

1 Chapter 10: Nature and Climate Change in 2 the US

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DRAFT

1 Summary

2 Earth is rapidly warming, largely as a result of human-caused greenhouse gas emissions
3 and changes in land use and land cover, especially deforestation (1). Currently, nature
4 provides an enormous benefit by sequestering more than half of annual human-caused
5 carbon dioxide emissions (2). The continuation of this sequestration depends on the health
6 of the ocean and of ecosystems on land. It also depends on the success of efforts to limit
7 warming: higher temperatures have already contributed to increased wildfire, leading to
8 carbon loss in US forests (3) and eutrophication of inland and coastal waters that
9 accelerates greenhouse gas emissions.

10 The US is warming faster than the global average. Nature is impacted substantially by this
11 warming at the same time it is also impacted by human land use, pollution, and invasive
12 species. Nature's responses to human-caused warming are widespread at all levels, from
13 changes in gene frequencies to the productivity of the global biome. Many of these
14 responses serve to improve the ability of organisms to survive. However, novel interactions
15 and limits to organisms' abilities to adapt can lead to substantial degradation of
16 biodiversity and ecosystem functioning.

17 Nature has the potential to be a powerful ally in the quest for climate solutions. Nature-
18 based solutions can support diverse modes of adaptation, from providing shade to
19 absorbing wave impacts, often at lower costs than engineering-based alternatives. Nature-
20 based climate solutions provide some of the lowest-cost options for reducing emissions
21 and removing existing greenhouse gases from the atmosphere, while also supporting a
22 wide range of co-benefits in environmental quality and rural livelihoods (4). Nature-based
23 solutions for adaptation and nature-based climate solutions cannot completely solve the
24 climate crisis, but they open doors to positive contributions consistent with sustaining
25 both nature and people. Success in capitalizing on this potential will require continued
26 research, ambitious deployment, and adaptive management based on learning from
27 experience.

28 Background

29 Earth's Rapidly Changing Climate

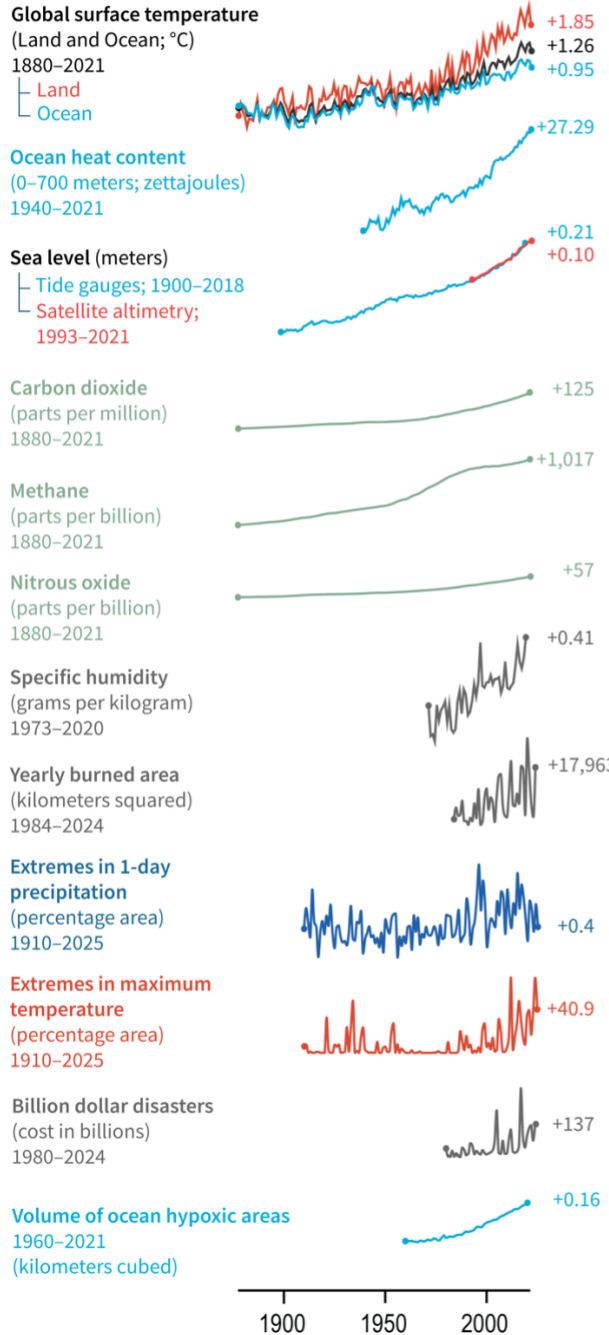
30 Humans are increasing atmospheric concentrations of greenhouse gases (primarily carbon
31 dioxide, CO₂; methane, CH₄; and nitrous oxide, N₂O), mostly through the burning of fossil
32 fuels and agricultural practices (Figure 10.1) (5,6). Compared to CO₂, N₂O is 273 times
33 more effective in trapping heat over century time scales, and CH₄ is 27–30 times more
34 effective (7). Accumulation of these greenhouse gases (GHGs), which are mostly well
35 mixed in the atmosphere, changes the balance of incoming solar energy and outgoing heat
36 radiation and rapidly warms Earth's surface (5,6). Today's atmospheric GHG
37 concentrations are higher than at any point in the history of human life (8,9) and continue
38 to rise (10).

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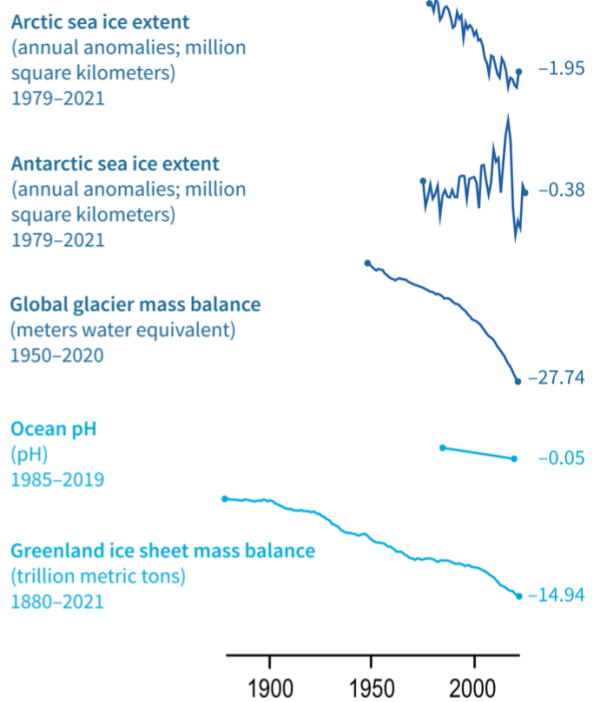
1 **Figure 10.1. Evidence for Climate Change Across Multiple Variables**

Evidence for Climate Change Across Multiple Variables

Increasing trends



Decreasing trends



2

3 **Climate change is apparent in many aspects of the Earth system.**

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1 *Data for a variety of key variables show rapid warming of the atmosphere and ocean and*
2 *corresponding changes in other aspects of the climate system. Many of these changes are*
3 *evidence of the human influence on the climate, reflecting the current scientific*
4 *understanding of how the planet responds to external influences (Ch. 3). Global changes*
5 *between the start and end of each time series (maximum range: 1880–2021) are shown as*
6 *numerical values to the right of each chart and are calculated by fitting each time series*
7 *with a localized linear regression with a bandwidth of 30 years. Adapted from Marvel et al.*
8 *2023 (11).*

9 The Integrated Earth System

10 The Earth system includes the atmosphere, the lithosphere (land and solid Earth), the
11 hydrosphere (water), the cryosphere (ice), and the biosphere, all of which are globally
12 linked and interact in the cycling of energy, water, and life-sustaining elements, including
13 carbon. Interactions between nature and the other components of the Earth system can
14 absorb or increase atmospheric CO₂, CH₄, and N₂O. Nature on land and in the ocean
15 (where the mechanisms include both living and non-living components) provide the
16 majority of Earth's carbon sinks; globally absorbing about 56% per year of CO₂ emissions
17 from human activities (KM 10.2) (9).

18 Changes to the climate system that affect average conditions as well as extreme events are
19 happening at unprecedented rates measured across a wide array of indicators, including
20 increasing average and seasonal temperatures, more frequent heat waves, changes to
21 average and heavy precipitation, intensity of storms and cyclones, flooding and drought,
22 increasing ocean heat content, decreasing ocean pH and oxygen, loss of sea ice, and sea
23 level rise (5). The continental US is warming faster than the global average (5). Across the
24 US, extreme heat events are increasing in frequency and intensity, and extreme cold events
25 are decreasing (5).

26 Rising temperatures are driving changes in the water cycle. Variability in precipitation is
27 increasing, leading to increases in both extreme precipitation and drought. In the US, more
28 precipitation is falling as rain and less as snow. Precipitation associated with hurricanes is
29 also increasing (5). Changes to temperature, precipitation, and winds are increasing the
30 rate of water movement between terrestrial ecosystems and the atmosphere through
31 increased **evapotranspiration**. The amount of water stored in the cryosphere (glacier ice,
32 seasonal snowpacks, and **permafrost**) is declining as the climate warms (12). The
33 continents, including the US, are drying out—that is, storing less water in vegetation, soils,
34 and aquifers—and now contribute more water to sea level rise than does melting of the ice
35 sheets (13,14).

36 Evapotranspiration increases with warming, leading to drier soils and surfaces, amplifying
37 drought and increasing wildfire risk (5,15,16). Large-scale wildfires can, in turn, profoundly
38 impact carbon storage capacity on land (17,18).

1 Oceans absorb a large proportion of **anthropogenic** CO₂ (i.e., CO₂ from human activities;
2 KM 10.2), leading to **ocean acidification**, which disrupts carbonate chemistry important
3 for ocean animals to build shells and skeletons. The ocean also continues to absorb
4 excess heat (KM 10.2). Extreme marine heat wave events are becoming more widespread
5 and increasing in duration and temperature in most US coastal waters, most notably in
6 recent years in the waters off the northeastern US and Alaska (19,20). Globally in 2023,
7 marine heat waves covered the largest total ocean area on record (10). Warming has other
8 cascading effects on ocean systems. For example, oxygen (O₂) is less soluble at higher
9 temperatures, and ocean warming reduces the mixing of O₂ into deeper waters. Both
10 processes reduce the levels of O₂ in the ocean. Exchange of colder and warmer ocean
11 waters sustain major vertical and horizontal ocean currents. Warming can impact these
12 currents with impacts to ocean life, weather, storm tracks, and sea level rise.

13 **Thermal expansion** of warmer waters contributes to sea level rise. In addition, ice on land
14 and the seas is melting, although there are uncertainties regarding how quickly this is
15 happening. Melting of ice on land contributes to sea level rise. The decline in sea ice affects
16 many critical functions: sea ice helps regulate climate by reflecting solar radiation, it
17 inhibits ocean–atmosphere exchange of heat and gases, and it supports deep ocean
18 circulation. Melting of land ice and thermal expansion of ocean waters will continue to lead
19 to sea level rise as well as high-tide and storm-induced flooding, impacting both nature
20 and human communities along US coasts. On average across the US coastline, sea level
21 has risen about 11 inches (28 cm) over the past 100 years (since 1920), with about half of
22 that rise occurring over the last 30 years (21). Sea levels are rising faster along the East and
23 Gulf Coasts than the West Coast because of variation in ocean currents and wind patterns,
24 whether land masses are sinking or rising, natural accretion of soils in wetlands, and local
25 variation in ocean temperatures.

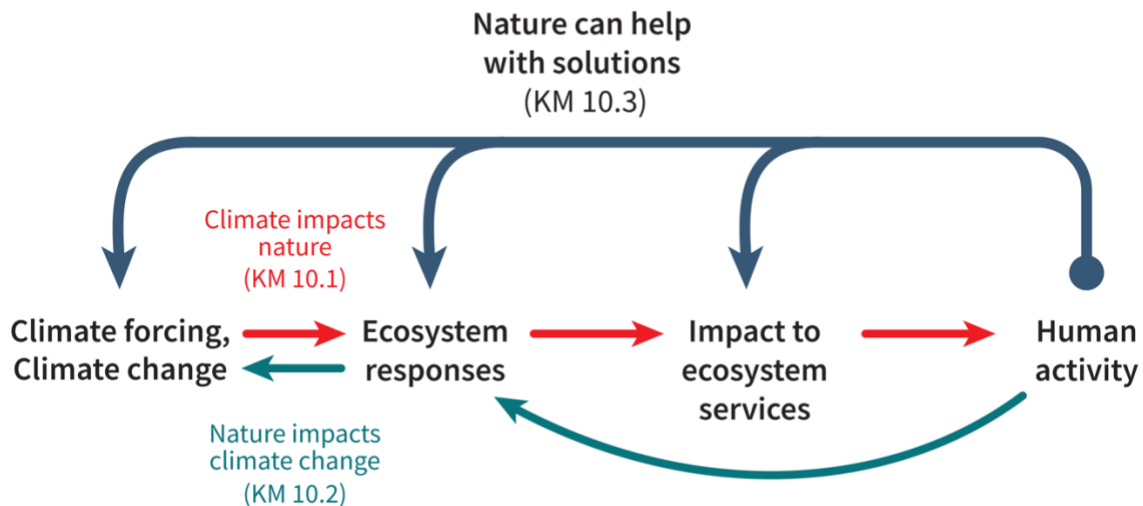
26 **Thresholds and Tipping Points**

27 Changes in physical conditions may be gradual or abrupt as thresholds or tipping points in
28 Earth’s climate system are reached, such that aspects of the system undergo large, rapid,
29 or irreversible changes. This can occur when changes in a process become self-reinforcing.
30 For example, in the Arctic, melting sea ice decreases surface albedo (the portion of the
31 sun’s energy that is reflected rather than absorbed) of northern oceans, increases heat
32 storage, and accelerates warming of the oceans in northern latitudes (10). During the last
33 ice age, 26,000 to 12,000 years ago, abrupt shifts between cold and warm phases were
34 amplified by interactions among sea ice, ocean circulation, and atmosphere dynamics.
35 Examples of potential future climate tipping points include abrupt changes to global
36 atmospheric and ocean circulation, rapid or irreversible loss of the polar ice sheets,
37 collapse of tropical rainforests, and release of carbon dioxide and methane from melting
38 permafrost. There are significant knowledge gaps and uncertainty in future tipping point
39 thresholds, possible impacts, timescales, and interactions (e.g., (22)). Although tipping
40 points can, if they are surpassed, accelerate climate change, the accumulation of
41 atmospheric carbon and associated warming can be slowed by human intervention (KM

1 10.3). Ultimately, the future speed and magnitude of change will depend on the amount of
 2 future greenhouse gas emissions and the shifting ability of the Earth system to absorb and
 3 store carbon (Figure 10.2) (5).

4 **Figure 10.2. Cascading, Bi-Directional Effects of Climate Change on Nature and**
 5 **Opportunities for Solutions Working with Nature**

Conceptual Summary of the Chapter



6

7 **Climate change alters ecosystems, and ecosystems alter the trajectory of climate**
 8 **change.**

9 *Linkages between climate change, ecosystem responses, impacts to ecosystem services,*
 10 *and potential solutions highlight how climate change affects ecosystems (KM 10.1) and*
 11 *how ecosystem processes influence climate change (KM 10.2). Shifts such as temperature*
 12 *rise, CO₂ increase, and changes in extreme events drive ecosystem responses (adaptation,*
 13 *relocation, or transformation), which in turn impact ecosystem services. There are*
 14 *opportunities for solutions based on humans working with nature at various points in the*
 15 *cascade (KM 10.3). Figure original to The Nature Record.*

16 **Key Message 10.1: Human-caused climate change is driving rapid**
 17 **transformation of nature and ecosystem services**

18 *Nature in the US has already responded to climate change in ways that are pervasive and*
 19 *span from genes to ecosystems and from local to global scales (virtually certain). Though*
 20 *these responses have helped nature survive, species extinction risks in the US are also*
 21 *higher and will continue growing with further climate change (well established). Climate-*
 22 *driven changes to nature are negatively affecting many ecosystem services for residents of*

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1 *the US, with impacts on food, clean water, human health, coastal protection, recreational*
2 *opportunities, and cultural heritage (virtually certain). The extent of future changes will*
3 *depend on the amount of climate change, with risks of irreversible or catastrophic losses to*
4 *nature and ecosystem services increasing rapidly at global temperatures warmer than*
5 *1.5°C above pre-industrial levels (well established).*

6 State of Knowledge 10.1

7 Genes, Populations, Species, Communities, and Ecosystems

8 Climate-driven environmental changes are occurring across the US and affect biological
9 processes from genes to ecosystems, from local to global spatial scales (Figure 10.3)
10 (23,24). Changes in nature include the seasonal timing of reproduction and growth,
11 behavior, morphology, reproductive and mortality rates, species geographic ranges and
12 migration, population productivity and abundance, species interactions, food web
13 structure, nutrient flows, evolution, and extinction (23,25). Climate change has played a
14 role in some very dramatic responses, including mass mortality of 4 million seabirds, a 90%
15 decline in kelp on the California coast, or the die-off of up to 50-75% of corals on reefs
16 globally (26–29). Sensitivities to the direct effects of climate change differ across species,
17 causing them to respond at different times, rates, and directions. Species therefore also
18 experience indirect effects of climate change from changes in their interactions with other
19 species, including competition, predation, and **facilitation**. The magnitude of these
20 changes generally increases with the amount of warming.

1 **Figure 10.3. Hierarchy of Climate Change Impacts from Organisms to Ecosystem**
2 **Services**

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3

4 **Species cope with climate change and variability through a hierarchy of processes**
5 **across scales of time and space.**

6 *Mechanisms through which species respond to a changing climate are shown distributed*
7 *across various spatial scales (y axis) and temporal scales (x axis). The relative importance*
8 *of each mechanism differs, on average, across terrestrial, freshwater, and marine realms*
9 *(as represented by the size of the icons). Changes in species abundance and occurrence*
10 *alter community composition, ecosystem functioning, and ecosystem service supply.*
11 *Confidence in the relative ratings (as represented by the degree of transparency) indicates*
12 *a qualitative assessment of the degree of support from the scientific literature. Adapted*
13 *from Pinsky et al. 2022 (30).*

14 Changes in climate are driving rapid and widespread redistribution of species in the US,
15 including expansions into historically unsuitable regions and contractions away from
16 historically occupied regions. Species redistributions are happening most rapidly in the
17 ocean, where barriers to movement are more limited than on land (e.g., (31)). Climate-
18 driven redistributions are often towards higher latitudes, higher elevations, and deeper
19 depths, though local and regional climate gradients modify this pattern. For example, the
20 center of the black sea bass distribution in the Northeast US shifted 120 miles north in 25
21 years, disrupting fishing operations and management (e.g., (32)), and one study found that
22 North American birds have shifted north at 9 miles per decade on average (33). Range

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1 shifts can result from gradual change or extreme events, such as the poleward range
2 extensions of 37 marine species in Northern California during the 2014–2016 marine
3 heatwave (34). Species distributions are expected to continue shifting with further
4 increases in temperatures and could extend more than 600 miles for some marine species
5 (35). However, range shifts are limited by species ability to disperse, the availability of
6 suitable habitat, and competition with other species. As a result, range shifts often lag
7 observed or projected temperature shifts (36). Certain species of corals, for example, are
8 dying faster than they can shift and are now largely extinct in Florida as the result of recent
9 heatwaves (37). When populations moving to higher elevations on mountains hit the top,
10 they cannot move further and risk extinction, including for birds like honeycreepers in
11 Hawaii (38). Species unable to undergo range shifts to keep pace with climate change are
12 at increased risk for decline or extinction.

13 Genetic variation is affected by climate-driven shifts in abundance and also provides the
14 raw material for future adaptation (39–43). **Selection** for particular traits can alter the
15 genetic composition of populations, with evidence that some populations can evolve to
16 tolerate new conditions (44,45). For example, lizards surviving a cold snap in Texas showed
17 greater cold tolerance, which was accompanied by shifts in genetic variation (46).
18 However, climate change also interacts with and often amplifies effects from other major
19 drivers of extinction, which include land-use and land-cover change, overfishing and
20 persecution of apex predators on land (47,48), and the spread of invasive species.
21 Ultimately, if species cannot move or adapt to changing conditions, population or species
22 extinctions occur.

23 Replacement of species within local ecosystems is occurring widely as local conditions
24 become unsuitable for some species and suitable for others, which then affects
25 ecosystem functioning (Figure 10.4) (49–51). One of many examples is the increase of
26 shrub growth in the US Arctic and subsequent increase in fuel loads and fires (52). In
27 addition, warmer winters allowed warmwater predators like bass, sunfish, and catfish to
28 expand their ranges into the western Great Lakes region, where they feed on the eggs and
29 juveniles of native cool-water fishes, including perch and Walleye (53,54). Alongside such
30 shifts, species composition in freshwater lakes has rapidly changed (55), and recreational
31 fishery yields have declined.

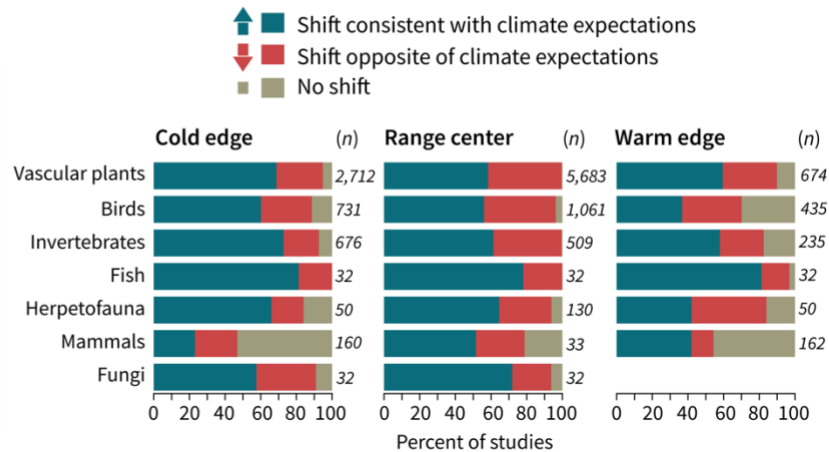
32 Climate change contributes to ecosystem transformation, including encroachment of
33 shrubs into grassland, increased wildfire risk, and changes in ecosystem productivity
34 (11,56). Rising sea levels have killed an estimated 10 million trees along the US Atlantic
35 coast, for example, converting them into “ghost forests” and eventually into tidal flats (57).
36 Ecosystems affected both by climate change and other stressors—including habitat loss
37 and fragmentation, invasive species, landscape alteration, hunting or fishing, and
38 pollution—are more likely to experience abrupt shifts to new types (11,58). Climate
39 impacts accumulate within ecosystems, which can lead to abrupt and unexpected
40 ecosystem changes that are difficult to reverse. Extreme events like floods and droughts
41 often contribute to abrupt ecosystem changes (24). For example, the Northeast Pacific

1 marine heatwave of 2014–2016 (colloquially called “The Warm Blob”) sparked a harmful
 2 algal bloom, an abrupt spike in whale entanglements with fishing gear, and substantial
 3 disruption to fishing livelihoods along the western US coast (59). As another example,
 4 climate change is exacerbating wildfires in the western US, with dramatic impacts on
 5 ecosystem structure and function and human communities (16,60).

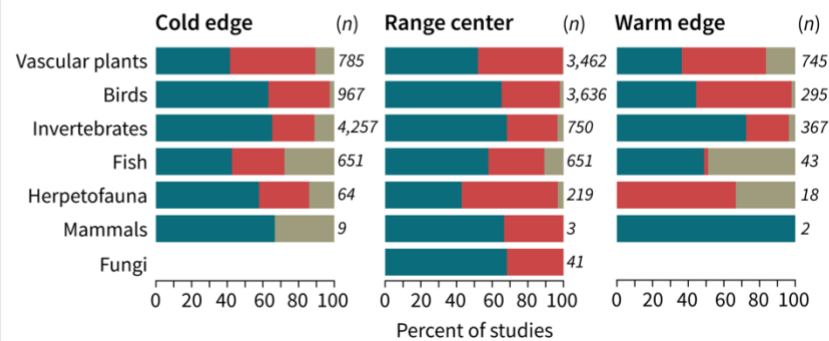
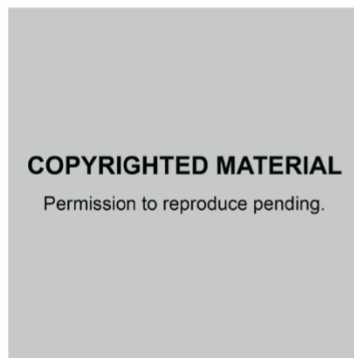
6 Figure 10.4. Observed Range Shifts on Land and in the Ocean

Elevational and Latitudinal Shifts

(a) Elevational shifts



(b) Latitudinal shifts



7

8 **Species ranges are shifting as the climate warms, in ways that are both consistent and**
 9 **inconsistent with expectations.**

10 *Shifts in elevational range (a) and latitudinal (terrestrial and marine) range (b) are shown as*
 11 *a percentage of total observed shifts consistent or inconsistent with climate expectations*
 12 *in the BioShifts database. Shifts are shown in aggregate (left) and decomposed into select*
 13 *taxonomic groups (right). The arrows and bars show the wide range of observed range*
 14 *shifts and the average shift towards higher elevations and higher latitudes. Arrows and bars*
 15 *denote observed range shifts (changes in range positions over time) that are in the*
 16 *expected (blue) or unexpected (red) direction of spatial shifts in average temperatures in*

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1 *the study area. Tan bars show the number of observations where the estimated range shift*
2 *is zero. The lengths of the arrow bars (on left) indicate the total number of range shift*
3 *estimates, percentages indicate the relative numbers, and numbers indicate the total*
4 *number of shifts in each group. Note that this shows agreement between range shifts and*
5 *climate changes, but not the direction of the shifts. Adapted from Lawlor et al. 2024 (61).*

6 Ecosystem Services

7 Climate-driven changes to nature affect and often degrade the full range of benefits on
8 which all people and other organisms rely (Figure 10.2) (62). These benefits include things
9 we use, like timber or food for people and animals. They also include nature's ability to
10 regulate the environment by storing carbon (KM 10.2), keeping soil healthy, cleaning the air
11 and water, controlling diseases, and protecting coasts. Changing benefits also include
12 nature's ability to support life by cycling nutrients, making oxygen through photosynthesis,
13 and maintaining genetic diversity. Finally, climate is affecting nature's ability to enrich our
14 lives by shaping our cultures, offering places for recreation, and supporting our mental and
15 physical health. For example, changes in climate are expected to decrease the production
16 of wheat, maize, and soybeans in the US (63,64). The distribution of disease-carrying
17 mosquitos is expanding in the southeast US, increasing the risk of disease (65). Changes in
18 these services have profound implications for the economy and human well-being,
19 especially for the poorest and most vulnerable US residents (24).

20 Climate change drives increases and decreases in ecosystem services, depending on the
21 service and the location (24). Many of the effects erode important services. Loss of coral
22 reefs, for example, increases flooding risk, with only some potential for restoration to
23 mitigate some impacts (66). Warmer waters are increasing fishery productivity for some
24 species in the US (like white hake in the Northeast) but decreasing productivity for others
25 (67). Overall impacts to fisheries in the US are largely negative (67,68). Similarly, changes to
26 growing seasons and crop yields include both increases and decreases, depending on the
27 region and crop, with changes that are overall negative (19,64). Over the last several
28 decades, the role of ecosystems in storing a large fraction of the CO₂ emitted by human
29 activities has been a hugely beneficial change (KM 10.2).

30 The continued provision of ecosystem services in a changing climate depends on
31 ecological processes, how we modify the climate, how we modify other stressors to nature,
32 and whether and how we adapt the ways in which we interact with nature. Loss of
33 ecosystem services is more likely in a climate that changes faster. Human behavior can
34 either amplify or mitigate these losses (KM 10.3) (62,64,69).

35 Description of the Evidence Base

36 The finding that nature in the US has already responded to climate change across all spatial
37 scales and from genes to ecosystems is *virtually certain*, based on robust evidence across
38 ecosystems and many published studies using both observations and models. Evidence
39 for increased extinction risks is *well established* and comes from a wide range of published

1 studies. The finding that it is *virtually certain* that climate-driven changes to nature are
2 affecting ecosystem services for residents of the US is based on published studies on
3 many ecosystems, using both observations and models. The conclusion that the extent of
4 future changes will depend on the degree of climate change is *well established*, based on
5 comprehensive evidence with minimal disagreement.

6 **Key Message 10.2: Lands and waters of the US play a critical role in the**
7 **global climate and in moderating the influences of greenhouse gas**
8 **emissions; management to sustain or improve their ability to mitigate**
9 **climate change will be increasingly difficult**

10 *Forests, agricultural lands, lakes, reservoirs, rivers, coasts, and oceans in the US play a*
11 *critical role in the global climate system (well established). US land and ocean waters*
12 *absorb a substantial portion of the annual greenhouse gas emissions from human activities*
13 *(virtually certain). Ecosystems on land also alter the reflectivity of Earth's surface, cooling*
14 *the atmosphere through evaporation, and moderating the transfer of heat between land*
15 *and atmosphere (virtually certain). These effects can be as or more important than effects*
16 *on greenhouse gases, especially for local comfort (very well established). The capacity for*
17 *land and water resources to mitigate climate change is influenced by many interactive*
18 *processes, including climate and the composition of the atmosphere, land-use change,*
19 *nutrient inputs, and agricultural and management practices, as well as climate-related*
20 *disturbances such as wildfire and extreme weather (very well established).*

21 State of Knowledge 10.2

22 Nature's Role in the US Greenhouse Gas Balance

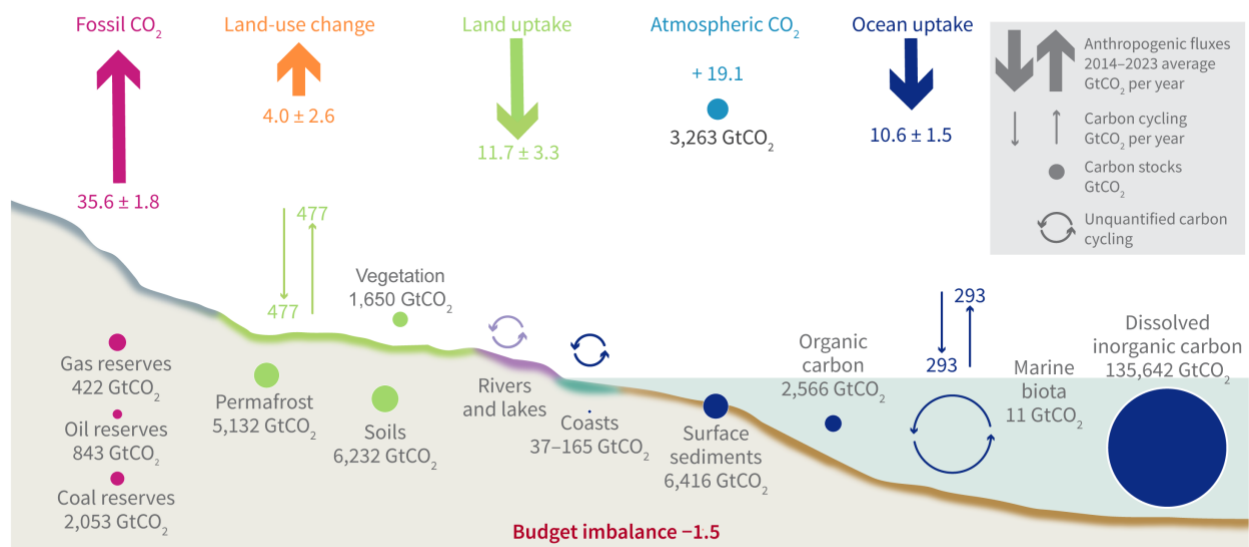
23 Ecosystems in the US (including natural and working lands, inland waters, and the ocean)
24 can operate as sinks (storing) or sources (emitting) for CO₂, CH₄, and N₂O. The
25 accumulation of GHGs in the atmosphere is the result not only of how much CO₂ and other
26 greenhouse gases are emitted to the atmosphere from human sources but also by how
27 much is naturally taken up and released from soils, vegetation, sediments, rocks, and the
28 ocean (Figure 10.5). This Key Message focuses on non-intentional effects of nature on
29 climate change. Intentional effects of nature on climate (e.g. nature-based solutions for
30 mitigation) are covered in Key Message 10.3.

31 By far the largest carbon stockpiles on Earth are in the **lithosphere** (rocks) (70). While some
32 of this carbon is released from rock weathering over millennia, industrial mining and
33 combustion of coal, oil, and natural gas currently transfer the most carbon (35.6 ± 1.8
34 gigatons of carbon dioxide, GtCO₂, per year; 90% of total human-caused emissions) to the
35 atmosphere (71). Land-use change, including conversion from natural lands to agricultural
36 or other uses, contributes another 4.0 ± 2.6 GtCO₂ per year (Figure 10.5; 10% of total) (71).
37 Forested ecosystems are Earth's largest terrestrial carbon (C) sink (72). As the amount of

1 CO₂ in the atmosphere has increased from about 280 parts per million (ppm) in pre-
 2 industrial times to 420 ppm in 2023, it has stimulated plant carbon uptake and is thought to
 3 be one of the largest drivers behind the current terrestrial carbon sink (73–75). Other
 4 prominent causes of increased C storage in vegetation and soils include increased nitrogen
 5 availability due to nitrogen deposition (76), recovery from previous land-use changes such
 6 as agriculture (77), and longer growing seasons due to increasing temperatures (78). Fluxes
 7 (i.e. flows) of carbon between terrestrial ecosystems and the atmosphere are also
 8 influenced by variability in water availability, temperature, disturbances such as fire, and
 9 land-use change (79,80).

10 **Figure 10.5. The Global Carbon Cycle**

Overall Perturbation of the Global Carbon Cycle Caused by Human Activities



©Global Carbon Project

11

12 Human activities are altering the global carbon cycle.

13 *The components of the global carbon cycle and the changes caused by human activities*
 14 *are shown, using average values for 2014–2023. Upward arrows indicate anthropogenic*
 15 *CO₂ sources, including fossil-fuel and industrial emissions (E_{FOS}) of 35.6 ± 1.8 Gigatons of*
 16 *carbon dioxide per year (GtCO₂ yr⁻¹) and land-use change emissions (E_{LUC}) of 4.0 ± 2.6*
 17 *GtCO₂ yr⁻¹, while downward arrows show natural sinks that remove CO₂ from the*
 18 *atmosphere, including uptake by land ecosystems (S_{LAND}) of 11.7 ± 3.3 GtCO₂ yr⁻¹ and the*
 19 *ocean (S_{OCEAN}) of 10.6 ± 1.5 GtCO₂ yr⁻¹. The atmospheric CO₂ growth rate (indicated by*
 20 *“Atmospheric CO₂”; G_{ATM}) is 19.1 GtCO₂ yr⁻¹, representing the emissions that remain*
 21 *airborne each year after land and ocean uptake. Circles represent major carbon sinks and*
 22 *their sizes. The budget imbalance (G_{IM}) of -1.5 GtCO₂ yr⁻¹ reflects the mismatch between*
 23 *estimated emissions and the estimated changes in the atmosphere, land, and ocean sinks:*
 24 *B_{IM} = E_{FOS} + E_{LUC} - (G_{ATM} + S_{OCEAN} + S_{LAND}). Adapted from Friedlingstein et al. 2025 (81).*

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1 Forests and their harvested products currently take up and store the equivalent of 14% of
2 economy-wide CO₂ emissions in the United States each year; actively managed
3 reforestation of underused or understocked forest lands could sequester an additional
4 20% of annual US emissions (82). While the carbon sink for temperate forests worldwide
5 increased in the 1990s and 2000s, other forested regions, including boreal and tropical
6 forests, showed a decreasing trend of carbon accumulation, attributed to greater tree
7 mortality from increasing climate variability and deforestation (83,84). Forty percent of the
8 US (and 83% of lands managed by the US Department of Interior) is arid or semi-arid
9 grasslands, steppe, shrublands, or deserts. While these lands store substantially less
10 carbon in vegetation and soils compared to forested lands, their highly variable carbon
11 uptake and emissions dynamics contribute strongly to the uncertainty in US carbon fluxes
12 (85,86). The future of US terrestrial carbon sinks is uncertain, and there is increasing
13 concern that climate impacts, such as disturbance from extreme heat, floods, drought,
14 storms, and fires, could drive terrestrial ecosystems to transition from a net carbon sink to
15 a carbon source over the 21st century (87–92).

16 Agriculture contributes to climate change through its exchanges of GHG with the
17 atmosphere. However, agricultural practices can also contribute to climate solutions,
18 including through management practices that sequester atmospheric CO₂ as soil organic
19 carbon or that minimize CH₄ and N₂O emissions (KM 10.3) (93).

20 Inland waters, such as lakes, ponds, reservoirs, streams, rivers, and floodplains are
21 sources of CO₂, CH₄, and N₂O to the atmosphere (94–97). Inorganic carbon from
22 watersheds is flushed or leached from **groundwaters** into inland waters and then
23 transferred to the atmosphere (98). In addition, CH₄ and N₂O are produced in water bodies
24 as nutrient enrichment and warming deplete oxygen and as anaerobic microbial
25 metabolism generates CH₄ and N₂O. (Figure 10.6) (98).

26 GHG emissions from inland waters are increasing, driven by land-use change, river
27 impoundments (reservoirs), eutrophication (nutrient enrichment), and climate. Reservoirs
28 are larger GHG sources than lakes and rivers (99), and emit more carbon as CO₂ and CH₄
29 than they bury in sediments, due to shrinking volumes and greater exposed sediments (95).
30 **Eutrophic** lakes and reservoirs are hotspots of CH₄ and N₂O emissions as they experience
31 hypoxia from microbial decomposition and warming (97). Rivers also increasingly emit CO₂
32 due to drying. Warming of the **cryosphere** of the US and Canada has increased aquatic
33 GHG emissions so much that they now offset that region's terrestrial carbon sink from
34 increased plant growth (94).

35 Although estimates vary widely, inland waters are potentially the largest global source of
36 CH₄ emissions from natural or human sources (71). Emissions from inland waters,
37 including lakes, reservoirs, and rivers, are projected to increase substantially as freshwater
38 eutrophication increases (100). These freshwater emissions are driven by transport of
39 nutrients and organic carbon from land to surface waters. Nutrients, especially
40 phosphorus and nitrogen, stimulate production of phytoplankton and aquatic plants.

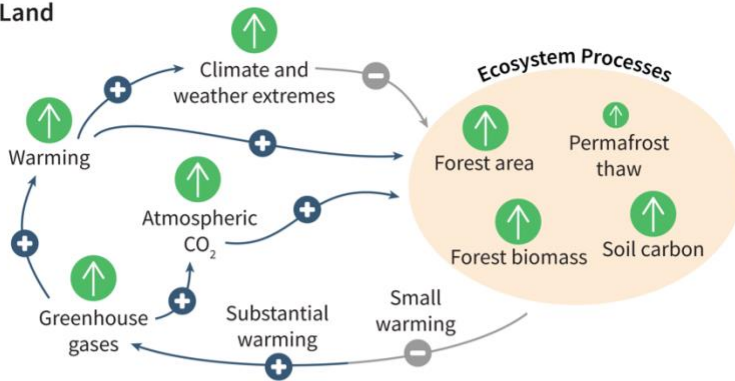
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- 1 Decomposition of this production and terrestrial organic carbon depletes oxygen (101,102)
- 2 and enables production of CH₄ and N₂O (103).

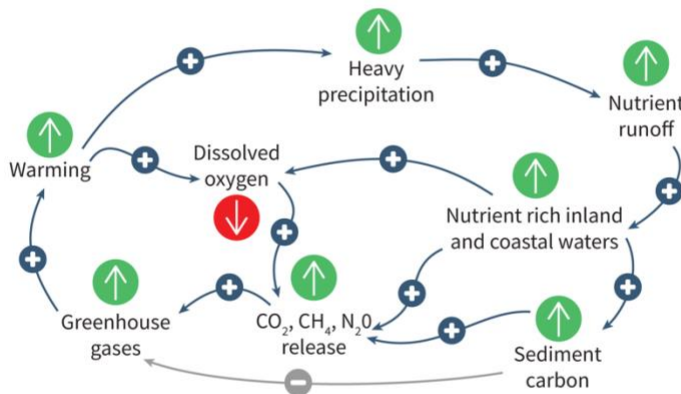
3 **Figure 10.6. Feedbacks Between Climate Warming and Ecosystems**

Feedbacks between climate warming and ecosystems

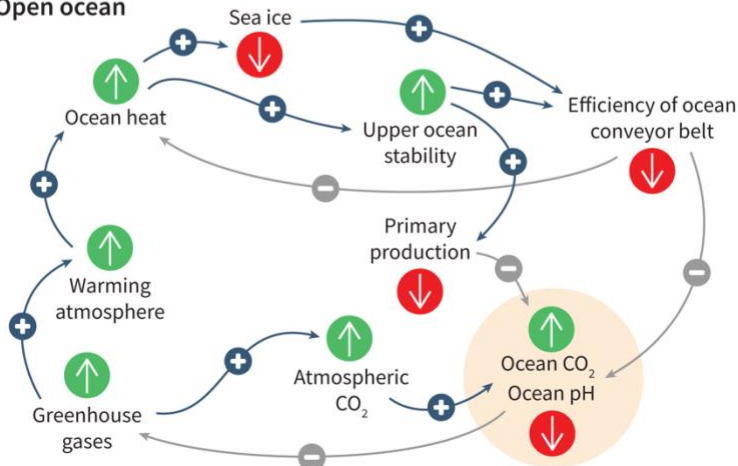
(a) Land



(b) Inland waters and coastal ocean



(c) Open ocean



4

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1 **Climate and ecosystem changes interact through both self-reinforcing and**
2 **counteracting feedbacks.**

3 *Ecosystems on land (a), inland waters and coastal ocean (b), and open ocean (c) respond*
4 *to increased greenhouse gases (GHGs) and atmospheric warming through diverse*
5 *mechanisms. Some mechanisms tend to increase the uptake of carbon dioxide (CO₂) or*
6 *decrease the release of methane (CH₄) and nitrous oxide (N₂O), providing a dampening or*
7 *counteracting feedback to the warming. Others tend to decrease the uptake of CO₂ or*
8 *increase the release of CH₄ and N₂O, leading to a self-reinforcing feedback, increasing*
9 *warming. The balance of counteracting and self-reinforcing feedbacks has led, in recent*
10 *decades, to net GHG sinks on land and the open ocean. It has led to a net GHG source*
11 *from inland waters and coastal oceans. Accumulating evidence indicates that land*
12 *ecosystems will tend to shift from net sinks to net sources as temperature increases. Figure*
13 *original to The Nature Record.*

14 Reduction of the transport of nutrients from land to water, and from rivers to oceans, is a
15 proven and effective method for reducing CH₄ production (KM 10.3) (104,105). Rivers are
16 important for moving carbon across the landscape and exchanging GHGs with the
17 atmosphere (106). Riverine transport of carbon through inland waters, estuaries, tidal
18 wetlands, and continental shelf waters to oceans has increased substantially due to
19 changes in land use and loss of inland and tidal wetlands and submerged coastal
20 vegetation (107).

21 Oceans play a substantial role in modulating global climate change by capturing and
22 redistributing heat and absorbing and storing GHGs, including CO₂, N₂O, and CH₄ (Figure
23 10.5) (71,108,109). The oceans have captured 26% of CO₂ emissions since 1850 (180 ± 35
24 GtC) (110) and more than 90% of excess heat added to the climate system since the
25 Industrial Revolution (71,111). The oceans take up CO₂ as the gas mixes into ocean water,
26 and the rates of uptake are fastest at mid- to high-latitudes where high wind speeds
27 facilitate mixing and where cold surface water sinking into the ocean's interior facilitates
28 continued CO₂ uptake at the surface (112).

29 The uptake of CO₂ in the oceans is modulated by nitrogen cycling, with marine
30 phytoplankton contributing significantly to the flux of N₂O to the atmosphere (113). Some
31 of the carbon fixed by photosynthesis is sequestered deep in the ocean for decades to
32 millennia (114,115) or in salt marshes, mangroves, and seagrasses in coastal marine
33 habitats (116,117). So far, the amount of CO₂ absorbed by the oceans has increased as
34 anthropogenic CO₂ emissions and atmospheric concentrations have increased.

35 The ocean's role as a carbon sink has significantly slowed the rate of human-caused
36 warming (71). The future of the ocean carbon sink depends not only on future
37 anthropogenic emissions but also on nutrient enrichment, changes in hypoxic zones, and
38 alkalinity discharge to the oceans (115), all of which are uncertain. Biological, physical, and
39 chemical processes are all vulnerable to the simultaneous impacts of increasing
40 temperatures, declining oceanic pH (ocean acidification), and rising sea levels (117). Many

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1 questions about countervailing effects of large-scale ocean chemistry manipulations on
2 global warming potential remain to be answered by research at relevant spatial scales.

3 Biophysical Feedbacks of Nature on Climate Change

4 Ecosystems in the US also affect Earth's climate, both at global and local scales, through
5 biophysical feedbacks in energy and water cycles (Figure 10.7). Biophysical feedbacks
6 occur when the properties of ecosystems, such as their reflectivity or structure, affect the
7 atmosphere and climate through mechanisms other than GHG exchange. Nature
8 influences the reflectance of land surfaces, cloudiness, and heat transfer, which can all
9 affect energy balance and atmospheric circulation, potentially amplifying or offsetting
10 efforts to increase carbon storage (Figure 10.7) (118–121).

11 **Figure 10.7. Energy, Water, and Carbon Feedbacks Between Terrestrial Ecosystems** 12 **and the Atmosphere**

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13

14 **Feedbacks involving flows of energy, water, and carbon between terrestrial**
15 **ecosystems and the atmosphere have significant effects on the climate system.**

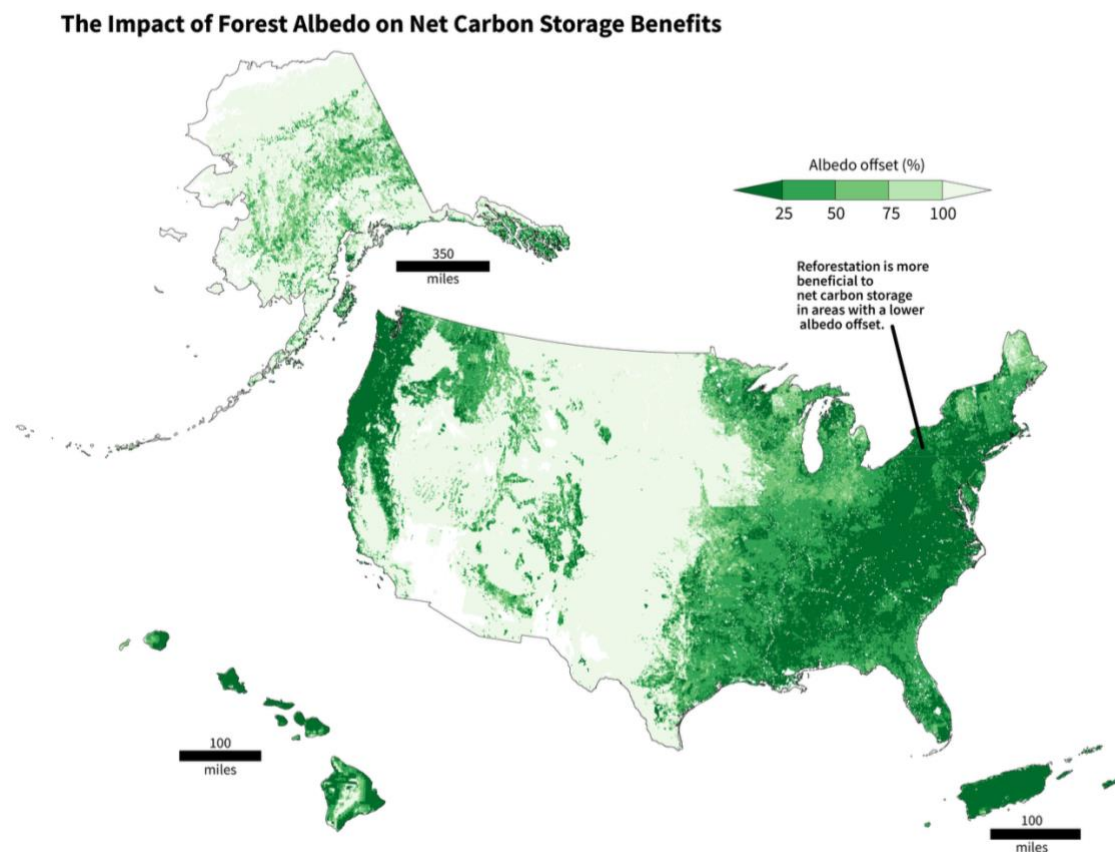
16 *Simplified schematic of some of the key ways through which ecosystems affect local and*
17 *global climate through energy, water, and carbon fluxes. Energy fluxes include how*
18 *radiation from the sun is reflected or absorbed by land surfaces, as well as how radiation is*
19 *emitted from surfaces (**left**). Prominent water fluxes include input from precipitation and*
20 *water loss from surfaces through transpiration in plants and evaporation of soils, bodies of*
21 *water, and other surfaces (**middle**). Important carbon fluxes include input through*

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1 *photosynthesis, loss of carbon through respiration and disturbance (right). Feedbacks*
2 *around clouds, circulation, and volatile organic compounds are not shown here. Adapted*
3 *from Anderegg et al. 2025 (122).*

4 Global feedbacks from changes in land-surface reflectance, termed albedo, can have
5 important global climate impacts (123). This is especially important where there are large
6 changes in albedo, such as when relatively dark trees (e.g., conifer species) are planted or
7 expand in regions with bright surface conditions, typically snow-dominated boreal, polar,
8 and alpine systems, as well as in arid regions with bright soils (Figure 10.8) (121,124). Such
9 information is crucial for guiding reforestation or afforestation efforts (KM 10.3) (121,125).
10 Changes in ecosystems that affect aerosol, water, and energy fluxes, such as deforestation
11 or reforestation, can also feed back to affect cloud patterns, atmospheric circulation and
12 radiation budgets (118,119,126,127).

13 **Figure 10.8. The Impact of Forest Albedo on Net Carbon Storage Benefits**



14

15 **The climate benefits of forest carbon storage in the US are partially or entirely offset**
16 **by forest's higher absorption of solar radiation.**

17 *The local net climate benefit reforestation in the US is the sum of the forest effect on carbon*
18 *storage and the effect of the forest on the total solar radiation absorbed by the surface.*

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1 *Because forests are darker than the vegetation they replace, they absorb more radiation,*
2 *producing a warming effect that offsets the carbon-storage effect. The net effect is*
3 *expressed as the percentage of the carbon effect offset by the solar radiation effect. The*
4 *solar radiation offset is a small fraction of the carbon effect for reforestation in Eastern and*
5 *Pacific Coast forests. It is higher in the Rockies and the Southwest, reaching values greater*
6 *than 100% (implying a net warming from reforestation), than in much of the desert*
7 *Southwest. Adapted from Hasler et al. 2024 (121).*

8 Biophysical feedbacks in the oceans also alter atmospheric conditions. Dimethyl sulfide
9 production in the oceans is increasing because of sea ice loss in the Arctic, leading to
10 increased cloud cover. The increased cloud cover can either cool the Earth's surface by
11 reflecting incoming sunlight, or warm it by trapping additional heat (128).

12 Causes and Future Trajectory of US Greenhouse Gas Sources and Sinks

13 Terrestrial ecosystems in the US have on average been a carbon sink of 0.93 gigatons of
14 carbon dioxide equivalent (GtCO₂eq) per year over 1973–2010 but with large year-to-year
15 variability, ranging from a 1.82 GtCO₂eq per year sink to a 0.56 GtCO₂eq per year source,
16 with years where ecosystems have been a net source being associated with severe drought
17 events (129). Forests have comprised the vast majority of this carbon sink (130). The
18 estimated US forest carbon sink declined by 35% over 1973–2010 due to land use and
19 increasing disturbance (129,131), and the overall US land carbon sink has declined by 10%
20 over 1990–2020 (Ch. 9: Drivers) (19). Satellite-derived estimates indicate the global land
21 carbon sink may be weaker than previously thought, in part due to increasing climate
22 impacts, highlighting the need for caution around durability of nature-based climate
23 solutions (91,132,133). Future projections of US greenhouse gas fluxes from terrestrial and
24 aquatic ecosystems are highly uncertain and sensitive to land use, management, CO₂
25 fertilization, nutrient runoff to inland and coastal waters, and climate change impacts like
26 disturbance, and range from a modest carbon sink to a modest carbon source (92,134–
27 136).

28 Description of the Evidence Base

29 The finding that forests, agricultural lands, lakes, reservoirs, rivers, coasts, and oceans in
30 the US play a critical role in the global climate system is assessed to be *very well*
31 *established*, as it is based on published studies using both observations and models. A
32 combination of top-down and bottom-up constraints based on forest inventories, eddy
33 flux, and atmospheric inversions, plus results from many well-calibrated models make it
34 *virtually certain* that US land and ocean waters absorb a substantial portion of the annual
35 greenhouse gas emissions from human activities. Similarly, many studies based on direct
36 energy flux measurements, plus satellite observations, models, and well-established
37 underlying physics demonstrate that it is *virtually certain* that ecosystems on land also
38 have other effects on climate by altering the reflectivity of Earth's surface, cooling the
39 atmosphere through evaporation, and moderating the transfer of heat between land and
40 atmosphere. Extensive published studies using both observations and models show that

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1 these effects can be as or more important than effects on greenhouse gases, especially for
2 local comfort—a finding assessed to be *very well established*. Based on many published
3 studies using both observations and models, it is also *very well established* that the
4 capacity for land and water resources to mitigate climate change is influenced by many
5 interactive processes, including climate and the composition of the atmosphere, land-use
6 change, nutrient inputs, and agricultural and management practices, as well as increasing
7 climate-related disturbances such as wildfire and extreme weather.

8 **Key Message 10.3: Nature-based solutions offer ways to lower** 9 **emissions, remove greenhouse gases from the atmosphere, and improve** 10 **resilience to climate change**

11 *Nature provides many mechanisms for decreasing emissions or increasing removals of*
12 *greenhouse gases, adapting to climate change, and enhancing resilience (very well*
13 *established). However, there are many uncertainties about the potential magnitude of*
14 *climate mitigation as well as non-climate benefits and harms to nature or human*
15 *communities. These uncertainties can be managed through risk assessments, engaging*
16 *with local and Indigenous communities, monitoring, sharing data, and being prepared to*
17 *change course (very well established). Some of the greatest challenges to nature are rapid*
18 *changes in climate, geopolitical dynamics, nonlinear or abrupt responses of nature and*
19 *society, and uncertainties of managing emerging problems under novel conditions (very*
20 *well established).*

21 **State of Knowledge 10.3**

22 **Nature-Based Solutions for Climate Mitigation**

23 Nature on land, inland waters, and oceans can be leveraged through management to
24 decrease emissions or increase removals of greenhouse gases (137,138). Such
25 interventions, termed nature-based solutions (NBS) for climate mitigation have the
26 potential to contribute to US progress toward net-zero greenhouse gas emissions and to
27 climate change adaptation, providing important benefits at reasonable costs (Figure 10.9).
28 NBS for mitigation are deliberate human actions that manage ecosystems to increase
29 carbon sequestration or reduce greenhouse gas emissions. Some NBS are focused almost
30 entirely on maintaining natural systems as they are, such as avoiding loss of natural forests
31 or grasslands that already store significant amounts of carbon and are expected to store
32 more over time (KM 10.2). Other NBS approaches involve creating or managing ecosystems
33 to increase carbon storage or reduce losses, such as afforestation, grassland restoration,
34 fire management, rotational grazing, and regenerative agriculture methods such as no-till
35 cropping or cover crops (Figure 10.10). Approximately one third of the US is forested,
36 pointing to the potential for using effective forest management practices, such as
37 extending timber harvest rotation periods, to help reduce emissions and increase carbon
38 removal (82).

1 **Figure 10.9. Nature-Based Solutions for Climate Mitigation and Ecosystem Resilience**

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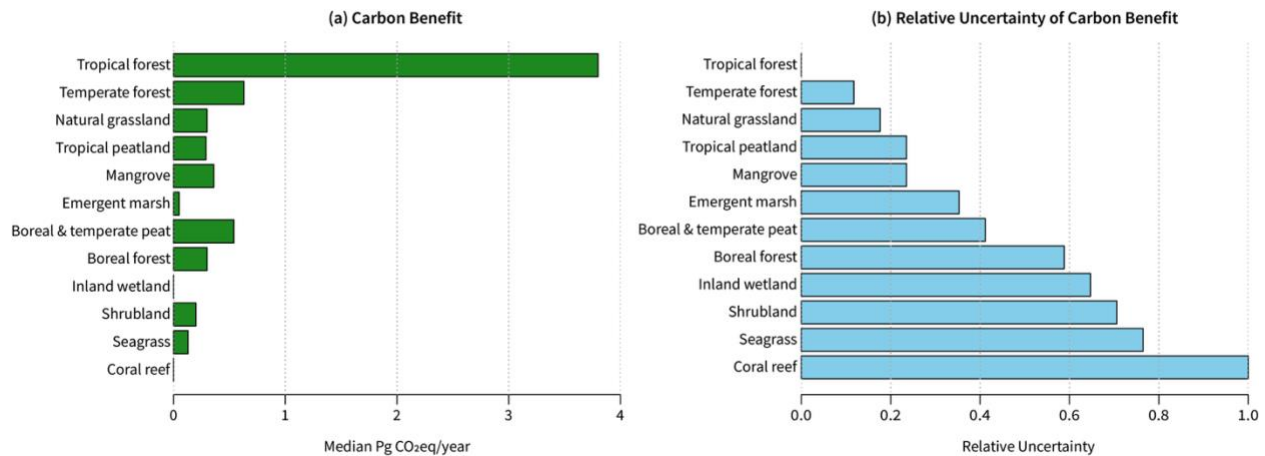
2

3 **Nature-based approaches can help limit future climate change while enhancing**
4 **biodiversity and ecosystem services.**

5 *Nature-based solutions for climate mitigation encompass actions that protect, restore, and*
6 *sustainably manage ecosystems to both reduce CO₂ emissions and enhance carbon*
7 *sequestration. Beyond the carbon cycle, nature-based solutions make important*
8 *contributions to biodiversity conservation and the maintenance of ecosystem services.*
9 *Adapted from myclimate.org.*

1 **Figure 10.10. Estimated Carbon Benefits and Relative Uncertainty**

Estimated Carbon Benefits and Relative Uncertainties



2

3 **Many ecosystems—especially tropical forests—have the potential to play an**
 4 **important role in absorbing carbon from the atmosphere.**

5 *Recent studies assessed potential carbon benefits (a) and relative uncertainties (b) for*
 6 *ecosystem types. Temperate forest and natural grassland, both prevalent across the United*
 7 *States, have significant carbon benefits and relatively low uncertainty of evidence.*
 8 *Tropical forests show both the highest sufficiency of evidence and the greatest potential*
 9 *carbon benefit. Figure original to The Nature Record. Data source: (137)*

10 To function as effective climate mitigation, NBS for climate mitigation must fulfill four key
 11 principles: (1) result in net cooling of the global climate, accounting for both GHG and
 12 biophysical feedbacks like changes in albedo (123); (2) lead to more net cooling (e.g., GHG
 13 removals or avoided emissions) than would have occurred absent the investment, termed
 14 **additionality**; (3) minimize and account for the shifting of activities (e.g., timber harvest) to
 15 non-project areas that could undermine effective mitigation, termed **leakage**; and (4)
 16 deliver climate mitigation benefits over a defined future period, typically decades to
 17 centuries, termed **durability** or **permanence** (121,125,138–140). Substantial concerns and
 18 issues have been raised about the quantitative benefits of many terrestrial carbon offset
 19 projects and whether they meet these core criteria, highlighting the need for future
 20 research and program improvements (121,141–145).

21 Management of agricultural systems to sequester atmospheric CO₂ as soil organic carbon
 22 and to minimize CH₄ and N₂O emissions make agriculture a potential contributor to climate
 23 solutions (93). Erosion control, integrated pest management, reduced tillage, organic
 24 matter amendments, and growing biomass crops such as switchgrass or poplar can all
 25 increase the amount of carbon in agricultural soils (93). Quantifying how much carbon is or
 26 could be sequestered in agricultural soils is challenging because it is difficult to measure
 27 changes in soil (146,147).

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1 Conditions on land, including use, cover, and management practices, influence GHG
2 emissions from inland and coastal waters (Figure 10.10; KM 10.2). Watersheds managed to
3 diversify land cover types (148), store carbon (149), decrease runoff of nutrients to surface
4 waters, and mitigate eutrophication (150–152) can allow aquatic ecosystems to maintain
5 oxygenated conditions and decrease emissions of CH₄ or N₂O. Because inland and coastal
6 waters may be the largest sources of these greenhouse gases (153), mitigation of
7 eutrophication and deoxygenation has substantial potential (100). However, complex
8 interactions of the processes that generate and release CO₂, CH₄, and N₂O must be
9 considered to gain maximum benefits from mitigation strategies (154).

10 Concepts for carbon removal in oceans are currently at very early stages of development,
11 and the potential for benefits and unintended impacts are both poorly constrained.
12 Concepts under consideration include ocean alkalinity enhancement, where minerals are
13 added to increase the ocean's ability to absorb CO₂, artificial upwelling to bring nutrient-
14 rich deep water to the surface, macroalgae cultivation (farming seaweed), restoring and
15 protecting coastal ecosystems (like mangroves and/or seagrass meadows), nutrient
16 fertilization to stimulate phytoplankton growth, enhanced weathering of ground rock, direct
17 ocean capture and/or deep storage, artificial downwelling, and electrochemical ocean CO₂
18 removal.

19 Alkalinity enhancement may cause shifts in plankton communities with positive or negative
20 effects on ocean carbon storage (155). Nutrient enrichment, including iron fertilization,
21 may expand hypoxic zones and thereby promote release of methane and nitrous oxide
22 (156,157). Yet anoxic regions could generate alkalinity through formation and burial of
23 pyrite and thereby remove significant amounts of CO₂ from the atmosphere (158).
24 Biological carbon removal methods for the ocean include the reduction of fish harvests,
25 restoration of apex predators, and efforts to recover whale populations, all of which
26 enhance the sinking of carbon in large-bodied vertebrates to deep ocean depths (159,160).

27 Nature-Based Solutions for Adaptation

28 In addition to mitigation, nature provides a wide range of opportunities for enhancing
29 climate adaptation, or the ability of ecosystems, human communities, and economies to
30 cope with stresses from a changing climate. Historically, dominant approaches to address
31 risks posed by climate change and natural disasters have focused on engineered
32 interventions (e.g., sea walls, levees, irrigation infrastructure). There is increasing evidence
33 that NBS—including protecting, managing, and restoring ecosystems on land and in waters
34 in the US and around the world—can support climate change adaptation (161,162). This
35 evidence has contributed to the support for initiatives such as 30 by 30, which aims to
36 protect 30% of Earth's lands and oceans by 2030 (163).

37 NBS for climate adaptation on land have been documented in both highly managed and
38 natural systems. Climate adaptation of cities, for example, can be bolstered by restoring
39 nature, such as urban forests, that can reduce impacts of urban heat, stormwater runoff,
40 and other challenges (164). Increases in urban leaf area can lead to local cooling through

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1 increases in evaporation (124,165,166), making vegetation a component of human climate
2 adaptation. Urban forests can also provide co-benefits such as food security and
3 counteracting historical patterns of marginalization that drive increased heat exposure in
4 low-income communities and communities of color (Ch. 2: Equity) (167–169). US cities
5 with higher levels of tree cover experience greater local cooling effects (89). Within cities,
6 temperatures are lower in city blocks with more trees. Temperatures average 2.6 °C hotter
7 in historically redlined neighborhoods (Ch. 2: Equity), in part because of lower tree canopy
8 (90).

9 Freshwater wetland restoration and forest management practices, such as supporting
10 regeneration of mixed-species forests after clear-cutting, can reduce heavy flows from
11 runoff and flood risk (162,170). Coastal and marine areas can also benefit from NBS for
12 adaptation. Protection of healthy coastal ecosystems such as mangroves, saltmarshes,
13 and coral reefs, bolsters resilience to climate change by reducing impacts from sea level
14 rise and storm surges (see Ch. 14: Risk and Security) (171). NBS that can enhance
15 adaptation in working lands and fisheries include protecting nature through empowering
16 stakeholders to lead conservation, enhancing flexibility for managers and stakeholders
17 without enabling or incentivizing overharvest, and preserving redundancy and
18 diversification in natural resource systems (172,173). Sustainable fisheries management to
19 maintain productive populations, international cooperation for sustainable use of shared
20 fisheries, management approaches that adapt to changing ocean conditions, and
21 measures to bolster human community resilience have the potential to maintain or even
22 increase US fisheries productivity despite the impacts of climate change, particularly if
23 GHG emissions are reduced (174).

24 Protection of freshwater wetlands, including carbon-rich peatlands, contributes to both
25 climate adaptation (e.g., by reducing flood risk and enhancing water quality) and mitigation
26 (by preventing carbon emissions that would occur with draining for agriculture or other
27 purposes) (175,176). However, methane emissions from wetlands are increasing as the
28 climate warms. Ecosystems were a significant source from 2020–2022, and long-term
29 increases are expected from warming (177,178). Locally, soils can be treated with sulfate
30 to decrease methane emissions, but the broader potential of using sulfate for intentional
31 suppression of wetland methane emissions is not known (177). Wetland protection or
32 restoration causing increased methane emissions is an example of an NBS that provides
33 benefits for adaptation but harm in terms of GHG emissions. Other interventions,
34 particularly when done poorly, can create contrasting outcomes for NBS for adaptation
35 versus mitigation. In a recent analysis, interventions involving created ecosystems, such as
36 afforestation, were more often associated with such win–lose trade-offs than those based
37 on natural ecosystems (179).

38 Market-based mechanisms are increasingly deployed to finance NBS for both mitigation
39 and adaptation. These markets include compliance (administered by a government as part
40 of a mandatory policy instrument) and voluntary (not directly included in a
41 compliance/government policy instrument) frameworks. Currently, NBS mitigation markets

1 are relatively more developed, particularly through carbon credit markets. More experience
2 with NBS markets for mitigation will be relevant to international deployment through Article
3 6 of the United Nations Framework Convention on Climate Change. Many science and
4 policy challenges exist for ensuring that NBS markets deliver climate mitigation benefits
5 (122,138,180–182). Nature-based solutions for adaptation may become increasingly
6 relevant, as more market-based incentives are developed (e.g., carbon markets,
7 biodiversity credits) and could help advance both climate and UN Sustainable
8 Development Goals (183).

9 Engaging Local and Indigenous Communities

10 Providing enhanced NBS for climate mitigation and adaptation will be most effective when
11 the objectives consider the needs, rights, and insights of local communities, often
12 Indigenous or rural, who are on the front lines of deployment (184). Indigenous Peoples
13 frequently face disproportionate vulnerability, as climate damage to nature can harm
14 traditional practices and ways of life, in some cases necessitating relocation from
15 ancestral lands (185). The Quinault Indian Nation of the Pacific Northwest Coast, for
16 example, is relocating two villages out of the Olympic Coast’s flooding and tsunami zone,
17 as climate change has increased threats. Arctic indigenous communities in Alaska, facing
18 increasing dangers and threats to their practices of marine mammal hunting, are seeking to
19 enact science-informed adaptive solutions (186).

20 Deep engagement with stakeholders can help achieve NBS implementations that reflect
21 community values and needs. Local and Indigenous people engage with and manage
22 nature in diverse ways, often bringing perspectives from relationships that span long time
23 scales, playing key roles in stewardship, and offering alternative concepts of interrelations
24 between people and nature (187). Cultural burning is one area of rapidly expanding
25 opportunities. Expanding the practice both strengthens communities and leads to
26 meaningful wildfire risk reduction (188,189). The Climate-Ready Tribes Initiative has
27 provided funding and technical assistance to ten US-based tribes for implementing
28 strategies to protect health from climate impacts, leading to each tribe developing
29 modifications of existing frameworks to make them more relevant and reflective of their
30 Indigenous values (185). Engaging stakeholders and rights holders in development of NBS
31 can enhance nature and communities in parallel while also building prospects for new
32 livelihoods.

33 Avoiding Unintended Consequences of Mitigation and Adaptation

34 While NBS provide opportunities, they also have the potential to harm nature or human
35 communities. An example is the US corn-based ethanol program, which increased the
36 spatial extent of row-crop agriculture but failed to meet its own GHG reduction targets,
37 decreased land area for nature, intensified eutrophication and deoxygenation of surface
38 waters, harmed native birds and beneficial insects, and adversely affected other
39 ecosystem processes (190).

1 Management of landscapes to mitigate climate change has implications for food
2 production, water supply, housing, transportation, recreational opportunities, and equity.
3 For a given proposed project, knowledge of what area of land can be modified, what
4 modifications are possible within constraints of human use and fairness, and the potential
5 effects on climate forcing by changes in albedo and net greenhouse gas emissions are all
6 essential components for estimating net effects on climate. Because estimates based on
7 currently available data will be approximate and uncertain, adaptive management can help
8 identify and address unintended outcomes.

9 Ocean interventions to remove carbon can exacerbate ocean acidification, disrupt marine
10 ecosystems, change food webs, and have adverse effects on fish (191). Thus, large-scale
11 interventions to offset or store carbon emissions interact with nature, neighboring
12 ecosystems, food production, resource economics, and rural communities (184,192,193).
13 Risks and trade-offs should be carefully considered before interventions are attempted,
14 and appropriate scaling is necessary (194,195).

15 Description of the Evidence Base

16 The finding that nature provides a wide range of mechanisms for decreasing emissions or
17 increasing removals of greenhouse gases, adapting to climate change, and enhancing
18 resilience is assessed to be *very well established* based on many studies using both
19 observations and models. It is also *very well established*, based on extensive evidence
20 across ecosystems using both observations and models, that uncertainties about climate
21 mitigation impacts can be addressed by conducting risk assessments, engaging with local
22 and Indigenous communities, monitoring, sharing data, and being prepared to change
23 course. And, based on extensive evidence across ecosystems using both observations and
24 models, it is also *very well established* that the greatest challenges to nature are rapid
25 changes in climate, geopolitical dynamics, nonlinear or abrupt responses of nature and
26 society, and uncertainties of managing emerging problems under novel conditions.

27 Environmental Justice and Equity Highlights

28 Long-standing inequities in access to nature can be amplified by the impacts of climate
29 change. The impacts of climate-driven nature loss are disproportionately felt by vulnerable
30 communities, people of color, Indigenous Peoples, and rural communities (196–199). The
31 US Census Bureau estimates more than twice as many African Americans as Whites live in
32 nature-depauperate urban heat islands, (200). Likewise, the lives and livelihood of many
33 Indigenous Peoples are being threatened as climate-driven shifts in temperature and
34 precipitation reduce access to culturally important species and tribal lands and decrease
35 the efficacy of traditional subsistence practices (201).

36 Strategies aimed at making the benefits of nature accessible to all—including investing in
37 urban green spaces; enhancing the biodiversity, health, and resilience of working lands;
38 and developing NBS—have the potential to reduce the environmental inequities associated

1 with climate change (202). There is growing evidence that direct climate actions, including
2 carbon emissions reductions, can be particularly impactful for the health and well-being of
3 minorities and vulnerable communities, through decreases in co-pollutants and the
4 creation of green jobs (203,204).

5 NBS provide a compelling means to simultaneously address climate change and nature
6 loss; however, legacies of historical structural inequities can limit access to and funding for
7 NBS for the vulnerable communities (205,206). As a result, the implementation of NBS has
8 the potential to either ameliorate or amplify environmental inequities, depending on design
9 (198,202). For example, NBS aimed at mitigating coastal flooding may be even more
10 beneficial for low-lying inland communities than for more affluent coastal communities,
11 where flooding is largely unavoidable (207). However, decisions about where and how to
12 implement NBS for coastal flooding do not always consider the input of marginalized
13 groups (205). Strategies to mitigate climate-driven inequities will be most just when they
14 are intentional about addressing existing inequities and co-designed with the communities
15 or on the front lines of deployment (199,205).

16 Emerging Issues

17 Novel Approaches to Conservation in a Changing Climate

18 The profound and unprecedented threats to nature from a changing climate, especially in
19 the context of other human-caused stresses, calls for careful but accelerated assessment
20 of a wide range of conservation and management strategies. These ambitious approaches
21 range from modest adjustments in conventional stewardship to methods beyond
22 traditional conservation (208,209).

23 New broad-scale conservation planning initiatives that incorporate climate change have
24 been used to identify focal conservation areas and actions. These approaches include
25 conserving “nature’s stage”—the physical environment in which species exist—to
26 safeguard both geodiversity (the variety of rocks, minerals, soils, landforms, and processes
27 of geology) and biodiversity (210) and identifying key areas for connectivity to sustain
28 species movement in response to climate change(211). Increased data availability,
29 education, outreach, and coordination are needed to implement many actions identified in
30 these and other planning initiatives (e.g.,(212)).

31 The continued provision of ecosystem services in a changing climate depends in part on
32 human behavior. For example, fishery productivity declines for many populations as ocean
33 waters warm, and, as a result, harvesting at historically sustainable levels leads to
34 overfishing (213). In contrast, lower rates of fishing can largely maintain fisheries yields to
35 provide food for people (69).

36 Beyond planning, on-the-ground management is critical, because healthy and diverse
37 ecosystems are more resilient to climate change. In situ conservation and management
38 actions can provide both climate mitigation and adaptation; examples include planting,

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1 thinning, and prescribed burning to restore and reforest wildfire-prone Western forests that
2 provide critical habitat, protect freshwater sources, and store carbon. In deploying such
3 management, new approaches can be leveraged to bolster genetic diversity, biological
4 diversity, and habitat heterogeneity, all of which are associated with resilience (214–217).
5 For example, managers are increasingly incorporating expected future climate in selecting
6 the source populations and species to be planted or established. This practice, known as
7 assisted migration, moves species or genes through fragmented landscapes otherwise
8 difficult to navigate and establishes them in locations with newly suitable climate, often
9 with a goal of supporting ecosystems that have more future climate-adapted species or
10 genotypes (e.g., (218–221). Though still relatively rare in practice, especially for animals,
11 species translocations have been deployed in terrestrial, aquatic, and marine ecosystems
12 (222).

13 Alongside these in situ strategies, ex situ methods can also support conservation and
14 management of nature under climate change. Zoos provide opportunities for conservation
15 research and mitigation of local climate change–induced threats, as well as opportunities
16 for the public to learn about and connect to climate change impacts (223,224). Seed or
17 gene banking—ranging from local, community-led efforts to globally coordinated initiatives
18 like the Millennium Seed Bank—provide a buffer against threats and uncertainties of
19 climate change (225–227). In addition to these more traditional ex situ methods, novel
20 approaches being implemented and explored include cryopreservation (the process of
21 storing biological material at very low temperatures to preserve it for future use) (228),
22 participatory gene banking through common gardens (e.g., for California oaks (229), for
23 coral reefs (230), and genetic rescue tools for marine conservation (e.g., through
24 biotechnology, (231)).

25 [Potential for Conflicts between Mitigating Climate Change and Conserving and Enhancing](#) 26 [Nature](#)

27 As new technologies are developed to mitigate climate change, there is an ongoing need
28 for assessing potential novel risks they pose to nature. The spread of renewable energy,
29 critical for addressing climate change, comes with ecosystem risks—for example, affecting
30 species from birds to bees as large areas of land are utilized for generating solar and wind
31 power (232–234). Other risks to nature from the “green energy” transition include loss of
32 habitat for salmon and other species from hydropower dams (potentially with cascading
33 evolutionary effects (235)), mining for rare earths and other critical minerals (236,237), and
34 leaks from pipelines or underground storage reservoirs for natural gas, hydrogen, or carbon
35 dioxide (238). Dams for hydropower may increase methane emissions that offset any green
36 energy benefits (239). Such novel risks may affect marine habitats as well, through
37 technologies such as ocean fertilization and altered ocean alkalinity or ocean thermal
38 profiles(240). Solar geoengineering, a set of technologies designed to cool the Earth by
39 reflecting sunlight back into space, is increasingly discussed as a potential strategy for
40 reducing climate change damages (241). Some effects of solar geoengineering on
41 agriculture (242), wildfire (243), and hydrology (244) have been considered, at least

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1 preliminarily, but risks of a wide range of unintended consequences have not yet been
2 adequately explored.

3 Pace of Change and Managing Under Uncertainty

4 Benefit–cost analyses can be used to evaluate trade-offs of NBS for mitigation and
5 adaptation. Ideally, environmental projects should evaluate trade-offs on the basis of
6 inclusive wealth (245), which encompasses multiple dimensions of capital, including
7 economic, social, and ecological components for current and future generations (245).
8 Measures of natural capital consider ecosystem services as well as factors such as effects
9 of land use on human health and equity and relationships between living standards and
10 land productivity (246,247). A recent guidance for ecosystem services assessment applies
11 these ideas to environmental interventions in the US. (248).

12 Some of the greatest challenges we face involve rapid changes in climate, geopolitical
13 dynamics, and nonlinear and possibly abrupt responses of nature and society. Standard
14 approaches for making rational decisions require information about how policy choices
15 affect outcomes, probabilities of alternative outcomes, and the net benefits of those
16 alternatives. In practice, however, the effects of management actions, potential outcomes,
17 their probabilities, and their net benefits are often unknown. In situations of potentially
18 rapid change and high uncertainty, decision theory provides useful tools but also poses
19 risks (249–251). Decision-makers may focus too narrowly on topics with sufficient data and
20 ignore options with limited data or understanding (252). In these cases, reassessments
21 based on updated information, resilience methods to include intuition and broader
22 perspectives, and scenario planning can lead to better scoping of possible future states
23 and outcomes, and hence better decisions (251).

24 Climate resilient development considers nature together with processes of social
25 organization (253) and systems of governance that enable people to organize for
26 sustainability (254), with sensitivity to the local situation (255). Approaches have been
27 developed for many systems of people and nature ,including US examples (256). Resilience
28 management involves open sharing of data, long-term monitoring of ecological conditions,
29 research to identify alternate states, thresholds, and possibilities for adaptation or
30 transformation (257,258). In systems subject to state shifts, successful management
31 involves long-term assessment of variables that control thresholds, using multiple data-
32 based models to infer dynamics, gathering before-and-after data for management
33 interventions, and experimenting at the scale of the question (259).

34 Scenarios explore alternative futures of a social ecological system with broad participation
35 across arts, cultures, sciences, civil society, and general public (260–264). Examples of
36 stewardship initiatives using scenarios include the Northern Highland Lake District of the
37 western Great Lakes region (265), the Yahara watershed around Madison, Wisconsin
38 (150,266), and the futures of New England forests (267).

1 Monitoring, Maintaining Flexibility, and Learning from Experience

2 Long-term monitoring with rigorous, open-access data analysis and sharing are essential
3 for successful climate resilient management in a changing world. Long-standing networks,
4 such as the National Science Foundation Long-term Ecological Research Program (268)
5 and the USDA Forest Inventory Analysis Program (269), as well as new initiatives like
6 NASA's BlueFlux Airborne Campaign (270), provide a foundation of ecological data upon
7 which to build. Increasing the number and scope of long-term monitoring networks can
8 provide the information needed to better reflect the diversity of ecosystems and
9 management practices. Investments in long-term monitoring networks would support full
10 integration of research, monitoring, modeling, paleoecology and remote sensing to
11 enhance understanding of environmental change as well as development of inter-
12 disciplinary approaches that integrate social and environmental science data for the public
13 and policymakers (271).

14 Collaborative monitoring and data-sharing across agencies, management programs, and
15 sectors enhance the utility and impact of such initiatives. The information helps decision-
16 makers at all levels, including individuals, business planners, and government officials
17 make informed judgements. Open-access data enable the scientific community to expand
18 the set of available models for policy.

19

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