent extinctions.</p>	<p>Marsupials (8)</p> <p>Vascular plants (11)</p> <p>Freshwater fish (16)</p> <p>Mountain birds (17)</p> <p>Sahel vegetation (18)</p> <p>Reptiles and amphibians (20)</p> <p>Arctic vegetation (22)</p> <p>Moths (26)</p> <p>Birds and possums (27)</p>
<p>17. Partnerships for the Goals</p>	<p>Significantly increase the exports of developing countries, in particular with a view to doubling the least developed countries' share of global exports by 2020.</p> <p>Realize timely implementation of duty-free and quota-free market access on a lasting basis for all least developed countries, consistent with World Trade Organization decisions, including by ensuring that preferential rules of origin applicable to imports from least developed countries are transparent and simple, and contribute to facilitating market access.</p> <p>Enhance the global partnership for sustainable development, complemented by multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology and financial resources, to support the achievement of the sustainable development goals in all countries, in particular developing countries.</p>	<p>As species cross national borders, partnerships will be essential, and 'who owns what' becomes an issue (see "mackerel wars" in the main text). Developing global partnerships for sustainable management of natural resources will require jurisdictions to manage species as transboundary stocks, rather than on a jurisdiction-by-jurisdiction basis.</p> <p>Addressing the challenges of changes in the distribution of pests, pathogens and pollinators may also require multi-jurisdictional strategic planning and cooperation.</p>	<p>Coffee (4)</p> <p>Skipjack tuna (9)</p> <p>Mackerel (12)</p> <p>Coastal fish (19)</p>