CCP1

Biodiversity Hotspots

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Cross-Chapter Paper Review Editor: Andreas Fischlin (Switzerland)

This cross-chapter paper should be cited as:

Costello, M.J., M.M. Vale, W. Kiessling, S. Maharaj, J. Price, and G.H. Talukdar, 2022: Cross-Chapter Paper 1: Biodiversity Hotspots. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2123–2161, doi:10.1017/9781009325844.018.

https://doi.org/10.1017/9781009325844.018 Published online by Cambridge University Press

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https://doi.org/10.1017/9781009325844.018 Published online by Cambridge University Press

Executive Summary

Geographic areas that are exceptionally rich in species, ecologically distinct and/or show high endemism (species occurring in that defined geographic area and nowhere else) are broadly recognised as biodiversity hotspots and prioritised for conservation. Here, we assess the impacts and vulnerability to climate change of terrestrial, freshwater and marine regions considered to be biodiversity hotspots. {CCP1.1}

Species in biodiversity hotspots already show changes in response to climate change (*high confidence*[1]). The geographic ranges of the animal and plant species assessed have shifted from low to high latitudes in response to climate warming on land and in the ocean (*very high confidence*). On land, climate change-induced shifts towards higher elevations are also common in biodiversity hotspots (*high confidence*); while, in the ocean, climate-induced shifts to greater water depths are little studied. In the ocean, abrupt mortality of habitat-forming species on coral reefs and kelp forests, especially following heatwaves, are increasing in frequency in biodiversity hotspots (*high confidence*). {CCP1.2.1; 1.2.2; 1.2.4}

All biodiversity hotspots are impacted, to differing degrees, by human activities (*very high confidence*). Climate change impacts are compounded by other anthropogenic impacts. These include habitat loss and fragmentation, hunting, fishing and its bycatch, over-exploitation, water abstraction, nutrient enrichment, pollution, human introduction of invasive species, pests and diseases. All of these reduce climate resilience (*very high confidence*), complicating the attribution of observed changes to climate change. {CCP1.2.1}

Observed climate velocities are approximately 20% lower inside than outside of terrestrial and freshwater biodiversity hotspots, but 69% higher inside than outside marine hotspots (*high confidence*). In spite of the lower climate velocities inside terrestrial hotspots, these areas are not projected to serve as effective climate refugia from the effects of global warming, especially for endemic species (unique to a hotspot) (*medium confidence*). The greater climate velocities inside marine hotspots exposes their species to greater climate-induced pressures inside than outside hotspots (*high confidence*). The differences between temperatures inside and outside of hotspots narrow with increasing warming (*medium confidence*). {CCP1.2.2}

The risk of species extinction increases with warming in all climate change projections for native species studied in hotspots (*high confidence*), being about 10-times greater for endemic species from 1.5°C to 3°C above pre-industrial levels (*medium confidence*). Of the 6116 projections for more than 2700 species assessed in biodiversity hotspots, ~44% were found to be at high extinction risk, and ~24% at very high extinction risk due to climate change (*medium confidence*). Very high extinction risk in biodiversity hotspots due to climate change is more common for endemic species than other native species (*high confidence*). For these endemic species, considering all scenarios and time periods evaluated, ~100% on islands, ~84% on mountains, ~12% on continents (*medium confidence*) and ~54% in the ocean (notably the Mediterranean) (*low confidence*) are projected to be threatened with extinction due to climate change. With further warming, increasingly high risks of local and global extinctions are projected in biodiversity hotspots from climate-related stressors (*high confidence*). {CCP1.2.1; Figure CCP1.7; Figure CCP1.6}

Adaptation options can enhance the persistence of biodiversity in hotspots (high confidence). Noting that over 3 billion people live within biodiversity hotspots, reduction of existing (non-climatic) pressures due to human activities is critical for building resilience within hotspots. Adaptation options for biodiversity (e.g., expanding fully protected areas, restoration and sustainable use practices) are as applicable inside biodiversity hotspots as outside (high confidence). Nevertheless, the protection of biodiversity hotspots is key to preventing a substantial global biodiversity decline from climate change. {CCP1.3; 2.6; 3.6; Table CCP1.2; Cross-Chapter Box NATURAL in Chapter 2}.

1 In this report, the following summary terms are used to describe the available evidence: limited, medium or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, for example, *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

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CCP1.1 Point of Departure

Biodiversity hotspots are geographic areas with an exceptionally high richness of species, including rare and endemic species. Such hotspots have deep evolutionary roots and are concentrated in areas where past climatic variability was moderate (Enquist et al., 2019; Brown et al., 2020; Trew and Maclean, 2021). An important limitation of the biodiversity hotspot concept is that there may be species highly threatened with extinction that do not occur within what has traditionally been classified as a hotspot (Grenyer et al., 2006). Thus, biodiversity hotspot assessments need to be paralleled by assessments of highly endangered species, and the threats they face.

Many studies have proposed biodiversity hotspots based on different criteria, taxa and geographic contexts (e.g., Myers et al., 2000; Mittermeier et al., 2004; Mittermeier et al., 2011; Williams et al., 2011; Noss et al., 2015; Asaad et al., 2017). A coherent comparative assessment of all such schemes is beyond the scope of this chapter but is provided in recent reviews (Asaad et al., 2017; Jefferson and Costello, 2019). We base this assessment on the 'WWF Global 200' areas of conservation importance (Olson and Dinerstein, 2002). These 238 ecoregions have been used in a previous climate risk assessment (Warren et al., 2018b) and cover terrestrial, freshwater and marine environments (Table CCP1.1; Figures CCP1.1; CCP1.2). In addition, we included terrestrial 'biodiversity hotspots' as defined by Myers et al. (2000) and extended later (Mittermeier et al., 2011; Williams et al., 2011; Noss et al., 2015). This assessment thus covers the 'Global 200' (hereafter G200) and 'Myers' biodiversity hotspots, rather than particular species or ecological systems, such as rainforests, coral reefs or the deep sea. Such systems are assessed in Chapters 2 and 3. Chapters 2 and 3 also cover observed and projected impacts, changes in ecosystem functioning, and species extinction risks at a global level.

Biodiversity hotspots were not explicitly covered in the Working Group II (WGII) Fifth Assessment Report (IPCC, 2014) (hereafter AR5). Thus, the point of departure is WGII AR4 (IPCC, 2007), which assessed that climate change exacerbates biodiversity risks in hotspots and that 15–40% of endemic species (species only occurring in one region) were projected to become extinct at 3.5°C global warming (Fischlin et al., 2007). Risks of extinction are assessed using the guidelines in Chapter 2, with species projected to lose 80% of their range or abundance being classified as at very high risk of extinction and those projected to lose 50% being at high risk of extinction (Figure 2.8 for definitions and a global overview).

CCP1.2 Assessment

Specific hotspot numbers (H) are indicated in this chapter text to aid their identification in Table CCP1.1 and Figures CCP1.1 and CCP1.2.

CCP1.2.1 Global Perspective

CCP1.2.1.1 Observed Impacts

CCP1.2.1.1.1 Observed climatic hazards

Terrestrial and freshwater hotspots have been warming less over the last 50 years than non-hotspot areas, whereas marine hotspots have been warming more (Kocsis et al., 2021). The warming inside terrestrial hotspots is 0.91°C (Myers) and 1.04°C (G200), respectively, while for freshwater hotspots it is 0.89°C, compared to 1.08°C warming outside (Kocsis et al., 2021). In contrast, mean annual sea surface temperatures in the G200 marine biodiversity hotspots have warmed 41% more than the regions outside (0.53°C compared with 0.38°C) (Kocsis et al., 2021). Thus, terrestrial biodiversity hotspots have been warming slightly less, and marine hotspots considerably more than non-hotspots (*medium confidence*).

Climate velocity, the direction and pace of movement in climate variables (typically temperature) in space, is key to understanding the origin and fate of biodiversity hotspots under climate change (Loarie et al., 2009; Burrows et al., 2011). Climate trajectories generally predict the direction and pace of past and future species range shifts (Pinsky et al., 2013; Brito-Morales et al., 2018), although there are exceptions (Fuchs et al., 2020). Spatial patterns of climate trajectories show regions where species are expected to leave, pass through, and/or arrive under climate change (Burrows et al., 2014). Regions of high climate velocities are those with low topographic relief on land, particularly flooded grasslands and deserts (Loarie et al., 2009), and tropical as well as offshore and polar sea regions (Burrows et al., 2011; Burrows et al., 2014; García Molinos et al., 2016; Brito-Morales et al., 2018; Brito-Morales et al., 2020).

On millennial time scales, some areas of low climate velocity have more endemic species and can be considered climate refugia, at least on land (Sandel et al., 2011) and, for marine species, around Antarctica (H213) (Costello et al., 2010). This suggests that, if these areas are subject to increased velocities, they will lose species that are not able to disperse fast enough to cope with the pace of climate change (*medium confidence*) (Sandel et al., 2011; Brito-Morales et al., 2018).

Climate velocities are 47% (Myers), 29% (G200, terrestrial) and 10% (G200, freshwater) lower inside biodiversity hotspots than outside, respectively (Kocsis et al., 2021), but are 69% higher inside marine hotspots than outside (*medium confidence*). Climate velocities from 1970 to 2019 ranged from 3–4 km per decade (terrestrial and freshwater) to ~11 km per decade in marine (Kocsis et al., 2021).

For terrestrial and freshwater hotspots, the highest climate velocities are in central South America, including the Amazon (H153, 154) (Figure CCP1.3). Terrestrial hotspots also have high velocities in the

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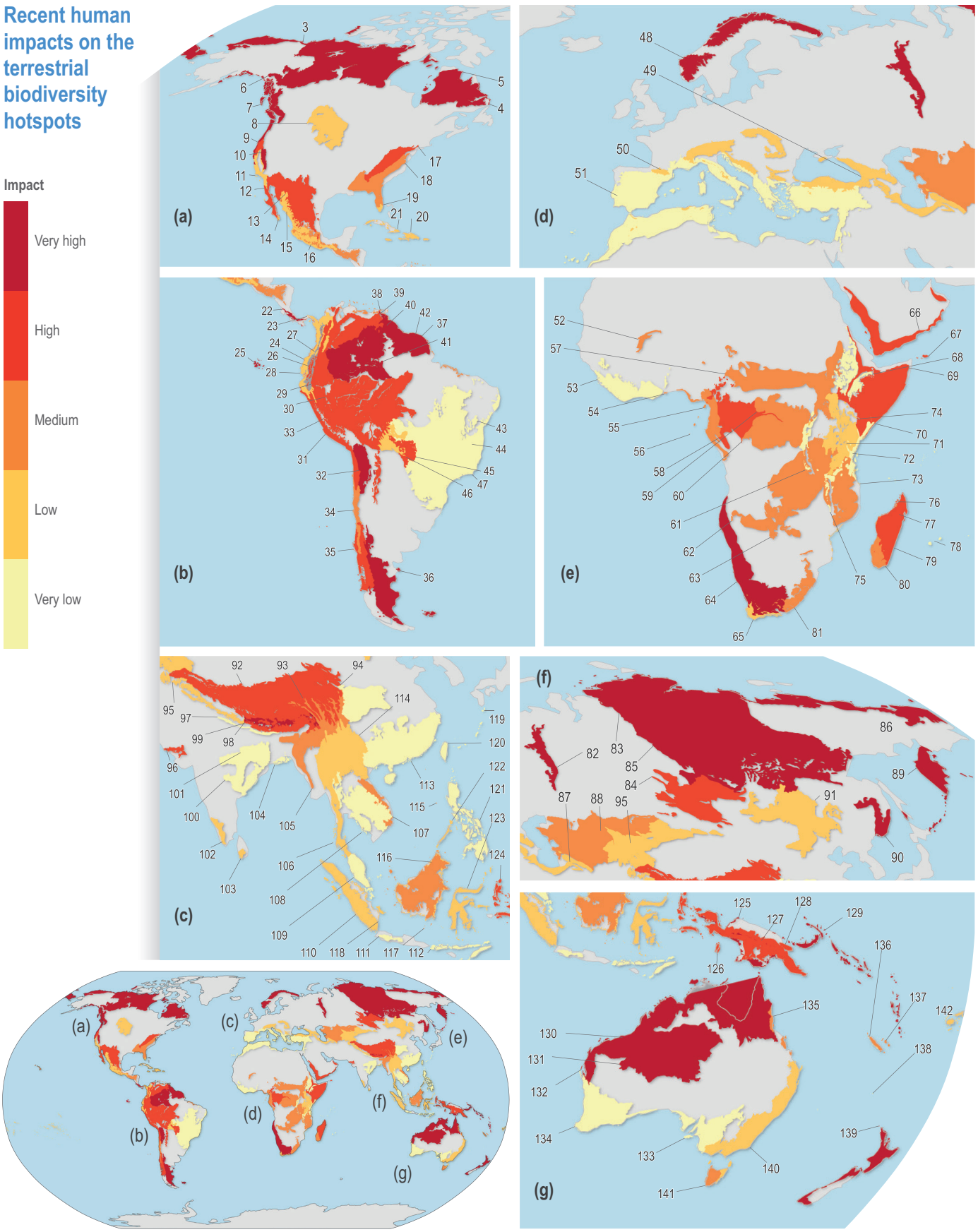


Figure CCP1.1 | Recent human impacts on the terrestrial biodiversity hotspots (coloured, grey is non hotspot) (Table CCP1.SM.1). Impacts are scaled in five equal 20% categories. **(a)** North and Central America; **(b)** South America; **(c)** Southeast Asia; **(d)** Europe and North Africa; **(e)** Africa and Arabia; **(f)** North Asia; **(g)** Southeast Asian archipelagos, Australia and New Zealand. See Table CCP1.1 for key to hotspot numbers.

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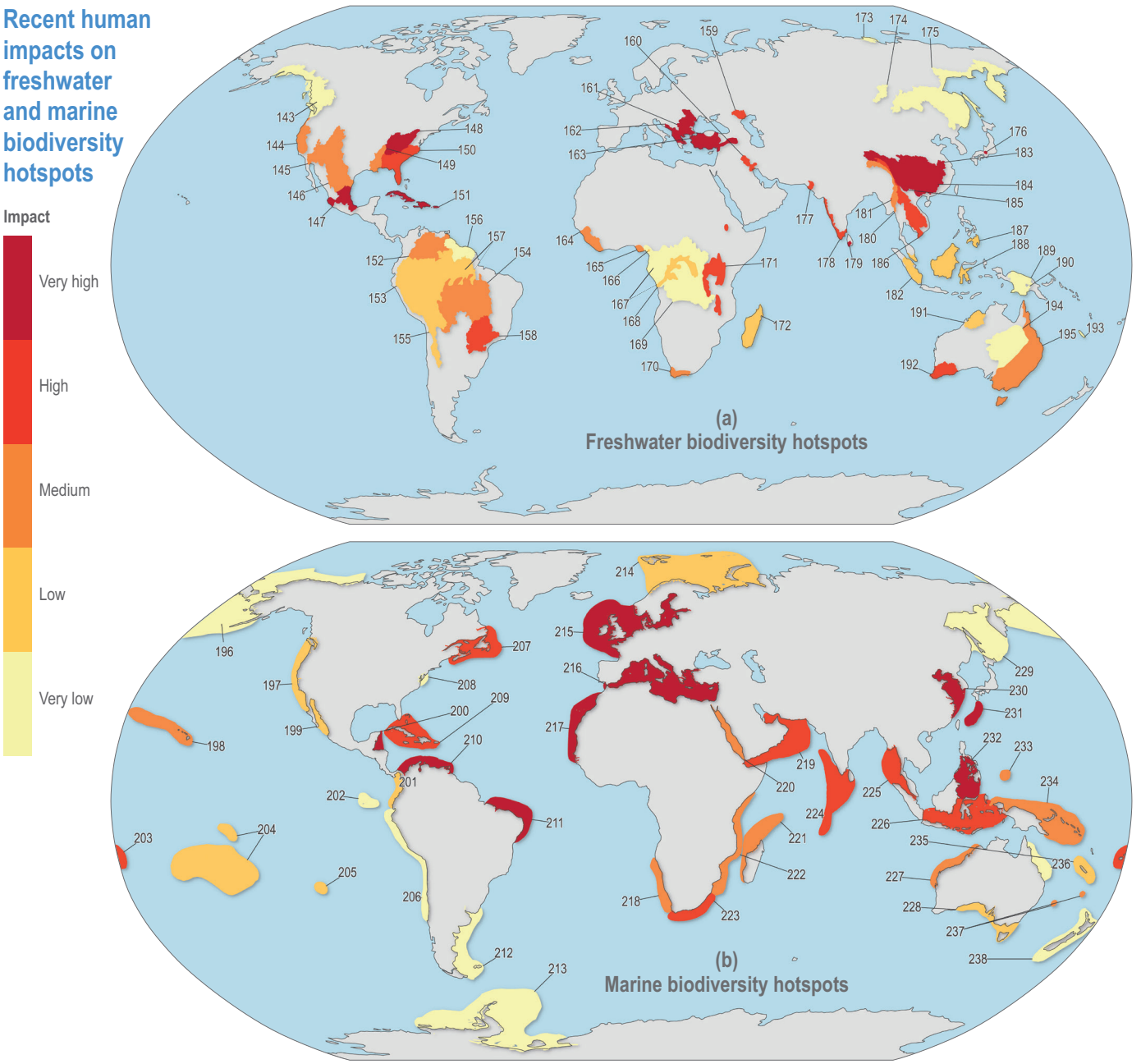


Figure CCP1.2 | Recent human impacts from multiple factors on (a) freshwater hotspots since 2000, based on Janse et al. (2015) and (b) marine hotspots based on Halpern et al. (2015). Human impacts in freshwater areas refer to the remaining wilderness. Marine impacts represent land-based, fishing, climate change and ocean-based stressors. Impacts are scaled into five equal 20% categories. See Table CCP1.1 for the key to hotspot numbers.

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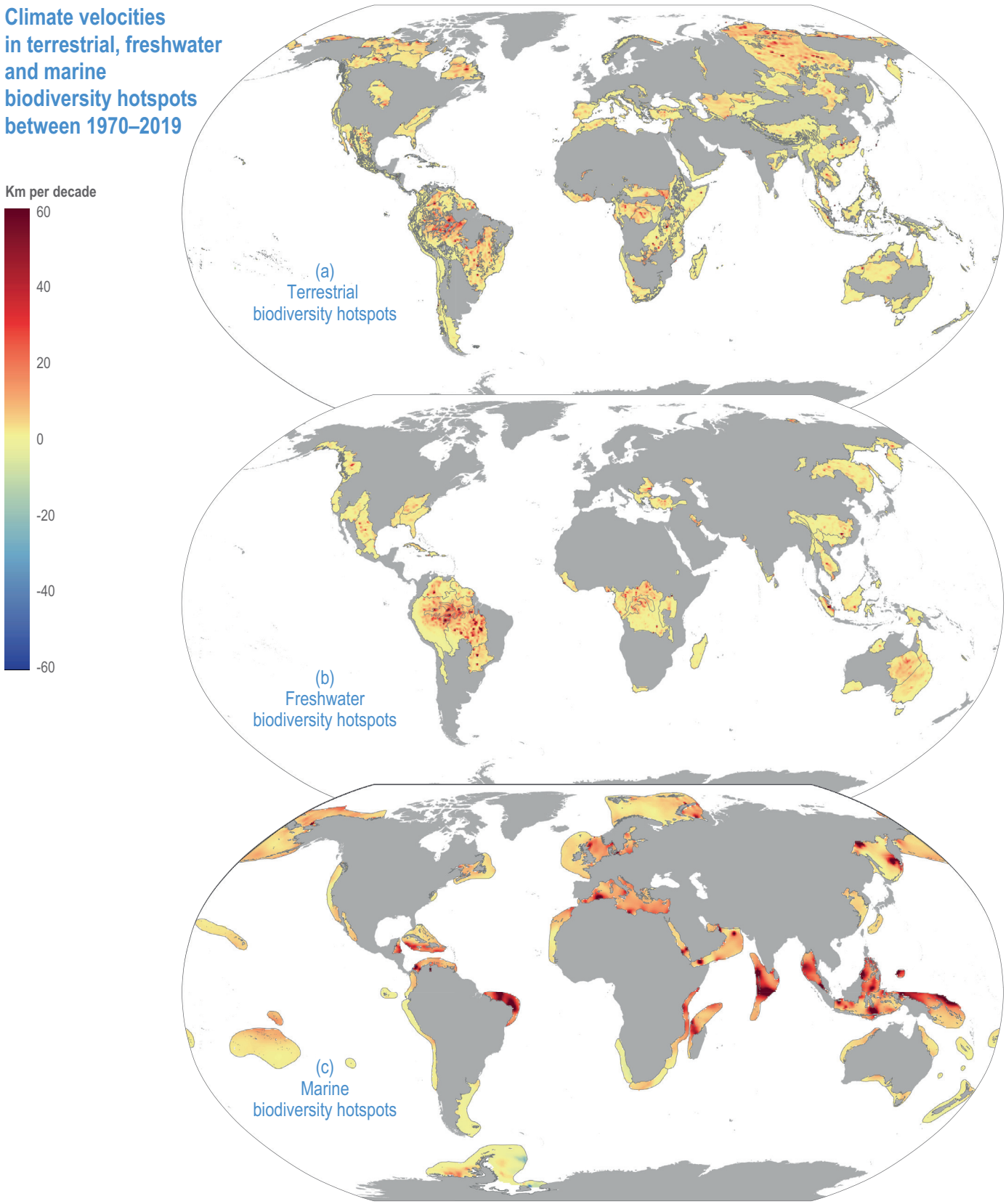


Figure CCP1.3 | Climate velocities in terrestrial (a), freshwater (b) and marine (c) hotspots between 1970–2019. Values are presented in kilometres per decade and derived using the analytical package VoCC (García Molinos et al., 2019) from gridded temperature data, sea surface temperatures for marine (Rayner et al., 2003) and near-surface air temperatures on land and freshwater (Harris et al., 2020). Positive and negative velocities indicate warming and cooling, respectively.

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Table CCP1.1 | List of biodiversity hotspots names from (Olson and Dinerstein, 2002) as mapped in Figures CCP1.1 for terrestrial (numbered 1 to 142) and CCP1.2 for freshwater (143 to 195) and marine (196 to 238). Hotspots containing islands (>100 km^2) are indicated with an asterisk.

1 Hawaii Moist Forest*	81 Drakensberg Montane Woodlands and Grasslands	161 Danube River Delta
2 Hawaii Dry Forest*	82 Ural Mountains Taiga and Tundra	162 Balkan Rivers and Streams*
3 Alaskan North Slope Coastal Tundra*	83 Taimyr and Russian Coastal Tundra*	163 Anatolian Freshwater
4 Canadian Boreal Taiga*	84 Altai-Sayan Montane Forests	164 Upper Guinea Rivers and Streams*
5 Canadian Low Arctic Tundra*	85 Central and Eastern Siberian Taiga	165 Niger River Delta*
6 Muskwa/Slave Lake Boreal Forests	86 Chukhote Coastal Tundra*	166 Cameroon Crater Lakes
7 Pacific Temperate Rainforests*	87 Central Asian Deserts	167 Gulf of Guinea Rivers and Streams*
8 Northern Prairies	88 Middle Asian Montane Woodlands and Steppe	168 Congo River and Flooded Forests
9 Klamath-Siskiyou Coniferous Forests	89 Kamchatka Taiga and Grasslands*	169 Congo Basin Piedmont Rivers and Streams
10 Sierra Nevada Coniferous Forests	90 Russian Far East Broadleaf and Mixed Forests*	170 Cape Rivers and Streams
11 California Chaparral and Woodlands*	91 Daurian/Mongolian Steppe	171 Rift Valley Lakes
12 Sonoran-Baja Deserts*	92 Tibetan Plateau Steppe	172 Madagascar Freshwater Ecosystem*
13 Chihuahuan-Tehuacan Deserts	93 Hengduan Shan Conifer Forests	173 Lena River Delta
14 Sierra Madre Oriental and Occidental Pine-Oak	94 Southwest China Temperate Forests	174 Lake Baikal
15 Southern Mexican Dry Forests*	95 Western Himalayan Temperate Forests	175 Russian Far East Rivers and Wetlands*
16 Mesoamerican Pine-Oak Forests	96 Rann of Kutch Flooded Grasslands	176 Lake Biwa*
17 Appalachian and Mixed Mesophytic Forests	97 Terai-Duar Savannas and Grasslands	177 Indus River Delta*
18 Southeastern Conifer and Broadleaf Forests*	98 Eastern Himalayan Alpine Meadows	178 Western Ghats Rivers and Streams
19 Everglades Flooded Grasslands	99 Eastern Himalayan Broadleaf and Conifer Forests	179 Southwestern Sri Lanka Rivers*
20 Greater Antillean Moist Forests*	100 Eastern Deccan Plateau Moist Forests*	180 Salween River
21 Greater Antillean Pine Forests*	101 Chhota-Nagpur Dry Forests	181 Lake Inle
22 Talamancan-Isthmian Pacific Forests	102 Southwestern Ghats Moist Forest	182 Sundaland Rivers and Swamps*
23 Choco-Darien Moist Forests*	103 Sri Lankan Moist Forest*	183 Yangtze River and Lakes
24 South American Pacific Mangroves*	104 Sundarbans Mangroves	184 Xi Jiang Rivers and Streams
25 Galapagos Islands Scrub*	105 Naga-Manapuri-Chin Hills Moist Forests*	185 Yunnan Lakes and Streams
26 Northern Andean Páramo	106 Kayah-Karen/Tenasserim Moist Forests	186 Mekong River*
27 Northern Andean Montane Forests	107 Indochina Dry Forests*	187 Philippines Freshwater*
28 Tumbesian-Andean Valleys Dry Forests*	108 Cardamom Mountains Moist Forests*	188 Central Sulawesi Lakes*
29 Napo Moist Forests	109 Peninsular Malaysia Lowland and Montane Forests*	189 New Guinea Rivers and Streams*
30 Southwestern Amazonian Moist Forests	110 Sumatran Islands Lowland and Montane Forests*	190 Lakes Kutubu and Sentani*
31 Atacama-Sechura Deserts	111 Western Java Montane Forests*	191 Kimberley Rivers and Streams
32 Central Andean Dry Puna	112 Nusu Tenggara Dry Forests*	192 Southwest Australia Rivers and Streams
33 Central Andean Yungas	113 Southeast China-Hainan Moist Forests	193 New Caledonia Rivers and Streams*
34 Chilean Matorral	114 North Indochina Subtropical Moist Forests	194 Central Australian Freshwater*
35 Valdivian Temp. Rain Forests Juan Fernandez*	115 Annamite Range Moist Forests	195 Eastern Australia Rivers and Streams
36 Patagonian Steppe*	116 Kinabalu Montane Shrublands*	196 Bering Sea*
37 Amazon-Orinoco-Southern Caribbean Mangroves*	117 Borneo Lowland and Montane Forests*	197 California Current*
38 Coastal Venezuela Montane Forests	118 Greater Sundas Mangroves*	198 Hawaiian Marine*
39 Llanos Savannas	119 Nansei Shoto Archipelago Forests*	199 Gulf of California*
40 Guianan Highlands Moist Forests	120 Taiwan Montane Forests*	200 Mesoamerican Reef*
41 Rio Negro-Jurua Moist Forests	121 Philippines Moist Forests*	201 Panama Bight*
42 Guianan Moist Forests	122 Palawan Moist Forests*	202 Galapagos Marine*
43 Atlantic Dry Forests	123 Sulawesi Moist Forests*	203 Fiji Barrier Reef*
44 Cerrado Woodlands and Savannas	124 Moluccas Moist Forests*	204 Tahitian Marine*
45 Pantanal Flooded Savannas	125 New Guinea Mangroves*	205 Rapa Nui*
46 Chiquitano Dry Forests	126 Southern New Guinea Lowland Forests*	206 Humboldt Current*

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47 Atlantic Forests*	127 Central Range Subalpine Grasslands*	207 Grand Banks*
48 Fenno-Scandia Alpine Tundra and Taiga*	128 New Guinea Montane Forests*	208 Chesapeake Bay
49 Caucasus-Anatolian-Hyrcanian Temp. Forests	129 Solomons-Vanuatu-Bismarck Moist Forests*	209 Greater Antillean Marine*
50 European Mediterranean Montane Forests	130 Northern Australia and Trans-Fly Savannas*	210 Southern Caribbean Sea*
51 Mediterranean Forests, Woodlands, Scrub*	131 Great Sandy-Tanami-Central Ranges Desert	211 Northeast Brazil Shelf Marine*
52 Sudd-Sahelian Flooded Grasslands and Savannas	132 Carnavon Xeric Shrubs*	212 Patagonian Southwest Atlantic*
53 Guinean Moist Forests	133 Southwestern Australia Forests and Scrub*	213 Antarctic Peninsula and Weddell Sea*
54 Gulf of Guinea Mangroves*	134 Southern Australia Mallee and Woodlands*	214 Barents-Kara Seas*
55 Cameroon Highlands Forests*	135 Queensland Tropical Forests*	215 Northeast Atlantic Shelf Marine*
56 Congolian Coastal Forests*	136 New Caledonia Moist Forests*	216 Mediterranean Sea*
57 Sudanian Savannas	137 New Caledonia Dry Forests	217 Canary Current*
58 Western Congo Basin Moist Forests	138 Lord Howe and Norfolk Island Forests*	218 Benguela Current
59 Northeastern Congo Basin Moist Forests	139 New Zealand Temperate Forests*	219 Arabian Sea*
60 Central Congo Basin Moist Forests	140 Eastern Australia Temperate Forests*	220 Red Sea*
61 Albertine Rift Montane Forests	141 Tasmanian Temperate Rainforests*	221 West Madagascar Marine*
62 Central and Eastern Miombo Woodlands	142 Southern Pacific Islands Forests*	222 East African Marine*
63 Zambezian Flooded Savannas	143 Gulf of Alaska Coastal Rivers*	223 Agulhas Current
64 Namib-Karoo-Kaokoveld Deserts and Shrublands*	144 Pacific Northwest Coastal Rivers	224 Maldives-Chagos-Lakshadweep Atolls*
65 Fynbos	145 Colorado River	225 Andaman Sea*
66 Arabian Highlands Woodlands and Shrublands*	146 Chihuahuan Freshwater	226 Banda-Flores Sea*
67 Socotra Island Desert*	147 Mexican Highland Lakes	227 Western Australia Marine*
68 Ethiopian Highlands	148 Mississippi Piedmont Rivers and Streams	228 Southern Australian Marine
69 Horn of Africa Acacia Savannas	149 Lower Mississippi River	229 Okhotsk Sea*
70 East African Coastal Forests*	150 Southeastern Rivers and Stream s*	230 Yellow Sea*
71 East African Moorlands	151 Greater Antillean Freshwater*	231 Nansei Shoto*
72 Eastern Arc Montane Forests	152 Orinoco River and Flooded Forests	232 Sulu-Sulawesi Seas
73 East African Mangroves*	153 Upper Amazon Rivers and Streams	233 Palau Marine*
74 East African Acacia Savannas	154 Brazilian Shield Amazonian Rivers and Streams	234 Bismarck-Solomon Seas
75 Southern Rift Montane Woodlands	155 High Andean Lakes	235 New Caledonia Barrier Reef*
76 Madagascar Mangroves*	156 Guianan Freshwater	236 Great Barrier Reef*
77 Madagascar Dry Forests*	157 Amazon River and Flooded Forests*	237 Lord Howe-Norfolk Islands Marine
78 Seychelles and Mascarenes Moist Forests*	158 Upper Paraná Rivers and Streams	238 New Zealand Marine*
79 Madagascar Forests and Shrublands*	159 Volga River Delta	
80 Madagascar Spiny Thicket*	160 Mesopotamian Delta and Marshes*	

Arctic (H196, 214) and east of the Caspian Sea, while freshwater hotspots have low velocities in the eastern European Mediterranean and eastern Australia.

Marine hotspots have a wider range of climate velocities than terrestrial and freshwater environments (Figure CCP1.3), being faster in equatorial, Mediterranean (H216), Baltic (H215), North and Okhotsk (H229), and Arctic hotspots (H196, 214), and slow in the Antarctic hotspot (H213). Marine species tend to follow climate velocities more closely than terrestrial species (*high confidence*) (Sunday et al., 2012; Pinsky et al., 2019; Lenoir et al., 2020). The reasons may be smaller thermal safety margins in the seas or greater human impacts on land impeding species range shifts. Climate velocities are particularly fast in equatorial seas (Figure CCP1.3; (Burrows et al., 2011), which are therefore expected to be source areas for species shifting their ranges towards the subtropics (Burrows et al., 2014). The subtropics are then source areas of species that shift to temperate latitudes and so forth, such that observed impacts in marine biodiversity hotspots are largely attributable to species range shifts (*high confidence*) (Pecl et al., 2017). Because marine climate velocities are significantly greater within than outside hotspots, marine hotspots are especially prone to species redistributions (*medium confidence*) (Figure CCP1.3; (Kocsis et al., 2021).

While species from lower latitudes may shift their geographic ranges to higher latitudes to adapt to changing climate, there are no species to replace low latitude species. Thus, as already observed in the oceans around the equator, the loss of species in low latitudes will continue with future climate warming (*high confidence*) (Yasuhara et al., 2020; Chaudhary et al., 2021). The issue also extends to altitudinal ranges

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in terrestrial environments, with species moving to higher elevations where surface area generally declines with increasing elevation; mountaintop species may have nowhere to go (Flousek et al., 2015; Freeman et al., 2018; Kidane et al., 2019).

CCP1.2.1.1.2 Observed impacts on biodiversity

Although conservation status has only been assessed globally for about 6% of all species (Costello, 2019) and most confirmed extinctions and threatened species are terrestrial, a higher proportion of freshwater species are threatened. This is reflected in the higher proportion of freshwater hotspots impacted by humans (Collen et al., 2014; Costello, 2015; Harrison et al., 2018). The rate of species endemicity is exceptionally high in freshwater biogeographic realms (i.e., large regions of distinct species composition and endemicity), at 89–96% for fish in all but one realm, compared to 11–98% for terrestrial vertebrate groups (Leroy et al., 2019) and 17–84% for marine realms (Costello et al., 2017). Already, one-third of wetlands have been lost and 9000 freshwater species are threatened with extinction without considering the effects of climate change (Darwall et al., 2018), and only 13% of world rivers were recently classified as least impacted (Su et al., 2021).

Globally, observed climate-driven changes in biodiversity are typically of species distributions shifting to higher latitudes (*virtually certain*) (Lenoir et al., 2020, Ch.2, Ch. 3.4). Since the 1950s, marine species richness has shifted poleward in the Northern Hemisphere, increased in mid-latitudes and declined at the equator in concert with ocean warming (*medium confidence*) (Chaudhary et al., 2021). Climate-driven altitudinal shifts are common on land (*high confidence*) (Lenoir and Svenning, 2015; Steinbauer et al., 2018), and depth shifts in the ocean may occur but are little studied (*low confidence*) (Burrows et al., 2019; Jorda et al., 2020). While climate-induced range expansions can be viewed as opportunities for increasing regional biodiversity, range contractions adversely affect biodiversity through regional extirpations (*high confidence*) (Cahill et al., 2013; Chaudhary et al., 2021).

Both of the two climate change associated global species extinctions to date support the predictions that endemic species on mountains and islands are at the greatest risk of extinction (Manes et al., 2021). The golden toad (*Bufo periglenes*) became extinct after some years of decline associated with changes in climate warming and precipitation in the Talamancan-Isthmian Pacific Forests biodiversity hotspot (H22) (Pounds et al., 1999; Cahill et al., 2013, WGII Ch2.4.2.2). The Bramble Cay melomys (*Melomys rubicola*), a rodent endemic to an island between Australia and Papua New Guinea and closely related to a mainland Australian species, became extinct due to habitat loss arising from climate change-related sea level rise and cyclone activity (Fulton, 2017; Roycroft et al., 2021, WGII Ch.11).

CCP1.2.1.2 Projected Impacts

CCP1.2.1.2.1 Projected climatic hazards

Comparison of climate warming projected for air and sea temperature shows biodiversity hotspots will continue to experience the greatest net increases in temperature at higher Northern Hemisphere latitudes, particularly in tundra regions (Figures CCP1.4; CCP1.5; Table CCP1.1). Generally, terrestrial and freshwater hotspots are projected to continue to warm more than marine (Figure CCP1.3). Modelled temperatures are projected to continue to be the highest in the tropics, indicating where there are more thermally stressful conditions for more species (*high confidence*) (Stuart-Smith et al., 2015; Stuart-Smith et al., 2017; Foster et al., 2018; Waldock et al., 2019). By the end of this century, all terrestrial biodiversity hotspots in Central and South America, Africa, India and southern and eastern Asia (including the Indo–West Pacific islands) are projected to experience climates unprecedented in their species' evolutionary history (*medium confidence*) (Williams et al., 2007).

Based on WGI *Interactive Atlas* data (Gutiérrez et al., 2021), global warming is projected to affect terrestrial hotspots less than non-hotspot areas: 80% less for Myers and 95–96% less for G200 terrestrial and freshwater hotspots at global warming of 1.5°C–3°C (*medium confidence*) (Kocsis et al., 2021). In contrast, warming is projected to be 12–13% greater inside than outside marine hotspots (*medium confidence*) (Kocsis et al., 2021). Precipitation is generally projected to increase more in terrestrial and freshwater biodiversity hotspots compared to outside them (*low confidence*) (Kocsis et al., 2021). The exception is Myers hotspots, which are projected to have, on average, ~28% less precipitation at 1.5°C warming, but ~33% more at 2°C and ~65% more at 3°C (*low confidence*). However, precipitation changes are often difficult to assess as many hotspots cover large areas, with some areas projected to be wetter and some drier with wide differences between different climate models.

CCP1.2.1.2.2 Projected impacts on biodiversity

Biodiversity hotspots are expected to be especially vulnerable to climate change because their endemic species have smaller geographic ranges (*high confidence*) (Sandel et al., 2011; Brown et al., 2020; Manes et al., 2021). Manes et al. (2021) reviewed over 8000 projections of climate change impacts on biodiversity in 232 studies, including 6116 projections on endemic, native and introduced species in terrestrial (200 studies), freshwater (14 studies) and marine (34 studies) environments in biodiversity hotspots. Only half of the hotspots had studies on climate change impacts. All measures of biodiversity were found to be negatively impacted by projected climate change, namely, species abundance, diversity, area, physiology and fisheries catch potential (*medium confidence*). However, introduced species' responses were neutral to positive (*medium confidence*). Land areas were projected to be more negatively affected by climate warming than marine. Land plants, insects, birds, reptiles and mammals were all projected to be negatively affected (*medium confidence*), as well as fish, coral reef, benthic, planktonic and other marine species (*medium confidence*).

Of the 6116 projections for more than 2,700 species assessed in biodiversity hotspots, ~44% were found to be at high extinction risk, and ~24% at very high extinction risk due to climate change (Manes et al., 2021) (*medium confidence*). Risks of extinction were estimated based on the projections for all warming levels combined, showing that endemic species were about 2.7 times more at very high risk of extinction compared to non-endemic native species (Manes et al., 2021). Extinction risks were highest for endemic species of both land

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Projected loss of climatically suitable area in terrestrial biodiversity hotspots

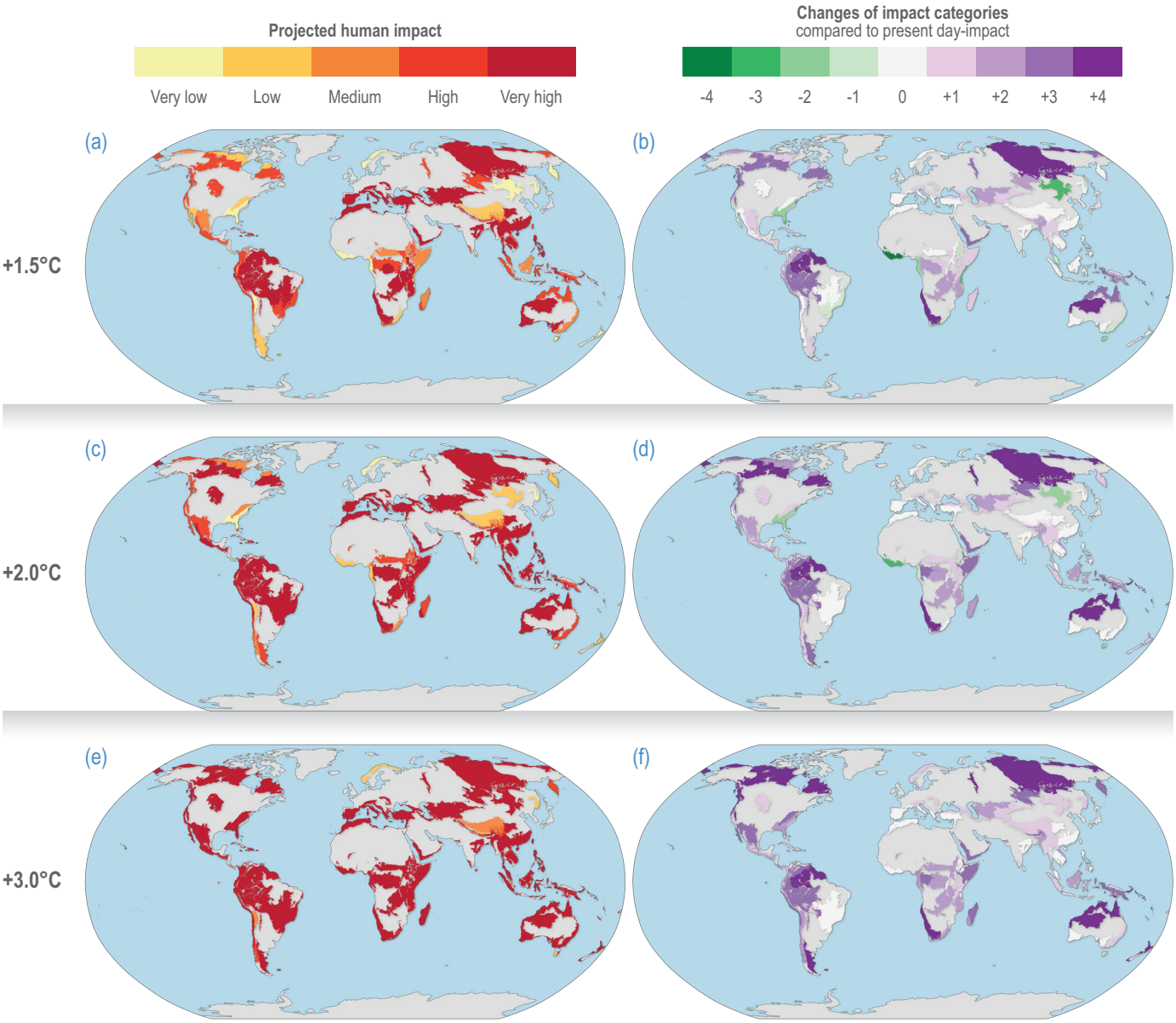


Figure CCP1.4 | Projected loss of climatically suitable area in terrestrial biodiversity hotspots for a global average of 1.5°C (upper row, a–b), 2°C (middle, c–d) and 3°C (lower, e–f). Left-hand column displays the projected human impact using the five equal 20% categories of present-day impact (Figure CCP1.1). The right-hand column indicates the changes of impact categories compared to present-day impact. See Table SMCCP1.1 for more details.

and ocean (*medium confidence*), and were higher for those living on islands (~100%, *medium confidence*) and mountains (~84%, *medium confidence*) than in the ocean (~54%, *low evidence, medium agreement*; *low confidence*) and on continents (~12%, *robust evidence, medium agreement, medium confidence*) (Figure CCP1.6). Extinction risks for non-endemic natives were ~20% for both terrestrial and marine species, with introduced species projected to become more rather than less invasive. At 1.5°C warming, ~2% of both terrestrial and marine species and at 3°C, ~20% and ~32% respectively, were projected to be at very high risk of extinction in the hotspots (Figure CCP1.6). Thus, a doubling of warming results in a roughly 10-fold increase in species at very high extinction risk.

Manes et al. (2021) found that any benefits to species (e.g., range or abundance increase) were projected to be localised and transient (e.g., Arctic, H196, 214). This and previous assessments indicate that, while climate change varies spatially and taxa may respond differently, a loss of biodiversity is projected across all terrestrial hotspots (*high confidence*) (Foden et al., 2013; Warren et al., 2018a; Manes et al., 2021). Abrupt changes across species assemblages may occur under all scenarios: in 9% of assemblages at 1.75°C and 35% at 4.4°C on both land and sea (Trisos et al., 2020). However, species losses may be reduced if species have thermal microclimate refugia and behavioural thermoregulation, or greater due to extreme events, such as heatwaves.

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Projected future warming for freshwater and marine biodiversity hotspots

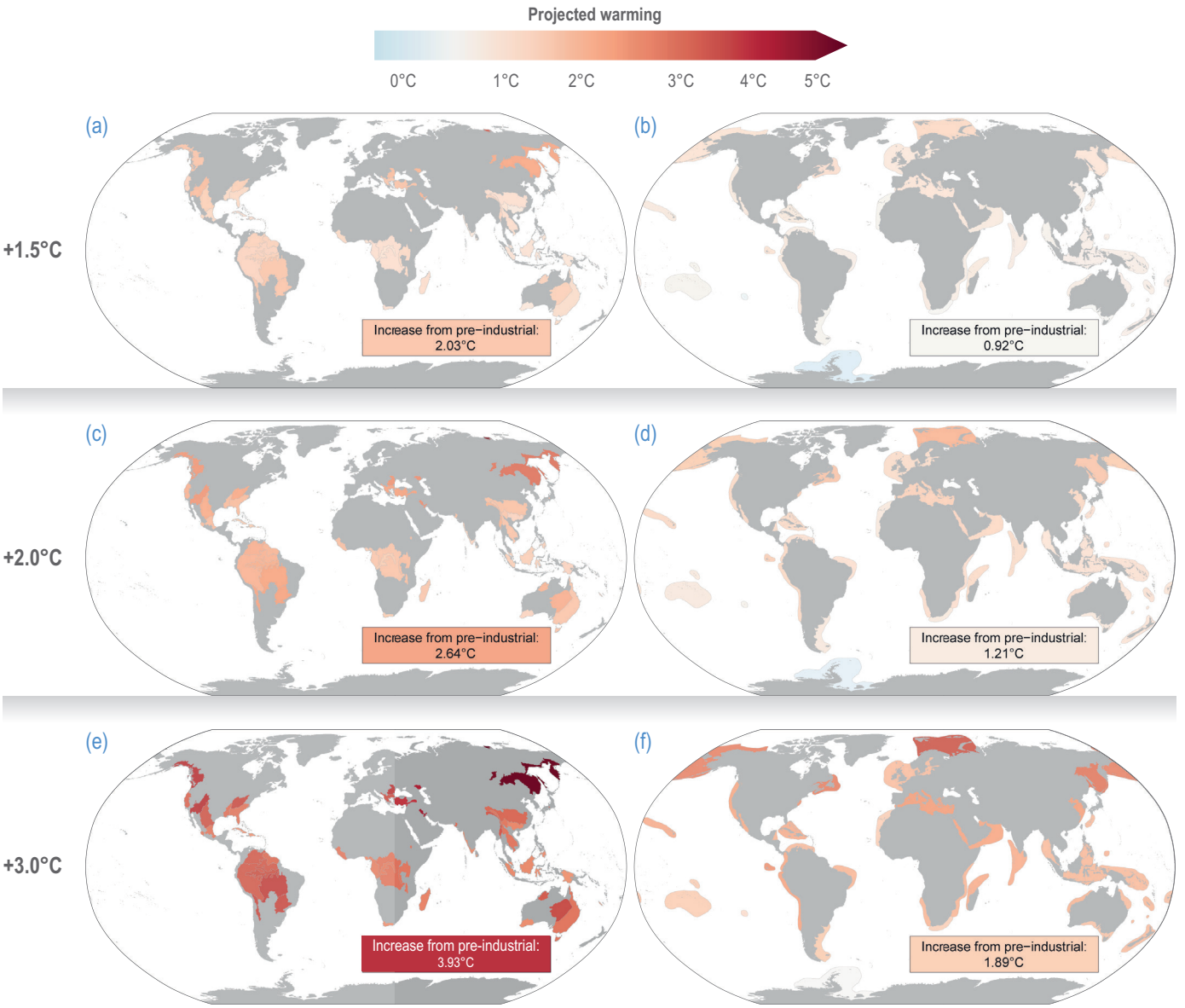


Figure CCP1.5 | Projected future warming in degrees Celsius for freshwater (left column, near-surface air temperature, panels a, c and e) and marine (right column as sea surface temperature, panels b, d and f) hotspots for a global average warming of +1.5°C (a, b), +2°C (c, d) and +3°C (e, f) compared to pre-industrial conditions. Values in text boxes in the figures indicate temperature increase from present-day (2005–2014) settings. Projected temperatures were calculated with averages of multi-model, yearly means across Shared Socioeconomic Pathways (SSP) 1.26 (only for +1.5°C), SSP2-45, SSP3-70 and SSP5-85.

CCP1.2.1.3 Compounding and Cascading Effects

All biodiversity hotspots are already impacted, to differing degrees, by human activities (*high confidence*) (Table CCP1.1, Figures CCP1.1, CCP1.2, Myers et al., 2000; Le Roux et al., 2019). At present, over three billion people live within terrestrial and (catchments of) freshwater biodiversity hotspots, many of which border marine hotspots (Figures CCP1.1; CCP1.2; Table SMCCP1.1; Gutiérrez et al., 2021). Thus, climate change impacts on biodiversity hotspots are compounded by other anthropogenic impacts, increasing the vulnerability and reducing the resilience of biodiversity to climate change (*very high confidence*). Projections of changing climate alone may overestimate or underestimate the impacts on biodiversity (*medium evidence, high agreement*). The additional risk of the combined effects of climate change and other impacts (e.g., land use change, overhunting, pollution and invasive species) on species has been raised since the Third Assessment Report. The terrestrial hotspots projected to be most affected by global warming are, in general, those already being impacted by loss of habitat due to land use change (Figure CCP1.4; Table SMCCP1.1) (Warren et al., 2018a). This remains a trend in the recent literature, although most studies still address only one stressor (Titeux et al., 2016). For example, Mantyka-Pringle et al. (2015) show that when the interaction between projected climate change and habitat loss is taken into account, the extinction risk of birds and

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Biodiversity Hotspots

Areas with many rare and unique species

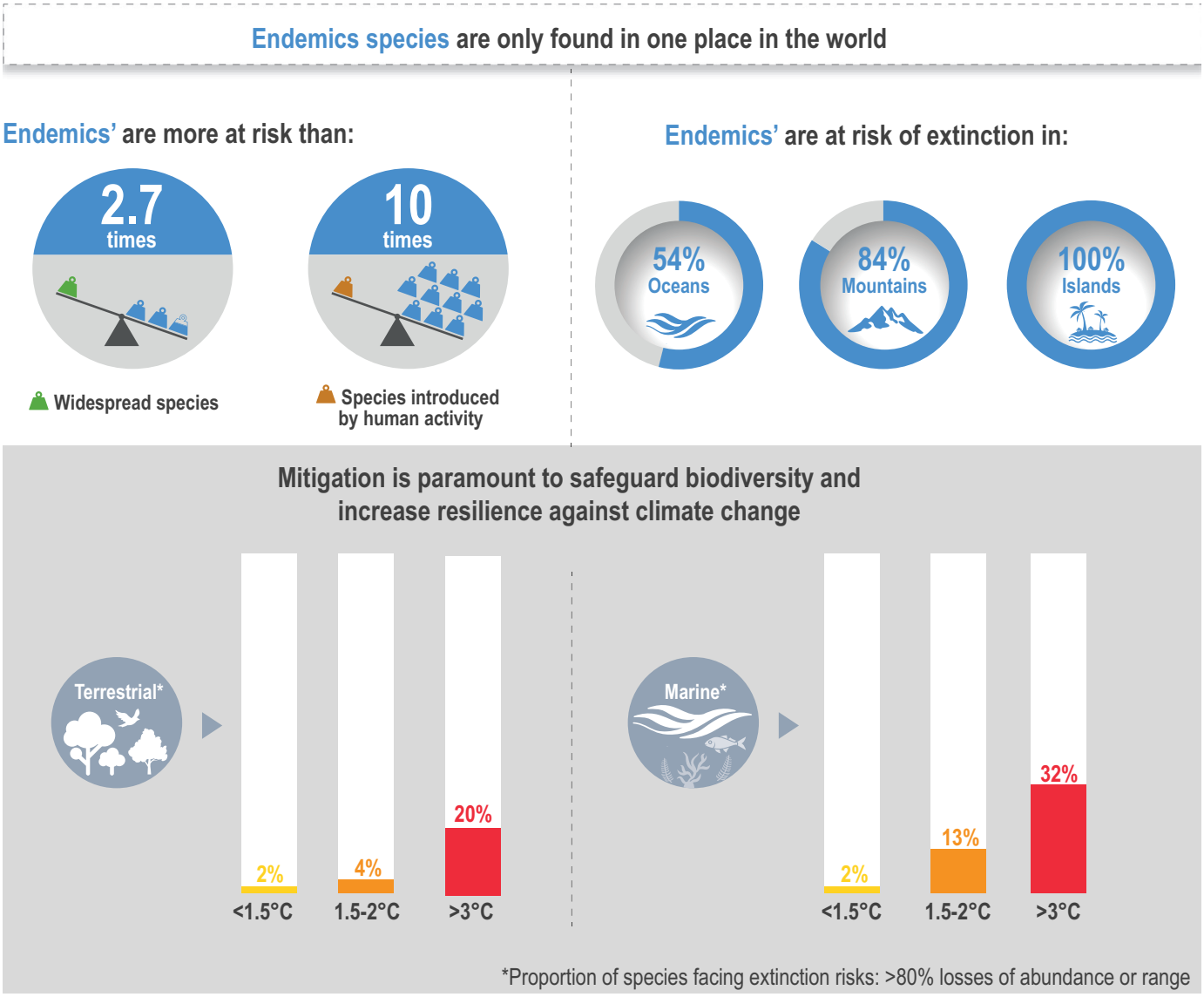


Figure CCP1.6 | A summary of the projected risks of species extinction at global warming levels of <1.5°C, 1.5–2.0°C and >3°C in terrestrial and marine biodiversity hotspots. Data from Manes et al. (2021).

mammals in 15–32% of terrestrial biodiversity hotspots changes. Similarly, Bellard et al. (2014b) found different results when examining the impact of climate change, invasive species and land use change independently, as opposed to synergistically. When combining those three impacts they identified the Atlantic Forest (H47), Cape Floristic Region (H65) and Polynesia-Micronesia (H1, 2, 138, 139, 142) as particularly vulnerable.

In a global assessment of the threat of climate change to river fish biodiversity, Tedesco et al. (2013) projected that current extinction rates of species may be 7% greater due to climate change. The main threat is due to the effects of drought and reduced river flows, which would be 18 times greater than without climate change. However, just 20 of the 110 river basins studied would experience sufficient climate-driven water loss to cause fish extinctions by 2090. Moreover, the present rates of species loss due to human activities are 130 times greater than those projected under future climate change (*medium confidence*) (Tedesco et al., 2013).

Marine systems are also vulnerable to cumulative human impacts, which can be direct (e.g., pollution, overfishing) and indirect (altered food webs) (*very high confidence*) (Halpern et al., 2008; Halpern et al., 2015). The marine hotspots most currently threatened by non-climate-related human impacts are all situated in the Northern Hemisphere, specifically along the northern European, Mediterranean and Asian coasts, where the overlap of overfishing and pollution is especially large

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(Figure CCP1.2b; Halpern et al., 2008; Halpern et al., 2015; Ramírez et al., 2018). Although there is a strong overlap of non-climatic and climatic impacts in marine ecosystems (Blowes et al., 2019; Bowler et al., 2020), the effects suggest that climate change impacts are most severe in tropical and northern high-latitude seas (*high confidence*) (Doney et al., 2012; Gattuso et al., 2015; Cheung et al., 2018; IPCC, 2019b). Temperature-driven range shifts and range expansions are projected to also lead to cascading effects on marine biodiversity through ecological interactions (*high confidence*) (Pecl et al., 2017; Vergés et al., 2019). Cascading effects may be especially pronounced in temperate reefs, where tropicalisation could lead to the arrival of herbivorous fish and predators previously absent (Vergés et al., 2019). However, how these indirect effects of climate change on species may change food webs and ecosystem function, including carbon sequestration, is unknown. Direct and indirect human impacts due to fisheries and pollution can also lead to cascading effects that may be additive to climate impacts on biodiversity. Destruction of marine biogenic habitats due to trawling and dredging and loss of large proportions of marine megafauna, particularly fish, mammals, birds and reptiles, alter food webs and reduce resilience to additional disturbances, such as those caused by climate change (*medium evidence, high agreement*) (Brander, 2007; Wernberg et al., 2011; Ramírez et al., 2017; Cheung et al., 2018; Bates et al., 2019; Costello, 2021).

The following sections report observed and projected climate change impacts on terrestrial, freshwater and marine environments.

CCP1.2.2 Terrestrial

The 177 terrestrial hotspots assessed here (including 142 G200) cover about 61,000,000 km^2 (41% of global land area), with a 37% overlap with freshwater hotspots (Table CCP1.1; Figure CCP1.2). They include wet and dry forests, woodland and scrub, highlands, mangroves, deserts, steppe, savanna, grasslands, moorlands and tundra (Figures CCP1.8-1.11). Over 77% of publications on climate change impacts on hotspots since AR5 have been on terrestrial ecosystems, most on projected (as opposed to observed) impacts (Manes et al., 2021).

CCP1.2.2.1 Observed Impacts

There is *high confidence* that climate change has already had impacts in North American hotspots. Phenological and range shifts have been reported for bird and mammal species within the boreal forest hotspot (Davidson et al., 2020), and earlier egg laying in birds in tundra hotspots (H3, 5) owing to changes in snowmelt (Grabowski et al., 2013). Woody vegetation is already shifting north into the tundra (Larsen et al., 2014).

In Central and South America, observed impacts within Mesoamerica (H15, 16) and the Tropical Andes hotspots (H26, 27, 28, 32, 33) comprise upward altitudinal range shifts of birds, frogs, beetles and butterflies (Narins and Meenderink, 2014; Molina-Martínez et al., 2016; Moret et al., 2016; Freeman et al., 2018) (*medium confidence*). A shift of the Guianan-Amazon mangroves (H37) to higher grounds inland was attributed to the effects of observed sea level rise (*low confidence*) (Cohen et al., 2018).

In Europe, the Mediterranean hotspot (H216) has seen increases in wildfires and droughts attributed to anthropogenic climate change (Gudmundsson et al., 2017; Barbero et al., 2020). Range shifts in birds have been observed at higher elevations (*medium confidence*) (Tellería, 2020).

In Africa, multiple lines of evidence suggest woody plants are increasing in area, density and cover in previously lightly wooded savanna and grassland hotspots (H65, 82) (Poulsen and Hoffman, 2015; Stevens et al., 2017). Significant vulture and cheetah range reductions in these hotspots are at least partially attributable to bush encroachment (Nghikembua et al., 2016; Wolter et al., 2016; Santangeli et al., 2018). Thus, climate-driven bush encroachment has adversely affected unique mammal and bird diversity (*robust evidence, medium agreement, medium confidence*). Warming and drying trends have historically been shown to reduce the range of the Ethiopian wolf (*Canis simensis*), and they interact with land use pressures in the Ethiopian hotspot (H68) (Sintayehu, 2018) and plant species richness in the Cape Fynbos (H65) of southern Africa to reduce post-wildfire recruitment (*low confidence*) (Slingsby et al., 2017).

Observed impacts in Asia were mostly restricted to the Himalaya (H95, 98, 99), Sundaland (H109, 110, 111, 112, 117, 118) and Indo-Burma (H105, 106, 107, 114, 115) hotspots, showing negative impacts through increased invasion by exotic plants, decreased suitable area for endemic species and significant changes in phenology (*medium confidence*) (Telwala et al., 2013; Braby et al., 2014; Padalia et al., 2015; Lamsal et al., 2017). In the Central Asian mountain landscape (H87), studies have shown increased aridity induced by climate change impacts on several shrub species (Seim et al., 2016). Some positive effects were observed for native species in terms of an increase of suitable habitat (*limited evidence, low agreement*) (Priti et al., 2016; Tang et al., 2017; Rathore et al., 2019).

In Australia, climate change has been implicated in: drought-induced canopy dieback across a range of forest and woodland types due to decades of declining rainfall in the southwestern hotspot (H133); fires in the palaeo-endemic pencil pine forests (Tasmania H142); declines in vertebrates in the Australian Wet Tropics World Heritage Area, which overlaps with the eastern part of the northern Australia hotspot (H131), related to warming and increased length of the dry season; and declines in grass and increases in shrubs in the Bogong High Plains (*high confidence*) (Hoffmann et al., 2019). The Australian Alps have seen increased species diversity following retreat of the snow line (Slatyer, 2010), replacement of long-lived trees by short-lived shrubs following multiple wildfires (Zylstra, 2018), and changing ecological interactions due to climate-related snow loss, drought and fires (*high confidence*) (Hoffmann et al., 2019). While warming is allowing mangroves to expand their range in coastal hotspots of Asia and Australia (Ward et al., 2016; Hughes et al., 2019a), drought and associated salinity stress has killed mangroves in northern Australia hotspots (Babcock et al., 2019).

Approximately 76% of biodiversity hotspots within this assessment either contain, or are comprised of islands >100 km^2 (Table CCP1.1). However, just 0.08% of these hotspots were represented in post-AR5 literature examining climate change impacts on terrestrial biodiversity. Most observed impacts were assessed with *low evidence*, but *high agreement*, and focused on plants and insects. Impacts

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described included abundance changes and extirpations (Jenouvrier et al., 2014), altitudinal range shifts (Koide et al., 2017), increased invasive alien species' abundance and extent in Madagascar (H76, 77), Balearic (H51) and Pacific islands (Ghulam, 2014; Silva-Rocha et al., 2015; Goulding et al., 2016; Dawson et al., 2017), increased temperature affecting physiology, body size and behaviour of frogs in the Caribbean (H20) (Narins and Meenderink, 2014) and phenological alterations (Fontúrbel et al., 2018). One positive observation was the high resilience to recovery of intact forest ecosystems to tropical cyclones within Caribbean (H20) and Pacific islands (*medium confidence*) (Keppel et al., 2014; Marler, 2014; Shiels et al., 2014).

CCP1.2.2.2 Projected Impacts

Most terrestrial species in biodiversity hotspots in North America have been projected to be negatively impacted by climate change (*medium evidence, medium agreement*, *medium confidence*). About ~80% of projections for assessed species showed a negative impact of climate change, with ~25% at very high risk of extinction (Figure CCP1.7; Manes et al., 2021). Alterations to vegetation that would have ecosystem-wide impacts, such as a shift from oak-dominated forests to predominantly hickory and maple species in the Appalachian Forests (H17) (Ma et al., 2016) or the continued shrinking of tundra ecosystems, have also been projected. Range shifts have been projected for a variety of plants (Beltrán et al., 2014; Riordan and Rundel, 2014) and vertebrate taxa (Warren et al., 2014; Stralberg et al., 2015; McKelvy and Burbrink, 2017). Sizeable range loss, which particularly affects endemic species, is projected with higher levels of climate change. Adaptation in the agricultural sector poses an additional risk to remaining wildlife habitat (e.g., wine in California: Roehrdanz and Hannah, 2016).

In Central and South America, risks have been assessed in at least 24 terrestrial hotspots, especially within the Atlantic Forest, Cerrado, Mesoamerica and the Caribbean, the most studied hotspots in the world in terms of climate change impacts (H47, 44, 15, 16, 20, respectively) (Manes et al., 2021). About 85% of projections for assessed species showed a negative impact of climate change (*high confidence*), with ~26% projecting species extinctions (Figure CCP1.7; Manes et al., 2021). Projected impacts include contraction or loss of species' geographic range, loss of diversity and high species turnover (*high confidence*). Most studies had focused on vertebrates and plants in the Atlantic Forest (H47) and Cerrado (H44) (Loyola et al., 2014; de Oliveira et al., 2015; Vale et al., 2018; Vasconcelos et al., 2018; Hidasi-Neto et al., 2019; Lima et al., 2019; Lourenço-de-Moraes et al., 2019; Vasconcelos and Prado, 2019; Velazco et al., 2019). Several insect species are projected to lose suitable climatic conditions, including moths in Cerrado (H44) (Khormi and Kumar, 2014). There were projected negative impacts on vegetation such as rupestrian grasslands in Cerrado (H44) (Fernandes et al., 2018) and tropical and temperate forests in Mesoamerica (H15, H16) (Mendoza-Ponce et al., 2018; Mendoza-Ponce et al., 2019). Endemic species face consistent risks of decrease in suitable habitat in the Atlantic Forest (H47) (Vale et al., 2018), Cerrado (H44) (Vasconcelos, 2014), Tumbes-Chocó-Magdalena (H28, H23) (Hermes et al., 2018), and Mesoamerica (H15, H16) (Garcia et al., 2014; Ramírez-Amezcua et al., 2016). Climate change may also benefit invasive plant species in terms of range expansion (Wang et al., 2017) and physiology (de Faria et al., 2018) in the region.

In European biodiversity hotspots, about 75% of projections for assessed species showed a negative impact of climate change, with ~30% at very high risk of extinction (*medium confidence*) (Figure CCP1.7; Manes et al., 2021). These threats are projected to be worse under higher levels of warming. Increased wildfire size and frequency is projected to have a strong effect on the Mediterranean basin (H216) ecosystems (*medium confidence*) (Lozano et al., 2017). Range reductions have been projected for endemic plants (Pérez-García et al., 2013; Casazza et al., 2014), reptiles (Ahmadi et al., 2019), birds (Abolafya et al., 2013) and insects (Sánchez-Guillén et al., 2013) (*medium confidence*).

In African biodiversity hotspots, about 80% of projections for assessed species showed a negative impact of climate change, with ~10% at very high risk of extinction, especially of endemic species including birds, plants, bees across several taxa and hotspots if warming exceeds 2°C (*high confidence*) (Figure CCP1.7; Huntley and Barnard, 2012; Kuhlmann et al., 2012; Baker et al., 2015; Lee and Barnard, 2016; Young et al., 2016; Hannah et al., 2020; Manes et al., 2021).

In Asia, there is a bias in studies towards Indo-Burma (H105, 106, 107, 114, 115), followed by Himalaya (H95, 98, 99) and Southeast Asian montane tropical and temperate forests. About ~70% of projections for assessed species showed a negative impact of climate change, with ~30% at very high risk of extinction (*medium confidence*) (Figure CCP1.7; Manes et al., 2021). Impacts include species' range changes, habitat loss for endemic plants, expansion of invasive species, decreased connectivity and overall species richness decline (*high confidence*) (DasGupta and Shaw, 2013; Telwala et al., 2013; Sridhar et al., 2014; Zomer et al., 2014; Ali and Begum, 2015; Aryal et al., 2016). A projected decrease in habitat suitability for large species like the Asiatic black bear (*Ursus thibetanus*) is of concern as alternative habitats are outside protected areas, and may lead to human–wildlife conflicts (Farashi and Erfani, 2018). The few positive impacts of climate change were projected as increases in suitable habitat and distribution range for a few endangered plants and mammals (*medium confidence*) (Banag et al., 2015; Shrestha et al., 2018). Animals benefiting from increased fruit and seed production in Southeast Asian forests during warm El Niño cycles were also projected to increase with climate warming (Corlett, 2011).

All projections for assessed species in Australia and New Zealand terrestrial biodiversity hotspots showed a negative impact of climate change, with half at very high risk of extinction (*low confidence*) (Manes et al., 2021). Observed impacts in the Australian Alps were projected to continue under future climate change (Zylstra, 2018). The northern Australia savanna (H131) may experience increased rainfall and carbon dioxide due to climate change (Scheiter et al., 2015), and the range of exotic grasses was projected to be reduced under climate warming (Gallagher et al., 2009). In Australian tropical wet forests, ground-living vertebrates may be more sensitive than arboreal species to unstable climates (Scheffers et al., 2017). Bellard et al. (2016) projected losses of land due to sea level rise in the East Australian Forest hotspot (H140), and González-Orozco et al. (2016) projected the contraction of eucalyptus species towards the coast of the Southwest Australia hotspot (H134), exposing them to sea level rise. In New Zealand forests (H139), native plants may be replaced by more fire-resistant introduced species following climate change-related fires (Perry et al., 2014). While forest growth is projected to potentially

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The projected impacts of climate change on species in 232 studies

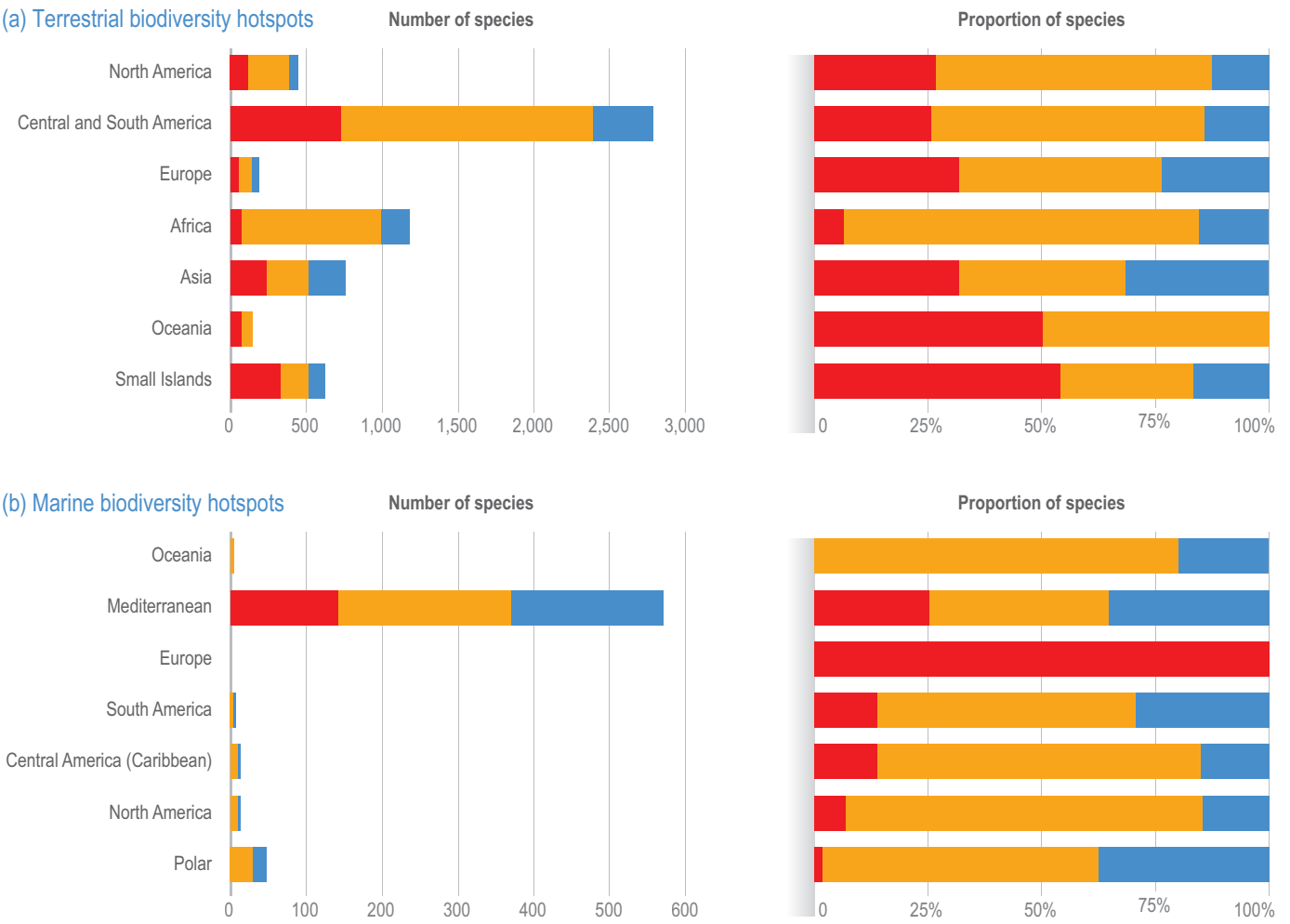


Figure CCP1.7 | The projected impacts of climate change on species in 232 studies (a) terrestrial and (b) marine hotspots (adapted from Manes et al., 2021), illustrating the number and percentage of species showing positive (blue) and negative (orange) responses to climate change, and threatened with extinction (red). Note Oceania includes Australia, New Zealand, Wallacea, New Guinea, New Caledonia, Polynesia and Micronesia and overlaps the global Small Islands category, which excludes Australia. The Small Islands category represents oceanic and continent-associated small islands, and thus overlaps with Oceania and continental data.

increase due to carbon dioxide fertilization, this may be compromised by drought (*low confidence*) (Ausseil et al., 2013). Seed production in native New Zealand beech forests is projected to increase due to climate warming, fuelling the abundance of invasive rats and stoats, which then predate native species and lead to loss of endemic fauna and flora (*medium confidence*) (Tompkins et al., 2013, Ch. 11).

About 80% of projections for assessed terrestrial species within insular biodiversity hotspots showed a negative impact of climate change, with ~50% at very high risk of extinction, including 100% of endemic species (*medium confidence*) (Figure CCP1.7; Manes et al., 2021). In addition to habitat loss and species range reductions, changes in precipitation are projected to be a major driver impacting tropical and subtropical island species (*medium confidence*) (Maharaj and New, 2013; Harter et al., 2015; Struebig et al., 2015; Vogiatzakis et al., 2016; Maharaj et al., 2018). Compared to continents, island species are projected to undergo greater impacts from changing climate, especially birds and amphibians (*high confidence*) (Fortini et al., 2015; Holmes et al., 2015; Manes et al., 2021, Box CCP1.1). Of all biodiversity hotspots, island species face the highest proportion of extirpation risk at high elevations due to decreasing habitat area (e.g., Brown et al., 2015) and at low elevations from sea level rise, habitat loss and introduced species (*medium confidence*) (Bellard et al., 2014a).

CCP1.2.3 Freshwater

The 53 hotspots in freshwater ecosystems assessed here cover about 32,830,000 km^2 (17% of global freshwater habitats and 22% of the global land area), with a 68% overlap with terrestrial ecosystems (Table CCP1.1; Figure CCP1.2). They include lakes, rivers and streams (Figure CCP1.12).

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Terrestrial biodiversity hotspots in the Americas, Asia and New Zealand

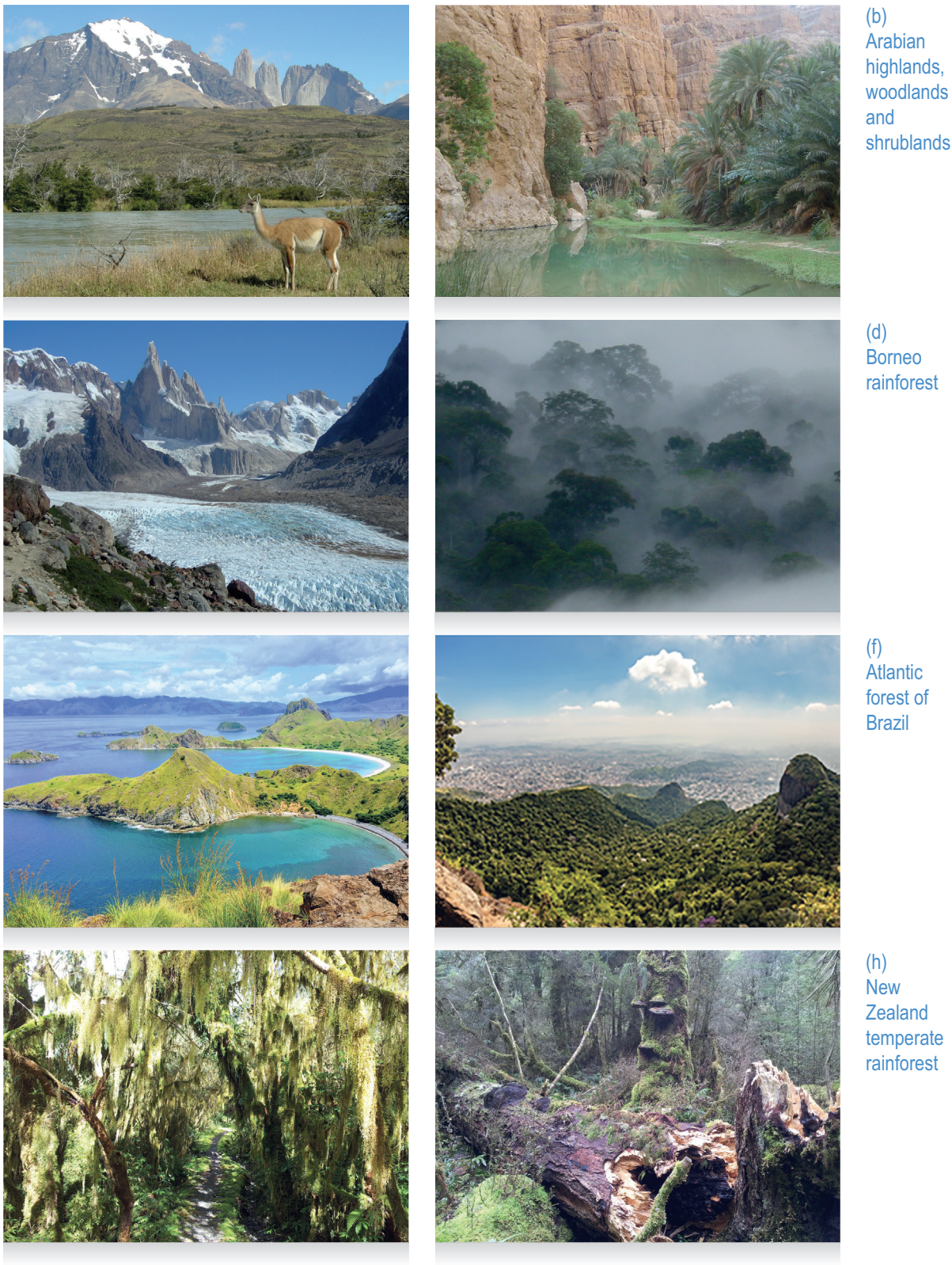


Figure CCP1.8 | Terrestrial biodiversity hotspots in the Americas, Asia and New Zealand. Photos by Denis Costello (top four), Mariana M. Vale (Brazil), and Mark Costello (other three).

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Polar and boreal biodiversity hotspots in the Arctic (Norway) taiga

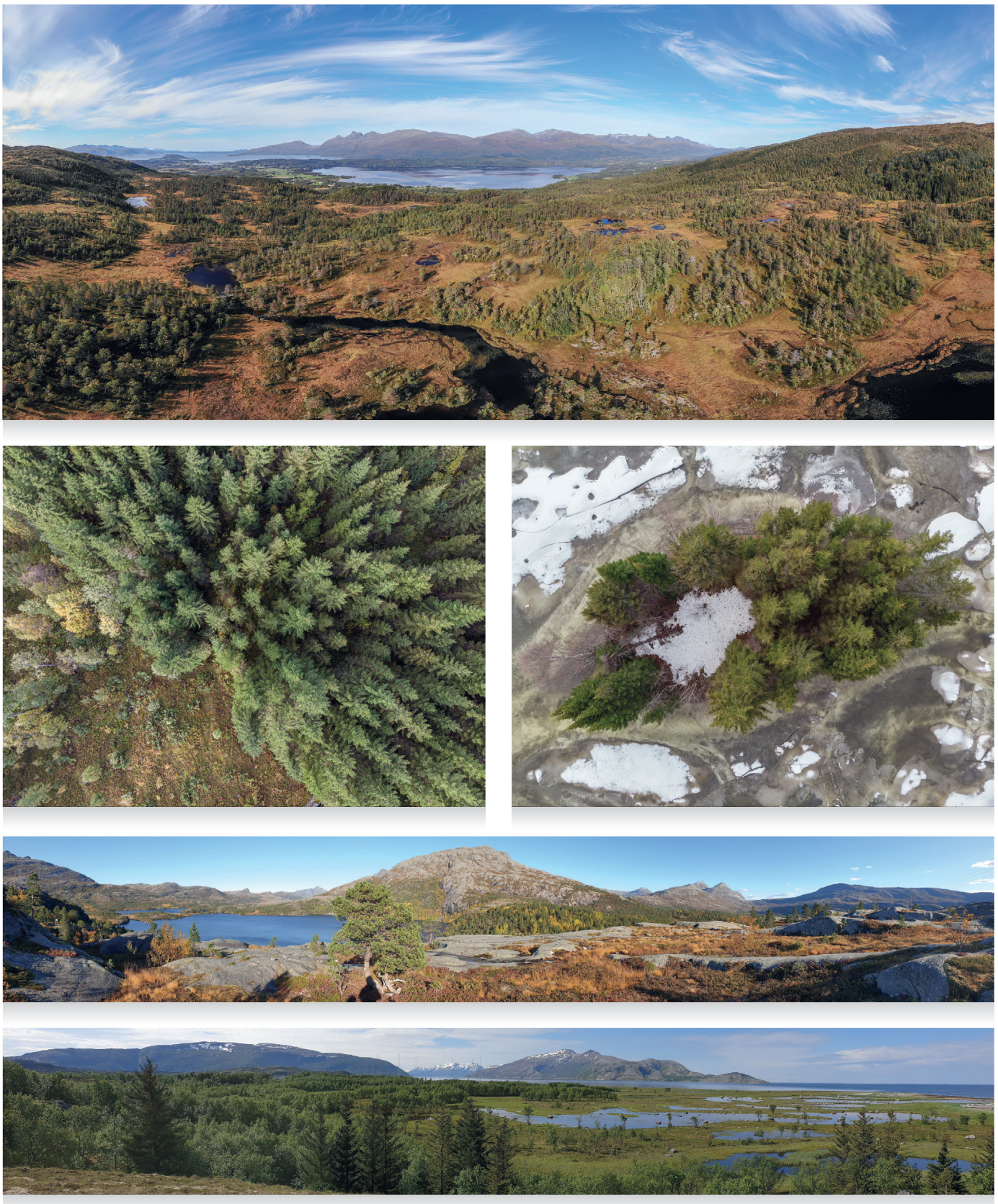


Figure CCP1.9 | Polar and boreal biodiversity hotspots in the Arctic (Norway) taiga. Photos by Galice Hoarau (top three) and Mark Costello (bottom two).

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African biodiversity hotspots.African biodiversity hotspots

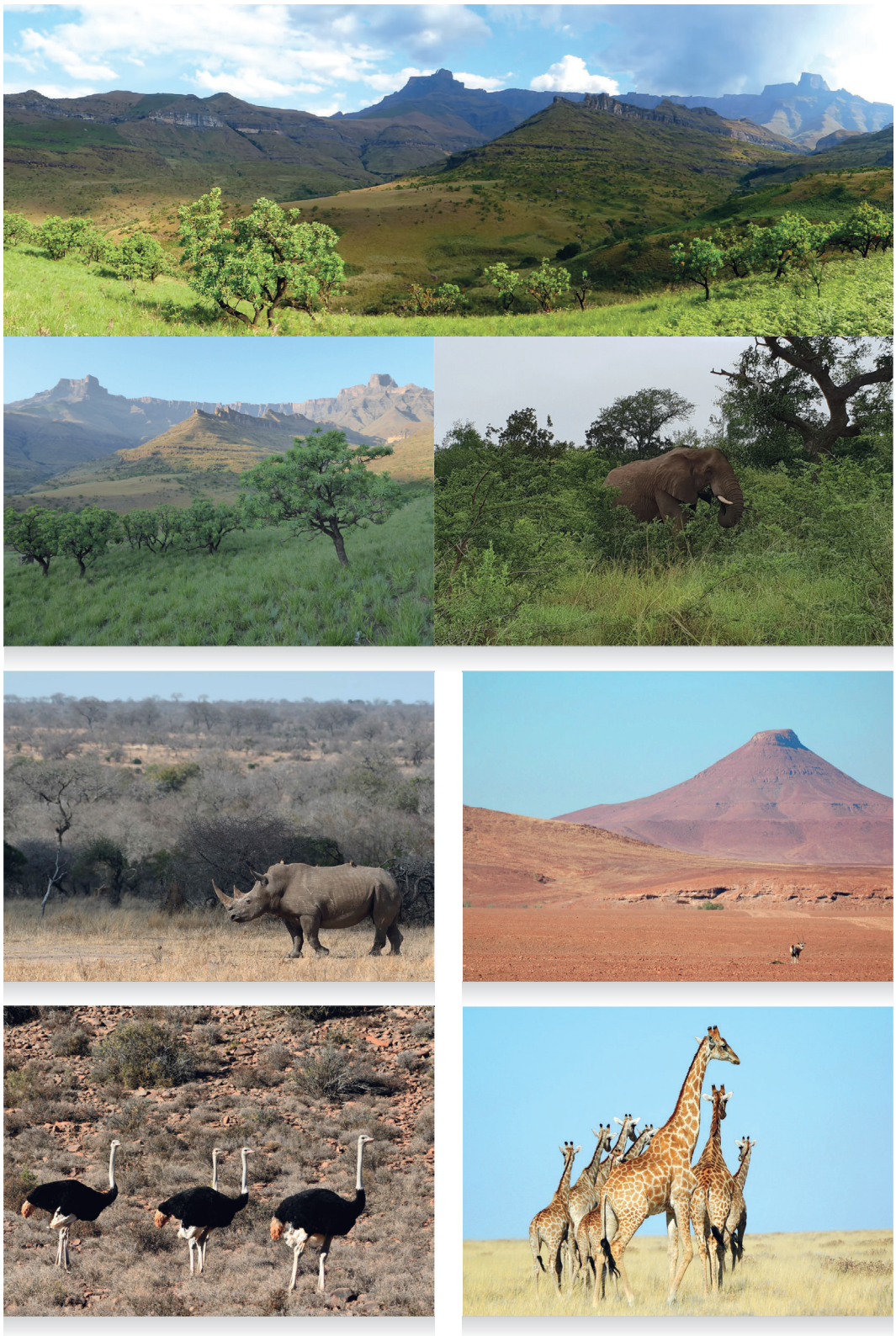


Figure CCP1.10 | African biodiversity hotspots. Photos by Denis Costello (top row and left second row) and Mark Costello (with elephant) for Drakensberg region, and Frank Zachos (lower four).

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Island biodiversity hotspots



Figure CCP1.11 | Island biodiversity hotspots. Photos by Galice Hoarau (top two) and Mark Costello (other four).

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CCP1.2.3.1 Observed Impacts

An analysis of trends in 190 river basins in Australia found that streamflows have been declining, including in the Central Australian (H194) and Kimberley (H191) hotspots, due to greater terrestrial plant uptake of water in response to climate-related increases in carbon dioxide (*low confidence*) (Ukkola et al., 2016). We did not find any other publications providing evidence of impacts of climate change on freshwater biodiversity within the hotspots. Whether this is because freshwater temperatures tend to be cooler due to inputs from groundwater and/or mountain streams (Knouft and Ficklin, 2017), resilience of freshwater species or lack of research is unclear.

CCP1.2.3.2 Projected Impacts

Cold-water species are projected to lose habitat in Canada and this may apply in the Alaskan river (H143) and Russian Far East Lake Inle (H181) hotspots (*medium confidence*) (Comte et al., 2013). Water abstraction is significant in the Colorado river hotspot (H145) and reduces its resilience to climate change effects on flow rates (Grafton et al., 2013).

In South America, in the Brazilian Amazon hotspot (H153, 154, 157), half the assessed fish species were considered sensitive to increased temperatures and reduced oxygen due to climate change (*low confidence*) (Frederico et al., 2016). The use of protected areas was recommended to reduce the impacts of deforestation and water pollution (Jézéquel et al., 2020). El Niño-related floods have led to declines in numbers of caiman, a top predator in the Brazilian Paraná river hotspot (H158), which indicates that increased floods due to climate change may reduce its population and alter food webs (Herrera et al., 2015).

In Europe, including the Mediterranean freshwater hotspots, climate change is projected to result in reduced river flow, low oxygen in summer, salinity incursions, further eutrophication and spread of invasive species, compromising the survival of native biodiversity (*medium confidence*) (Moss et al., 2009). The longer growth season in the boreal and Arctic latitudes is projected to aid the invasion of exotic species, and increase lake stratification resulting in lower oxygen below the hypolimnion (*medium confidence*). In addition, strict cold-water species are projected to lose suitable habitat (Moss et al., 2009). An analysis of 1648 species of freshwater fish, amphibians, turtles, plants, molluscs, crayfish and dragonflies, projected ~6% of common and ~77% of rare species to lose 90% of their geographic range (*low confidence*) (Markovic et al., 2014). Even if some species can spread to other areas and follow the climate, Markovic et al. (2014) projected a loss of species, especially molluscs, from the southeastern Mediterranean, including the Balkan biodiversity hotspot (H162) (*medium confidence*). Similarly, within Europe, Mediterranean fish (Jarić et al., 2019) and insects (Conti et al., 2014) are the most threatened by climate warming, droughts and floods. The fish species of the Danube river delta hotspot (H161) are less susceptible to climate change than in the Balkans (H162) and Anatolian (H163) hotspots. The rest of Europe, from the Iberian Peninsula to Scandinavia is not classified as a biodiversity hotspot. Thus, the areas where freshwater biodiversity is most threatened by climate change in Europe are in two of the three hotspots (*high confidence*).

The African Rift Valley Lakes (H171), including Lakes Tanganyika and Turkana, are suffering from climate change influenced drought, potentially impacting freshwater biodiversity (*medium confidence*) (Dudgeon et al., 2006). Africa and Madagascar (H172) are projected to see a climate-driven 10% reduction in freshwater flow that is projected to threaten the survival of ~9% of freshwater-dependent fish and birds (*low confidence*) (Thieme et al., 2010). Climate change is projected to increase the extinction vulnerability of most freshwater fish in the western South Africa Cape hotspot (H170) (*low confidence*) (Shelton et al., 2018).

In Asia, although climate change impacts on the Yangtze (H183) and Mekong river (H186) biodiversity hotspots have not been reported, they are subject to the range of human impacts of over-exploitation, pollution, water abstraction, altered flow regimes, habitat loss and spread of invasive species, which makes them more vulnerable to climate effects (*medium confidence*) (Dudgeon et al., 2006). The release of water from shrinking glaciers in Asia to some extent protects downstream freshwaters against drought, but half of these glaciers are projected to disappear by 2100 (*medium confidence*) (Pritchard, 2019).

In Australia, the Murray-Darling river basin occupies much of the Eastern Rivers hotspot (H195) and climate-related drought exacerbated by water abstraction is projected to drive declines in freshwater birds, fish and invertebrates (*high confidence*) (Grafton et al., 2013). However, a national scale analysis projected climate change to cause freshwater species range shifts, but no losses of species in this hotspot (*low confidence*) (James et al., 2017, WG2 Ch. 11).

CCP1.2.4 Marine

The 43 hotspots in marine ecosystems cover 46,600,000 km^2, representing 9% of the ocean area (Table CCP1.1; Figure CCP1.2). They include coral reef ecosystems, kelp forests, seagrass meadows, polar and upwelling zones (Figures CCP1.13; CCP1.14).

CCP1.2.4.1 Observed Impacts

Observed impacts attributable to climate change are strongly biased geographically, with most data from the temperate Northern Hemisphere, followed by subtropical to temperate Australia and few long-term data in the tropics (Poloczanska et al., 2013; Poloczanska et al., 2016). Marine heatwaves have increased over the past century, causing mass mortalities in the hotspots of the Mediterranean (H216), Great Barrier Reef (H236), western and southern Australia (H227, 228), northwest Atlantic (H207) and northeast Pacific (H197) (*high confidence*) (Hobday et al., 2018; Oliver et al., 2018). The shift of thousands of species from equatorial latitudes since the 1950s has been attributed to climate warming (*medium confidence*) (Chaudhary et al., 2021).

Climate change-related hazards, particularly marine heat events, have caused widespread coral bleaching and mass mortalities as the time between consecutive bleaching events decreases (*high confidence*) (IPCC, 2018; Bindoff et al., 2019; IPCC, 2019b). Coral reefs in some Indian Ocean hotspots (H230, 234) already exhibit net loss of coral reefs (*low confidence*) (Perry et al., 2018). While coral bleaching is a

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Freshwater biodiversity hotspots

(a) Headwaters of the Amazon Basin, Bolivia



(b) Bua River



(c) Lake Malawi

(d) Lake Titicaca, high Andes



(e) Riverbank in Borneo, Sundaland

(f) Mangroves in Papua New Guinea



Figure CCP1.12 | Photographs of freshwater biodiversity hotspots. Photos by Will Darwall **(b, c)**, Pablo Tedesco **(a, d)**, and Mark Costello **(e, f)**.

https://doi.org/10.1017/9781009325844.018 Published online by Cambridge University Press

visible symptom of heat stress, warming has also induced restructuring of associated fish and invertebrate communities in the Great Barrier Reef (H236) (*medium confidence*) (Stuart-Smith et al., 2018).

Although the number of coral species that are both exposed and vulnerable to climate hazards is greatest in the central Indo-Pacific, the proportion of corals at risk is greater in the lower diversity Caribbean hotspots (H209) (*medium confidence*) (Foden et al., 2013). Some reef corals are able to acclimate to heatwaves (*low confidence*) (DeCarlo et al., 2019), and some have expanded their latitudinal ranges polewards (*high confidence*), up to 14 km yr^{-1} in the northwest Pacific (Yamano et al., 2011). Although future latitudinal expansions may be limited by winter light availability (Muir et al., 2015), new coral reefs are already emerging in Japan (Kumagai et al., 2018).

The Mediterranean Sea hotspot (H216) is negatively affected by climate change (*high confidence*) (Cross-Chapter Paper 4). Species entering via the Suez Canal from the Red Sea (H220) are facilitated by warming and lead to profound community changes (*high confidence*) (Yeruham et al., 2015; Rilov, 2016; Vasilakopoulos et al., 2017; Givan et al., 2018; Bianchi et al., 2019). In contrast, the more open coastal seas of the Atlantic and Pacific coasts of North America have had increasing species richness since the 1970s (Batt et al., 2017).

Kelp forests are in decline in mid-latitudes due to warming and associated increased herbivory (*medium confidence*) (Section 3.4.2.3, Chapter 11). South and southeastern (H228), and southwestern (H227) Australia have experienced a climate-related decline of kelp forests (Wernberg et al., 2011; Vergés et al., 2016; Wernberg et al., 2016). West Australia (H227) has been affected by extreme climate events characterised by the replacement of kelp and sessile invertebrates by algal turfs and warm-water fish species (Wernberg et al., 2013; Wernberg et al., 2016). Australia's Great Barrier Reef (H236), kelp forests, seagrass meadows and mangroves (due to drought), have suffered mortalities due to climate change (*medium confidence*) (Babcock et al., 2019). Climate warming driven changes in seaweed assemblages have been reported not only in Australia, but in the marine biodiversity hotspots of Atlantic Canada, Japan, Mediterranean, New Zealand (Laffoley and Baxter, 2016; Thomsen et al., 2019; Thomsen and South, 2019) and California (H207, 231, 216, 238, 199) (Arafeh-Dalmau et al., 2019; McPherson et al., 2021). However, while climate change is having measurable effects on kelp, the dominant effects on kelp projected to 2025 are fishing, through its effects on herbivores and predators (*medium confidence*) (Steneck et al., 2002). Although fishing affected Atlantic cod in the Barents Sea (H214) and Gulf of Maine (H207) biodiversity hotspots, it was also affected by climate change, but negatively and positively, respectively (Kjesbu et al., 2014; Pershing et al., 2015).

Range expansions out of the Nansei Shoto (H231) hotspot south of Japan has led to the replacement of temperate kelp forests by tropical coral and herbivorous fishes on Japanese coasts (Kumagai et al., 2018). The Yellow Sea (H230) is one of the most exploited marine hotspots, with decreasing ecosystem services compounded by climate change but there is *low confidence* for climate change contributing substantially to ecological degradation (Wang et al., 2016; Song and Duan, 2019).

Upwelling systems are best known for bringing nutrients to the surface. These stimulate phytoplankton blooms, which in turn support important fisheries (Section 3.4.2.11). However, this deep water also tends to be low in oxygen, which can be further depleted by respiration and surface warming. Prolonged marine heatwaves in the Californian Current hotspot (H197) drove major shifts in the geographic range of birds, mammals, fish, crustaceans, molluscs and other species, and toxic algal blooms (Sanford et al., 2019).

In both the Antarctic (H213) and Arctic (H196, 214), the loss of ice impacts on the behaviour and foraging ability of marine mammals and birds (Doney et al., 2012). The retreat of sea ice in the Bering Sea (H196) hotspot has been followed by a reorganisation of the seabed and fish communities, a northward shift in species, and greater species' biomass and richness (Mueter and Litzow, 2008; Grebmeier et al., 2018). In the Eurasian Arctic (H214), species richness has similarly been increasing (Węsławski et al., 2011; Kortsch et al., 2012; Certain and Planque, 2015; Fossheim et al., 2015; Węsławski et al., 2018), as has phytoplankton productivity (Arrigo et al., 2008). The distribution of krill has already contracted with ocean warming in the Southern Ocean (*medium confidence*) (Cox et al., 2018; Atkinson et al., 2019).

CCP1.2.4.2 Projected Impacts

Tropical extirpations, already underway (Section 1.2.4.1), are projected to reduce hotspot diversity especially in the Coral Triangle (H226, 232, 234), Maldives (H224) and, to a lesser extent, in the Caribbean (H200, H210) (Jones and Cheung, 2015; García Molinos et al., 2016) and Persian Gulf (H219) (Wabnitz et al., 2018). Paleo evidence supports projections of tropical biodiversity loss under high global warming (*high confidence*) (Kiessling et al., 2012; Yasuhara et al., 2020).

Warm-water coral reefs are expected to decline with 1.5°C warming *(very high confidence*) (King et al., 2017; Bindoff et al., 2019) leading to systems with reduced biodiversity and structural complexity (*high confidence*) (Chapters 3; 11; Box 11.2). In the Coral Triangle, marine heatwaves are projected to have the same effect as an added mean annual 0.5°C sea surface temperature increase (McManus et al., 2020). While some corals are expected to survive in deep 'mesophotic' reefs (Laverick and Rogers, 2019), the shallow coral reefs of today will not last the century if climate warming continues without mitigation (*high confidence*) (Hughes et al., 2018a; Hughes et al., 2018b; IPCC, 2018; Bindoff et al., 2019; Hughes et al., 2019b).

In the Mediterranean, ocean acidification has been projected to lead to increases of fleshy algae at the expense of calcifying algae (Zunino et al., 2017). However, seagrass has been projected to decline (Chefaoui et al., 2018) and increase (Zunino et al., 2017) in the Mediterranean Sea hotspot (H216). Kelp forests are expected to decline in the northwest Atlantic (Grand Banks, H207), whereas gains and losses are projected to be approximately balanced in the Northeast Atlantic Shelf (H215) under Representative Concentration Pathway (RCP) 8.5 (Assis et al., 2018; Wilson et al., 2019), but may lead to impoverished benthic assemblages (Teagle and Smale, 2018).

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High latitude marine biodiversity hotspots

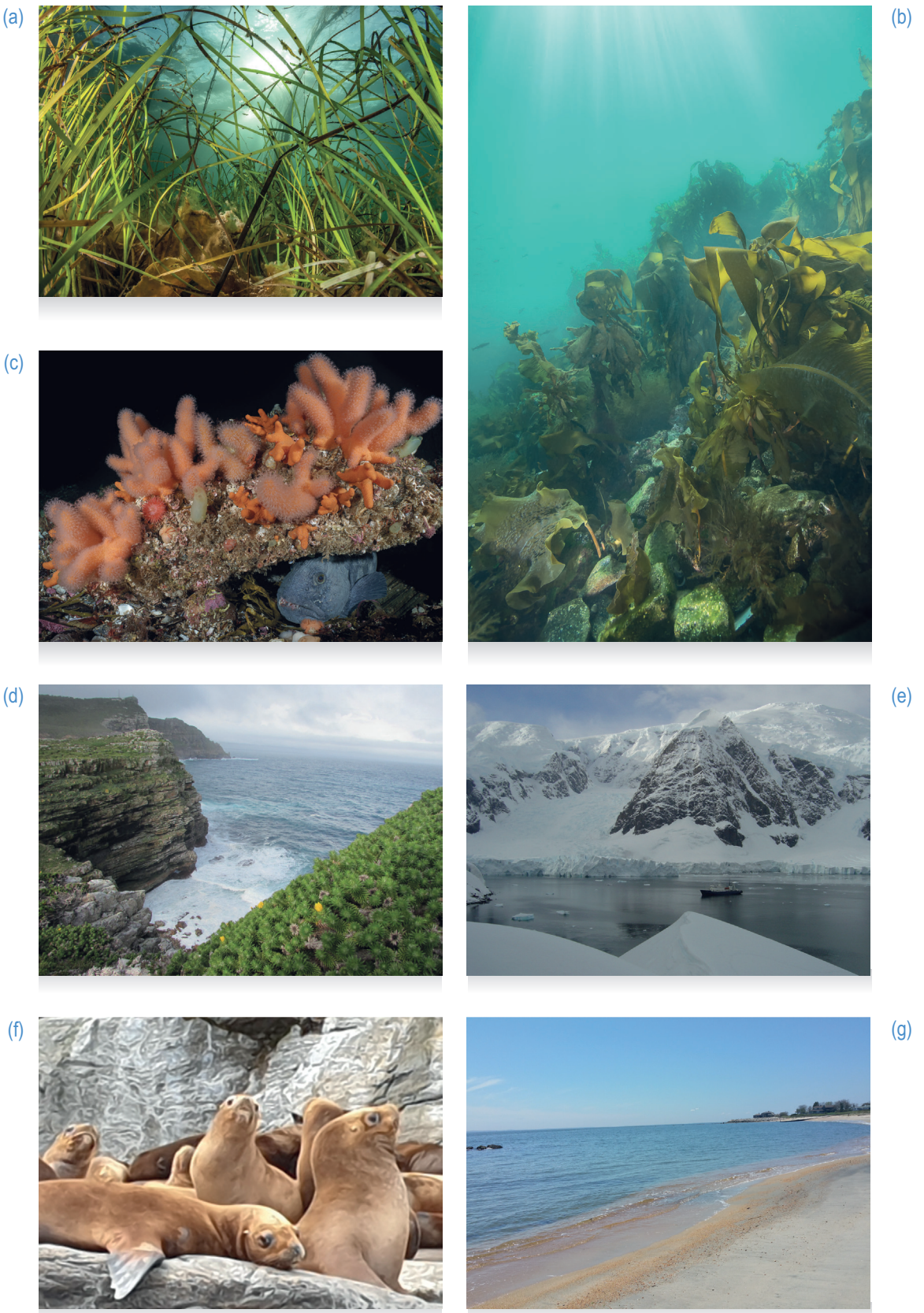


Figure CCP1.13 | High-latitude marine biodiversity hotspots. Northeast Atlantic temperate seagrass beds, soft-corals, and kelp forests in Norway (photos by Galice Hoarau). South African fynbos and Agulhas current and Antarctic Peninsula and Weddell Sea (photos by Denis Costello). In the Americas, the Humboldt Current Chile and Chesapeake Bay (photos by Mark Costello).

https://doi.org/10.1017/9781009325844.018 Published online by Cambridge University Press

Species in island coral and rocky reef biodiversity richspots

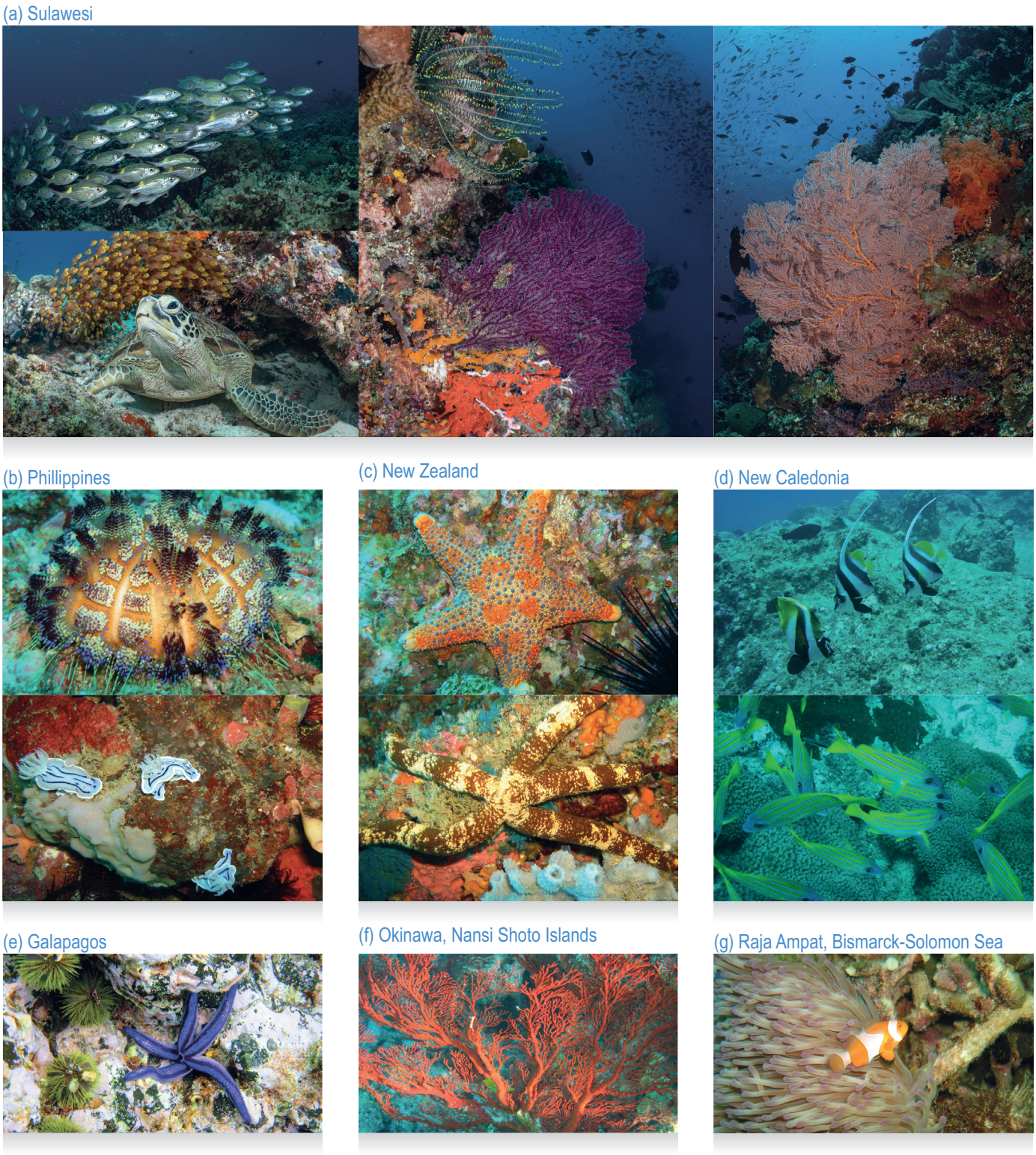


Figure CCP1.14 | Species in island coral and rocky reef biodiversity hotspots. Photos by Galice Hoarau (top four Sulawesi), and Mark Costello (other nine).

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Table CCP1.2 | Examples of adaptation actions that benefit the conservation of biodiversity and climate change mitigation.

Actions	Terrestrial	Freshwater	Marine
Protect biodiversity hotspots	Protect native forests, bush and grasslands	Stop pollution and sedimentation into streams, rivers, ponds and lakes	Ban seabed trawling and dredging
	Control introduction and spread of invasive species and pests		
Increase connectivity	Use riverbank and hedgerow corridors to connect protected native habitats		Already connected
	Reduce habitat and species loss outside protected areas to add species dispersal (corridors)		
Outside biodiversity hotspots	Environmentally sustainable agriculture, tourism and other land and freshwater uses		Environmentally sustainable aquaculture, fisheries and tourism
Restoration and recovery	Actively rehabilitate old mines, quarries and industrial lands	Stabilise riverbanks Remove weirs and artificial barriers to fish migration	Ban removal of marine life and habitat and fishing in selected areas to allow passive recovery of habitats, natural population structure, and food webs
	Reintroduce extirpated native species		
Reduce erosion, soil loss and flooding	Preserve, reduce degradation and restore habitats to enable uplands to absorb rainfall and reduce flash floods Protect sand-dune systems from erosion due to human and farm animal trampling Set aside land for salt marshes and mangroves to buffer against river and seawater flooding Link estuarine and upriver protected areas to provide more wildlife habitat and absorb storm surges and floods		
Urban development	Concentrate development to more cost efficiently manage transport and waste management infrastructure	Limit upland development where it may affect freshwater quality	Avoid construction in areas at risk of sea level rise and associated storm surges
Greenhouse gas mitigation	Prevent deforestation Reforestation (especially mangroves) Revegetation Fewer farm mammals Minimise release of greenhouse gases from soils	Expand wetlands to capture and deposit carbon in soils	Limit seabed disturbance by trawling and dredging that releases CO_2 and CH_4 Eliminate fishery subsidies and remove tax breaks on fuel for fishing boats
Carbon sequestration and preservation	Allow plants and other organisms to flourish and capture CO_2 from the air and water, and sequester it in biomass, soils and sediments		
	Manage forestry to maximise *in situ* food web biomass	Manage fisheries to maximise *in situ* food web biomass	
Social	Communicate information on the benefits of adaptation measures to the public		
Political and economic	Provide leadership and governance of mitigation and adaptation measures, including through regulations and economic incentives that guide the transition to a low carbon emissions economy		
Scientific	Address data gaps and make monitoring data and its meaning rapidly available to society so that the public and policy makers are informed of trends in biodiversity and related factors, including climate variables, extreme weather related events, threatened and invasive species, natural habitats, and their relationships		
	Conduct research to improve understanding of cause-effect relationships regarding environmental factors and biodiversity trends, including in nature conservation, forestry, agriculture, fisheries and food production sectors, and improve projections of consequences of management action and inaction		

Projected climate caused changes in biodiversity in coastal upwelling regions are uncertain. While productivity in the California Current (H197) system is projected to increase with future climate change, nonlinear plankton responses and uncertain interactions with food web dynamics hinder predictions of ecosystem responses (Xiu et al., 2018). In addition, this hotspot is projected to suffer from ocean acidification by 2050 (Gruber et al., 2012).

Around Antarctica (H213), almost half of all species are endemic (Costello et al., 2010), and warming during this century is projected to cause a reduction in suitable thermal environment for 79% of its species (RCP8.5) (*low confidence*) (Basher and Costello, 2016; Griffiths et al., 2017). The previously mentioned declines in Southern Ocean krill due to climate change contribute to projected declines in baleen whales there (Tulloch et al., 2019).

Species richness in the northern polar hotspots is expected to increase substantially (*high confidence*) (Cheung et al., 2015). However, population sizes of presently occurring native species are expected to decline, especially in the Barents Sea (H214) (Koenigstein et al., 2018). Ocean acidification is projected to continue globally, and while its impact is uncertain and projected to be less than the effect of warming, it may lead to changes in marine food webs due to varying effects on marine species (Terhaar et al., 2020). Hotspots in temperate latitudes are projected to have assemblages modified by immigration from the tropics and emigration to polar waters. Where land barriers and other geographical limits to range shifts occur, limited dispersal and habitat fragmentation may also limit the capacity of some species to track climate velocities, such as in the Baltic Sea (H215) (Jonsson et al., 2018), Mediterranean Sea (H216) (Burrows et al., 2014; Arafeh-Dalmau et al., 2021) and Antarctica (H213) (*medium confidence*) (Cristofari et al., 2018).

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CCP1.3 Adaptation and Solutions

Terrestrial, freshwater and coastal marine ecosystems are impacted by the 3 billion people that currently live in in biodiversity hotspots (Gutiérrez et al., 2021). At the same time, biodiversity in hotspots supports the livelihoods of the local communities. The suite of adaptation options for biodiversity are as applicable inside as outside hotspots (Table CCP1.2). Many of these hotspots are now faced with widespread fragmentation and habitat degradation (*high confidence*) (Table SMCCP1.1).

Because projected changes in biodiversity increase disproportionately with warming, climate change mitigation is the primary action to conserve biodiversity within hotspots. If global warming is kept within the 1.5°C limit of the Paris Agreement, just ~4% of endemic species in biodiversity hotspots would be threatened with extinction from climate change. However, at the current commitments there is projected to be ~3°C warming by 2100 and ~20% and ~32% for terrestrial and marine species, respectively, fall into the category of very high extinction risk (Figure CCP1.6; Manes et al., 2021).

Although mitigation can sharply reduce extinction risk associated with climate change (*high confidence*), it cannot reduce all of the risk, nor the risk associated with other drivers that can have a compound effect with climate change. Thus, in addition to mitigation, the literature consistently calls for reducing current non-climate impacts (e.g., habitat conversion, over-exploitation, hunting, fishing, wildfire, pollution, human-introduced invasive species) in order to increase biodiversity resilience to climate change (*very high confidence*) (Table CCP1.2; e.g., Mantyka-Pringle et al., 2015; Warren et al., 2018a; Costello, 2021). The main strategies to increase resilience rely on the combination of well-planned protected areas, restoration of degraded areas and the sustainable use of biodiversity (*high confidence*) (IPCC, 2019a; Pörtner et al., 2021) . On land, creating corridors for species is key for facilitating species movements (*high confidence*) (McGuire et al., 2016; Heikkinen et al., 2020; Pörtner et al., 2021). Habitat protection has numerous co-benefits, including potential climate mitigation through carbon storage and sequestration, in addition to climatic regulation (Alkama and Cescatti, 2016; Mackey et al., 2020) and pandemic prevention (Allen et al., 2017; Dobson et al., 2020, Cross-Chapter Box COVID-19 in Chapter 7).

Active relocation of endangered species to areas where they may be safer from predation and human impacts, as already practised for a few charismatic fauna, is expensive and fraught with complex regulations and concerns over impacts on native species (Brodie et al., 2021). Therefore, managed relocation of species threatened by climate change is questionable for most species.

Healthier marine ecosystems are more resilient to additional stressors, such as storms and climate change (*high confidence*) (Isbell et al., 2015; Duffy et al., 2016; Roberts et al., 2017; Bates et al., 2019; Mariani et al., 2020; Costello, 2021; Donovan et al., 2021). Extinction risk is lower when populations are larger and more genetically diverse, individuals are larger and older, and seabed habitats (e.g., coral, kelp, seagrass) are flourishing, as occurs in marine reserves (*high confidence*) (Costello, 2014; Roberts et al., 2017; Bates et al., 2019; Costello, 2021). Similarly, global fish biomass may be less affected by climate change if biodiversity is greater (Duffy et al., 2016). Thus, a network of reserves representative of global biodiversity, helps attenuate the effects of climate change (*medium confidence*), for example, by having more abundant fish and top predator populations (Roberts et al., 2017; Beyer et al., 2018; Carter et al., 2020; Sala et al., 2021). However, the impacts of marine heatwaves on corals across marine reserves illustrates that enhanced resilience is not enough to protect against extreme and future climate change conditions (*high confidence*) (Bruno et al., 2018; Hughes et al., 2018a; Kleypas et al., 2021).

Mangroves occupy the interface of terrestrial, freshwater and marine environments, dominate in eight hotspots (Table CCP1.1) and are connected to or integral habitats within one-third of all terrestrial and freshwater, and two-thirds of marine, hotspots (Figures CCP1.1; CCP1.2). A global analysis of sediment cores from mangroves indicated that mangroves can accrete sediment at levels of sea level rise projected under low emission scenarios, but may decline at their seaward edge under high emission scenarios (Saintilan et al., 2020, Chapter 3.4.2, Cross-Chapter Box Sea-level rise). However, even if this seaward erosion occurs, the expansion of mangroves inland due to sea level rise will increase carbon sequestration, because they capture carbon from seawater and freshwater runoff, in addition to photosynthesis, into their underlying sediments. If coastal management permits the expansion of mangroves inland with rising sea level, this will increase carbon sequestration because mangroves capture and preserve more carbon in their sediments than other terrestrial and marine forests and biomes (*high confidence*) (Table CCP1.2; Alongi, 2020; Goldstein et al., 2020; Lovelock and Reef, 2020; Saintilan et al., 2020).

On land, fragmentation and habitat degradation are particularly pervasive, imposing hard limits to adaptation of terrestrial and freshwater ecosystems (Ibisch et al., 2016; Lenoir et al., 2020; Mechler et al., 2020). Thus, the protection of existing natural habitats coupled with the restoration of the surrounding non-protected habitat can increase the effectiveness of adaptation strategies in terrestrial and freshwater hotspots (*very high confidence*) (Table CCP1.2; IPCC, 2019a; Jung et al., 2021). Additionally, strategic allocation of new protected areas within gaps across elevational and climatic gradients could enhance biodiversity conservation across hotspots. This would align with Target 3 of the Convention on Biological Diversity's post-2020 draft Global Biodiversity Framework, and could include underrepresented climate and elevation spaces as well as potential climate refugia currently not under protection (Pörtner et al., 2021). In terrestrial ecosystems, restoration initiatives can help sustain biodiversity, improve resilience in a changing climate, and avoid maladaptation by selecting appropriate native species to be planted (Cross-Chapter Box Bioeconomy in Chapter 5; (Gann et al., 2019). In freshwater ecosystems, conservation needs catchment level management of human activities (Saunders et al., 2002; Dudgeon et al., 2006), especially as 37% of the terrestrial biodiversity hotspots overlap with freshwater (Figure CCP1.2) and 23% border marine hotspots (Olson and Dinerstein, 2002).

Protecting biodiversity hotspots is a pragmatic way to conserve biodiversity that is representative of a substantive fraction of genetic and species diversity on Earth (Mittermeier et al., 2011) while achieving

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co-benefits (Bonan, 2016; Sala et al., 2021). Protecting hotspots also helps protect important ecosystem services. In a global ranking of areas that combine biodiversity conservation while maximising carbon retention and water quality regulation, for example, the terrestrial and freshwater hotspots assessed here ranked high (41st and 34th on average, respectively, on a scale of 100) (Jung et al., 2021). The solutions needed to reverse biodiversity decline are well known and articulated in numerous international agreements and goals, such as the Convention of Biological Diversity the United Nations' Sustainable Development Goals, the Nationally Determined Contributions under the Paris Agreement, the International Union for Nature Conservation's Bonn Restoration Challenge and the Ramsar Convention on Wetland Conservation. Thus, expanding and enhancing protection of a worldwide network of fully protected areas and protection and restoration of non-protected areas representative of the biodiversity hotspots, including marine, freshwater and terrestrial environments, is a highly recommended adaptation strategy to increase resilience of biodiversity to climate change (Brito-Morales et al., 2018). However, adaptation strategies alone cannot protect biodiversity from climate impacts without complementary and concomitant reduction of greenhouse gas emissions.

Box CCP1.1 | Climate change and terrestrial biodiversity hotspots on small islands

Despite covering approximately 2% of the Earth's land area, islands harbour more than 20% of extant terrestrial species (Wetzel et al., 2013). Islands have disproportionately higher rates of endemism and threat when compared to continents, with 80% of historical extinctions (since 1500 CE) having occurred on islands (*high confidence*) (Taylor and Kumar, 2016; Spatz et al., 2017; Dueñas et al., 2021). Current climate change projections suggest that insular species are particularly sensitive and, even at mild warming levels, substantial losses are expected (*high confidence*) (Pouteau and Birnbaum, 2016; Taylor and Kumar, 2016; Dawson et al., 2017; Manes et al., 2021). Given islands' characteristic high endemicity, current high threat levels and the fact that islands host almost half of all species currently considered to be at risk of extinction, especially at higher warming levels (*high confidence*) (Taylor and Kumar, 2016; Spatz et al., 2017), further losses could contribute disproportionately to global biodiversity decline (*medium evidence, high agreement*) (Harter et al., 2015; Pouteau and Birnbaum, 2016; Manes et al., 2021).

The high vulnerability of terrestrial biodiversity on islands to global change can be explained by a number of limitations, characteristic of both islands and insular species. Older, isolated islands tend to have fewer species and lower functional redundancy but a higher proportion of endemism (Pouteau and Birnbaum, 2016; Médail, 2017). Many of these islands contain species with inherently high sensitivity to environmental change (narrow habitat ranges, small population sizes, low genetic diversity and poor adaptive, dispersal and defensive capabilities) (Harter et al., 2015). Unlike continental environments, insular species often have limited opportunities for autonomous adaptation from not having enough geographic space to shift their ranges to track suitable climatic conditions (*high confidence*) (Fortini et al., 2015; Manes et al., 2021). Local extinction risks are amplified by even small losses of habitat due to global change including human-induced disturbances, extreme events, sea level rise (Chapter 15; Cross-Chapter Box SLR in Chapter 3) and invasive species.

However, some insular species have shown resilience to climate change. Intact island forests, for example, have shown rapid recovery rates after tropical cyclones, despite high levels of initial damage, especially in the Caribbean (*medium confidence*) (Luke et al., 2016; Richardson et al., 2018). Additionally, many Mediterranean islands are 'disturbance adapted', with continued persistence of some single-island endemic plants, despite exposure to multiple threats (Vogiatzakis et al., 2016). This continued persistence has been attributed, at least partially, to climate refugia, oceanic buffering and high habitat heterogeneity within topographically complex mountainous regions (Pouteau and Birnbaum, 2016; Médail, 2017, Chapter 15, Table 15.1). However, this climate resilience will not be sustained under climate change, especially when coupled with habitat degradation (*high confidence*) (Wiens, 2016).

Adaptation strategies depend on the ability to project future impacts from climate change, but this is hampered by lack of fine-scale climate data, especially for developing small island nations. There is a paucity of robust impacts-based modelling output for terrestrial biodiversity from these islands due to the wide, chronic unavailability of Regional Climate Model (RCM) data premised on the most recent suite of scenarios (RCPs and especially SSPs) *(medium evidence*, *high agreement*) (Gutiérrez et al., 2021, Ch.15.8; Pörtner et al., 2021; WMO, 2021). Additionally, realistic assessments of changing climate on such small ecosystems require further RCM downscaling and verification to sub-island resolutions of <5 km. Furthermore, widely used statistically (bias-corrected) downscaled data at sub-5 km resolutions, such as WorldClim are often unsuitable due to limited spatial and temporal resolutions of observation station data from small islands (Maharaj and New, 2013; Gutiérrez et al., 2021) and higher errors associated with statistical downscaling and locations with complex topography and coastlines (Fick and Hijmans, 2017; Lanzante et al., 2018). Widespread unavailability of such data constrains accurate simulations of climatic variation within the small-scale mountainous and coastal regions of islands, associated with climate refugia and high habitat heterogeneity (*high confidence*) (Balzan et al., 2018). This is a key element contributing to the continued delay in development of robust adaptation strategies towards not only biodiversity conservation but other important cross-sectoral issues (*medium confidence*) (Robinson, 2020b).

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Box CCP1.1 (continued)

Due to islands' limited size and isolation, conventional conservation measures focused on expanding protected areas, dispersal corridors and buffer zones are of limited effectiveness on islands (*high confidence*) (Vogiatzakis et al., 2016). Instead, multifaceted, locally driven holistic climate-smart strategies across mosaics of human-impacted, often heavily degraded and fragmented, landscapes are required. These should ideally be long-term, flexible and sustainable solutions that incorporate social and biocultural knowledge as well as economic co-benefits to island communities in order to 'buy time' (Betzold, 2015; Robinson, 2020a). Examples include ecosystem-based approaches such as ridge-to-reef management (Struebig et al., 2015; Ferreira et al., 2019, Figure CCP1.15.4), which incorporates conservation partnerships among lands inside and outside protected areas to increase connectivity and reduce land use impacts, while building on the interconnections among terrestrial, freshwater, coastal and marine ecosystems. Such strategies require raising awareness of biodiversity values among local communities, and cross-sectoral planning and policy at both island, regional and trans-boundary scales. These lend to private–public partnerships, increasing the potential of solutions reaching beyond protected areas boundaries and affecting socio-political change (*high confidence*) (Scobie, 2016).

Limited terrain, natural, economic and data resources across small developing nation islands mean that unconstrained habitat destruction and degradation cannot be sustained, as this harms both people and the biodiversity upon which they depend. This limitation of resources compromises climate adaptation, which is often further complicated by varying governance and states of economic development (Petzold and Magnan, 2019). With changing climate conditions, there is an increased urgency to re-think how progress can be measured, and to create opportunities building on synergies between disaster risk reduction, food security and social justice, so that islands can most benefit from their natural resources and biodiversity in a sustained manner (Box 15.2; Section 15.3.4.4).

Frequently Asked Questions

FAQ CCP1.1 | Why are biodiversity hotspots important?

Biodiversity hotspots are regions that are exceptionally rich in species, ecologically unique and which may contain geographically restricted species. They are thus priority targets for nature conservation.

Recognising that the Convention on Biological Diversity definition of biodiversity includes the variation within and between species and of ecosystems, different schemes have been applied to define hotspots, leading to hundreds of different areas being proposed as hotspots. However, all identify a set of priority areas that cover a small portion of the Earth, but house an exceptionally high proportion of its biodiversity. Because biodiversity underpins all life on Earth, these hotspots have significant global value as they contain species and habitats that are found nowhere else. Their loss would mean loss of species and habitats that provide wild and farmed food, medicine and other materials, and services such as climate regulation, pollination and water purification, all of which maintain the health of the ecosystems we depend upon.

Healthy ecosystems, with flourishing biodiversity in natural conditions, are more resilient to disturbances, whether natural or human in origin. Environmentally sustainable development inside and outside hotspots could help reverse human impacts on biodiversity. The hotspots also capture and store carbon, thereby helping to mitigate climate change. Prioritisation of protecting biodiversity in hotspots thus benefits nature conservation and helps mitigate climate change. A global network of protected areas and restoration initiatives inside biodiversity hotspots can also help increase resilience to the effects of climate change on biodiversity.

https://doi.org/10.1017/9781009325844.018 Published online by Cambridge University Press

Frequently Asked Questions

FAQ CCP1.2 | How can society ensure conservation of biodiversity in climate policies?

To reduce the effects of climate change on biodiversity, it is first essential to address direct human impacts that are already leading to a loss of biodiversity. This can be achieved by protecting biodiversity in conservation areas, restoring biodiversity everywhere possible and promoting sustainable development. Climate policies should thus integrate with policies to protect and restore nature.

Avoiding further loss of biodiversity is implicit in sustainable development. This needs to happen on land, rivers, lakes and in the oceans. It is especially important in 'biodiversity hotspots' (FAQ 1.1) and protected areas to minimise species losses. Hence calls by the International Union for the Conservation of Nature, Convention on Biological Diversity, United Nations Sustainable Development Goals (SDGs) to increase the size and connectivity of fully protected areas (which aim to have biodiversity in a near natural condition) and include in them the biodiversity hotspots, need to be immediately implemented.

Five of the SDGs are life on land, life below water, good health and well-being, food security and climate action. They underpin and interact with many other SDGs. Healthy ecosystems play a role in mitigating greenhouse gas emissions, not only protecting areas to prevent the release of carbon through land conversion activities but also restoring otherwise degraded land. The United Nations has declared 2021–2030 as the Decade on Ecosystem Restoration and the Decade of Ocean Science for Sustainable Development. Restoration means actively or passively allowing habitat to return to its natural state (e.g., grassland, forest, peatland, oyster beds), including replanting native vegetation. This can benefit the recovery of biodiversity, help remove carbon dioxide from the atmosphere and improve the delivery of nature's contributions to people, such as climate regulation, water purification, pollination, and pest and disease control. Thus, protecting biodiversity helps to meet two SDGs directly, and three indirectly.

On land, the loss of natural forests and grasslands not only means a loss of carbon and many of their associated species, but exposes soils to erosion, affecting food production, and can affect the climate by altering the water cycle. Sustainable development, even within hotspots, involves active restoration of natural biodiversity, reducing poaching and trafficking of wildlife (UN SDG 15), and needs to include agriculture. This includes working to ensure biodiverse soils and supporting healthy pollinator populations. Biodiversity includes not only wild species but also genetic diversity, including crops and wild crop relatives. These wild relatives may contain important genes that could help farmed crops survive better in a changed climate. At least some of these wild relatives come from areas designated as hotspots. In the ocean, sustainable development means reducing pollution, carefully managed aquaculture development, increased protected areas (from the present 2.5% of the ocean area), enforcement of fisheries regulations, and removal of fishery subsidies that perpetuate overfishing within Exclusive Economic Zones and on the High Seas (UN SDG 14). Generally, the use of freshwaters, rivers, lakes and groundwaters, has not been sustainable and there is a need to restore biodiversity and water quality by eliminating pollution and to better manage abstraction, river flows, fishing and invasive species. Thus, as is the case with land and oceans, climate policies must prioritise the restoration of freshwater biodiversity, and reduction of the current negative impacts of human activities.

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