

1 Chapter 9: Status, Trends, and Future
2 Projections of Drivers of Change in
3 Nature in the US

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27 **Date**

28 February 23, 2026

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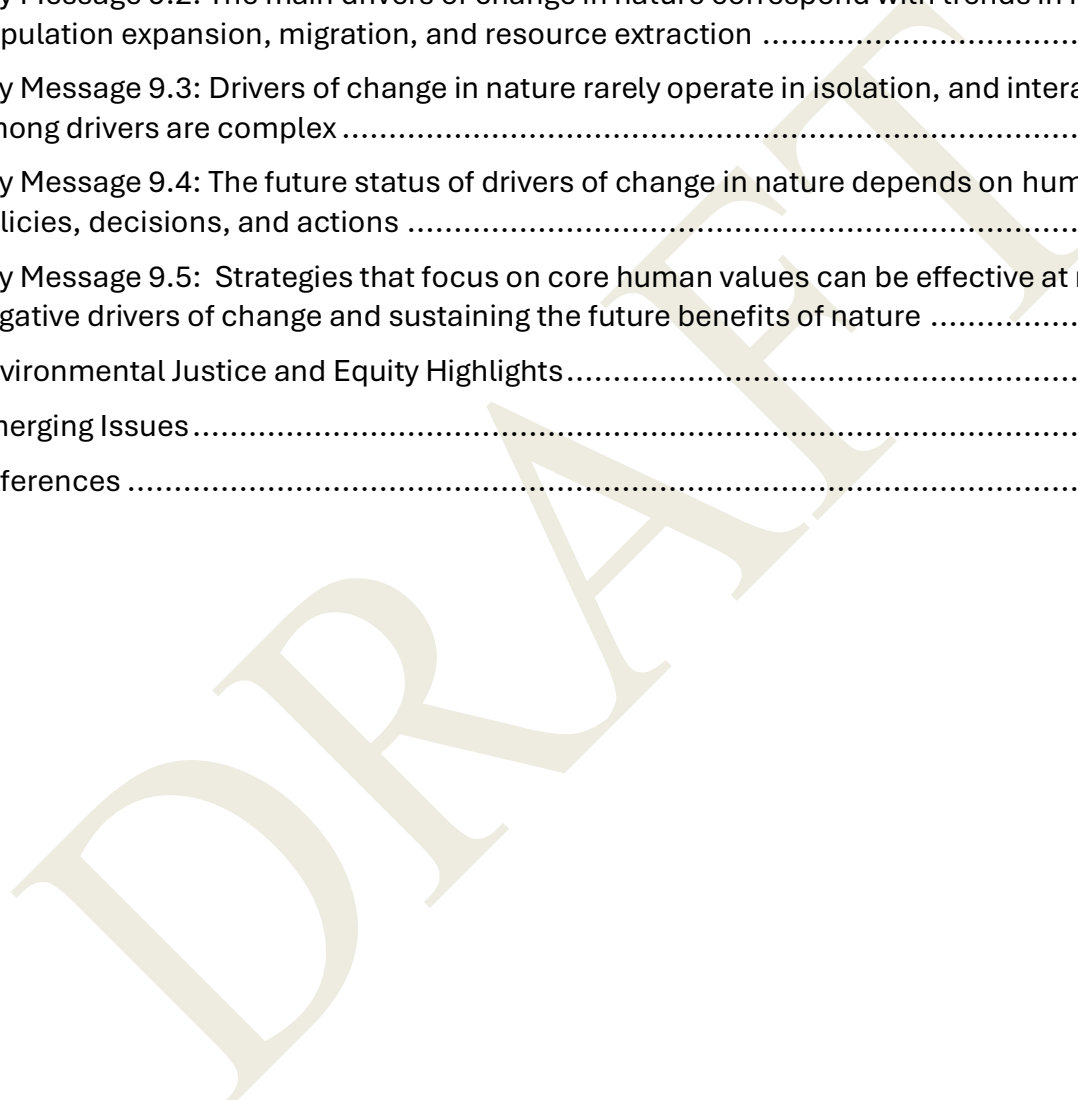
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1 Summary

2 Drivers of change in nature have a history as long and complex as Earth itself. Nature has
3 always been impacted and shaped by Earth system processes, but the greatest proportion
4 of nature change now and over the last two centuries has resulted from human activities.
5 Throughout the 20th century, economic development relied on the extraction of water,
6 energy, and minerals. Associated dam building, drilling, mining, and industrial activities
7 degraded and polluted many habitats. Introductions of exotic, invasive species peaked in
8 the 20th century, though their abundance and impact continue to grow. New technologies
9 enabled many of these activities to expand into new places and made each of them more
10 destructive. For example, in the ocean, new technologies for finding, catching, and
11 transporting fish to market enabled an expansion of the footprint and impact of the US
12 fishing fleet. Similarly, a variety of technological advances enabled more efficient tree
13 removal, mechanized soil tillage, improved fencing that made it possible to fence vast
14 areas of prairie and greatly expanded the acreage that individual farmers could convert to
15 cropland.

16 Policies are another important driver of change in nature. Several national policies
17 developed since the 1960s offer hope that economic development can coexist with nature.
18 The Clean Air and Clean Water Acts have markedly reduced pollution, the Endangered
19 Species Act has protected species and the ecosystems on which they depend, and the
20 Magnuson–Stevens Act has ameliorated overfishing in US waters. Salmon and other fishes
21 are returning to rivers like the Klamath following recent dam removals. Cropland expansion
22 and forest loss have slowed dramatically in the 21st century, and energy transitions have
23 reduced coal mining by half since its peak in 2008. Overturning of such policies is equally a
24 consequential driver of change in nature.

25 Projecting the future trajectories of drivers of change in nature requires scientific analysis
26 of drivers and their interactions; it also entails the development and analysis of scenarios
27 that account for underlying forces, such as complex socioeconomic interactions and
28 evolving economic and political systems. For example, this approach has been used to
29 provide consistent future scenarios of some of the most important drivers, including
30 population growth, gross domestic product (GDP), land use, and climate.

31 Negative impacts of drivers of change in nature may be mitigated by prioritizing values and
32 policies that support and improve nature and that sustain its long-term benefits to
33 humanity. To that end, it is important to recognize that anthropogenic drivers of change in
34 nature are rooted in the values and decisions made by those in power and by other social
35 influencers. Marginalized communities may have different relationships with, and values
36 about nature, but are often the most impacted by the effects of changes made by others.
37 Further, sustainability and policy efforts are significantly influenced by inclusive versus
38 non-inclusive local, national, and global governance structures.

1 Background

2 Throughout Earth’s history, nature was continually shaped by non-human forces. North
3 America has a history that spans tens of millions of years since separating from other
4 tectonic plates after the end of the Cretaceous period (about 65 million years ago). The
5 continent has undergone repeated episodes of ecological fluctuation resulting from
6 changing sea levels and other large-scale geologic processes (uplifting, mountain building,
7 glaciation, etc.). The northern tier of the continent was covered by shifting ice sheets and
8 corresponding changes in coastlines as sea levels fluctuated over the last 2.5 million years
9 or so (1). More broadly, these large-scale forces on continents and in the ocean shaped
10 nature significantly. Mountains rose through the movements of plate tectonics and then
11 eroded over time, changing watersheds, ecological communities, separating some
12 species and bringing others into closer contact. Vast ocean currents distributed heat,
13 nutrients, and carbon around the world, which regulated the climate and influenced
14 different ecosystems. Changes in those currents over time directly influenced natural
15 systems. These large-scale geologic processes also interacted with each other to shape
16 the distribution of life on earth.

17 Much of the current distribution of North American ecosystems (2) and nature is the result
18 of patterns established during the Pleistocene (2.6 million to 11,700 years ago) or earlier
19 (3), and subsequent range shifts (expansions and contractions) occurred as climatic and
20 environmental conditions evolved (4). No ecosystems remained static, and some
21 fluctuated dramatically even over short time scales, well before the arrival of European
22 colonizers (5). Moreover, the ecological communities that emerged during this time were
23 unique (“no-analog”) products of the specific environments in which they developed (6).
24 These novel communities arose as individual species exhibited distinct responses to
25 environmental change, resulting in new combinations of species outside their historical
26 ecological contexts. Such individual responses and reshuffling of communities
27 experiencing change are natural phenomena that continue today. Complex ecological and
28 evolutionary relationships and varying adaptive capacities influence whether and how
29 distinct species respond.

30 Land-use transitions have changed and varied spatially and temporally throughout the
31 precolonial period. Prior to European colonization in North America (Figures 9.1 and 9.2),
32 the Americas were interconnected by a rich history of societies and civilizations that
33 established trade routes and agricultural activities (7,8). Charcoal records, raised fields,
34 subsistence agriculture, urban centers, and market economies provide key insights into
35 the historic land and ocean use and management practices of early modern humans (8–
36 10). Indigenous Knowledge systems provide a rich source of information regarding both
37 pre-and post-European land use conditions. Further, historical ecology is a scientific
38 discipline dedicated to understanding how human–environment interactions have shaped
39 ecosystems and the environment before and after human interventions, employing
40 methods that use fossil records (e.g., pollen, stable isotopes, packrat middens,
41 archaeological sites) and oral histories (e.g., community science) (11–13).

1 Early modern humans adapted to many diverse ecosystems. A reconstruction of Late
2 Holocene (11,700 years ago to the present day) biomass burning in the tropical Americas
3 found evidence of a reduction in burns that coincided with European conquest and
4 decreased populations of **Indigenous Peoples** (9). With the Doctrine of Discovery – a legal
5 and religious justification used by European colonizers the **dispossession** of lands
6 escalated from the mid-1400s through the mid-20th century, which was followed by
7 Indigenous depopulation (14) and a marked shift in the **stewardship** of land and of inland
8 and marine waters. In the precolonial period, Indigenous management practices
9 contributed to habitat productivity using various methods, including controlled burning,
10 coppicing, and pruning for regenerative and productive forests (15,16). Indigenous forest
11 gardens are one example of these activities in the Pacific Northwest (17–19). Although
12 there are uncertainties about the distribution and abundance of grasslands, shrublands,
13 and heathlands in coastal New England in the precolonial period, one study estimated that
14 the region was mainly wooded prior to land clearing that accelerated in the seventeenth
15 century (20). There is evidence of field camps and maize cultivation in the New England
16 area dating back to the late Woodland period in ancient America (21). In the Northwest,
17 mariculture practices evidenced by clam gardens throughout the Holocene reveal
18 intertidal management in the Salish Sea (22). Native Hawaiian fishponds provide another
19 example from the Pacific islands of traditional aquaculture systems (23). Over millennia,
20 Indigenous Peoples throughout the US and US territories have carried out **place-based**
21 practices that continue to shape **social-ecological relationships** today. Resilient
22 ecosystems have been linked to long-term Indigenous stewardship and land management
23 practices that enhance biodiversity and ecosystem stability, such as oyster harvesting,
24 shell middens, and cultural burning (24–26).

25 With the onset of **European expansion** in the Americas in the mid-1500s, the
26 establishment of colonies was followed by the killing and forced removal of Indigenous
27 Peoples. By the 19th century, Indigenous populations and territories in the US were
28 reduced in size substantially, which reshaped the North American natural landscape due
29 to land dispossession and forced migration of Native Americans. The full impact of land
30 dispossession has not been determined due to limited data availability (27). **Regenerative**
31 land stewardship practices long upheld by Indigenous Peoples were disrupted by
32 extractive land use and industrialized agriculture that were focused on short-term
33 maximization of profit and crop yields, and natural resources and cultural assets were
34 diminished (28). Notable changes in the environmental practices included plantation
35 agriculture and deforestation from clear-cutting, resulting in timber shortages and soil
36 erosion that were evident as early as the 18th century (29,30). During this time, the fur
37 trade, hide-hunting of beavers and bison, bounties on large predators, and unregulated
38 hunting of game species drastically reduced populations of many species, with
39 ecosystem-level ripple effects. Loss of these ecological and **cultural keystone species**
40 and their vital roles in ecosystem functioning (e.g., maintaining grassland ecosystems and
41 increasing aquatic biodiversity) had negative environmental impacts (e.g., pollution,
42 hydrology, water quality). These activities not only impacted natural systems but also
43 upset critical cultural keystone species for affected communities.

1 The **transatlantic slave trade** and the system of plantation slavery were major drivers of
2 environmental transformation in what became the United States, reshaping landscapes
3 through coerced labor, intensive resource extraction, and global commodity production.
4 Enslaved people were forced to clear vast tracts of forest and wetlands to establish
5 plantations—particularly for cotton, tobacco, rice, and sugar—resulting in widespread
6 deforestation, habitat loss, and declines in biodiversity (31,32). Plantation agriculture
7 relied heavily on monocultures, which depleted soil nutrients, altered soil composition,
8 increased erosion, and reduced ecological resilience. This in turn contributed to long-term
9 land degradation and encouraged continual westward expansion as soils were exhausted
10 (33–35). In coastal regions of the Southeast, enslaved Africans—many drawing on
11 agricultural knowledge from West Africa—constructed extensive irrigation, diking, and
12 canal systems for rice cultivation, fundamentally altering wetland hydrology and
13 biogeochemical processes (32,36). Mining activities also negatively impacted the health of
14 streams, forests, and whole biomes (34). The slave trade also brought in new species, as
15 the peak of transatlantic migration of mosquitoes coincided with the height of the
16 transatlantic slave trade (around 1800), leading to yellow fever easily affecting people
17 onboard (37,38). These transformations produced enduring environmental legacies;
18 plantation systems reshaped landscapes through widespread deforestation, soil
19 degradation, and hydrologic alteration, leaving land-use patterns that continue to reflect
20 plantation-era organization.

21 **The Industrial Revolution** marks a time of rapid and extensive industrial growth, beginning
22 in Britain during the second half of the 18th century, with subsequent spread to the United
23 States (39). A shift to an industrialized urban society from an agrarian society led to
24 economic growth and a greater availability of goods (see Ch. 12: Economy). The Industrial
25 Revolution led to a marked increase in greenhouse gas (GHG) emissions, primarily due to
26 the burning of fossil fuels such as coal (39–41). Since the industrial and technological
27 revolutions, the planet has warmed between about 1.1° to 1.2°C (about 2° to 2.2°F), largely
28 driven by an increase in GHGs with very high confidence that this warming is human-
29 caused (41). While the climate system is also influenced by events such as volcanic
30 eruptions and solar activity, these drivers of change have minimal influence on long-term
31 climate forcing (42). Climate change and biodiversity dynamics have been deeply
32 interconnected throughout the evolutionary history of life, and biodiversity loss is
33 unequivocally entwined with direct and indirect human-caused stressors.

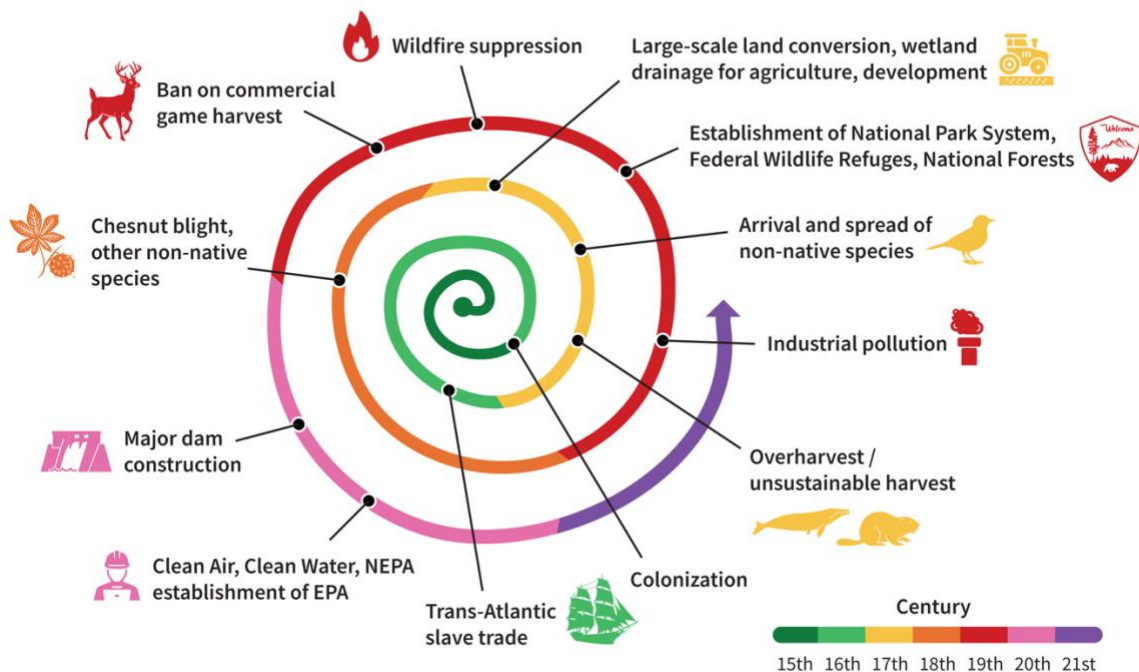
34 In addition to their influence on the climate, humans disproportionately impact the natural
35 environment through other direct and indirect mechanisms. All aspects of nature have
36 been impacted, leading to extensive air and water pollution, habitat degradation,
37 deforestation, and loss of biodiversity, all now exacerbated by climate change (see Ch. 10:
38 Climate Change) (43). Moreover, the interaction among drivers operates in both directions:
39 changes in land-use and land degradation combined have led to about 35% of human-
40 caused CO₂ emissions to the atmosphere since 1850, further amplifying the effects of
41 climate change (44). Likewise, rapid population growth and urbanization have led to an
42 increase in manufacturing and resource extraction that pollute marine and freshwater

1 resources with heavy metals and anthropogenic chemicals, which have degraded the
 2 environment (45). In contemporary science and social policy, we characterize the sum of
 3 those activities as anthropogenic drivers of change in nature.

4 The capacity to drive change for the better often aligns with economic, technological, and
 5 policy advances that support ecosystem restoration and resilience. The expansion of
 6 urban green infrastructure, including green roofs, urban forests, and stormwater
 7 management systems, also promotes ecological benefits by reducing heat islands,
 8 improving water quality, and providing habitat in cities (46). Finally, reforestation and
 9 afforestation initiatives can sequester carbon, restore degraded landscapes, and support
 10 wildlife connectivity, contributing to climate mitigation and biodiversity conservation
 11 simultaneously (47).

12 **Figure 9.1. Timeline of Historical Human Events That Influenced Drivers and Related**
 13 **Major Changes in Nature**

Timeline of Historical Human Events that Influenced Drivers and Related Major Changes in Nature



14

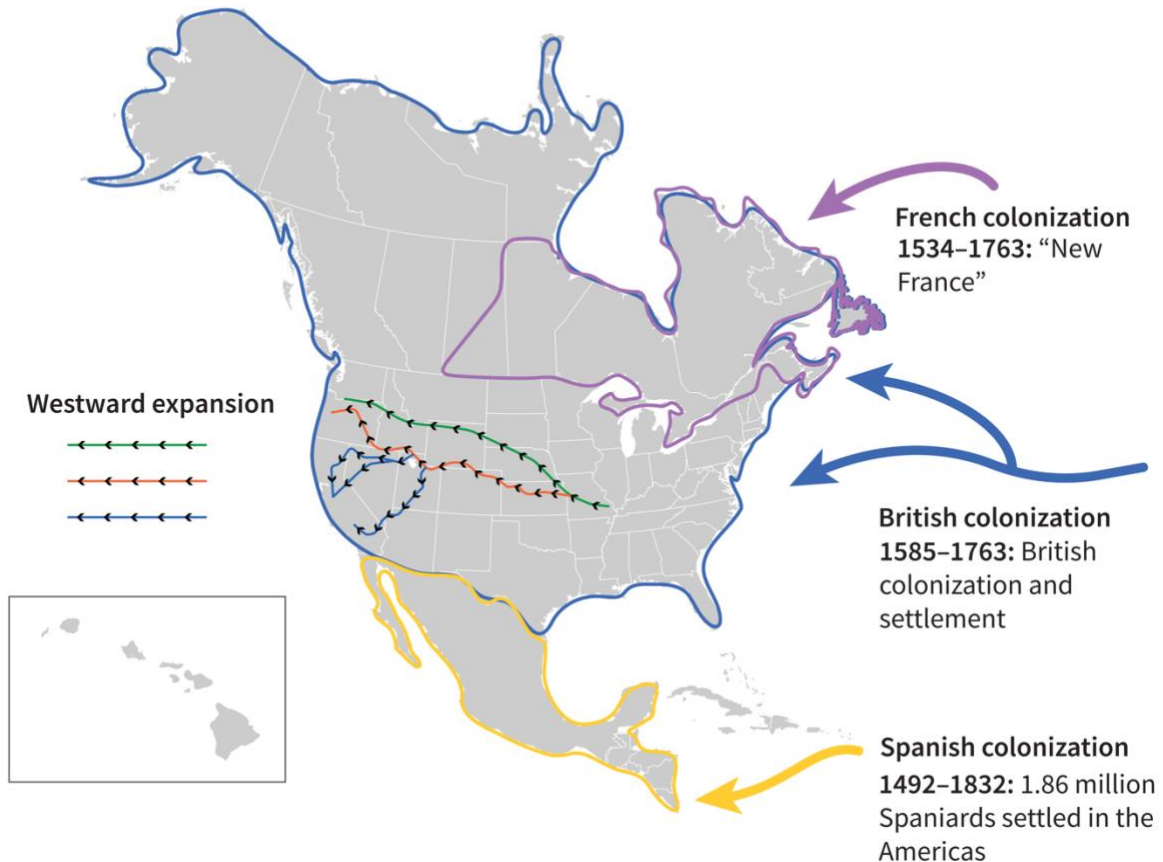
15 **The current and future state of the environment, ecosystems, and biodiversity in the**
 16 **United States has been substantially affected by a cumulative and ongoing series of**
 17 **anthropogenic drivers since the arrival and subsequent expansion of European**
 18 **colonization and settlement.**

19 *The timeline begins with the onset of European colonization. Starting at the center of*
 20 *diagram, nodes (with symbols) indicate the onset of notable historical human events that*

1 *influenced drivers of change of nature that continued for extended periods of time.*
 2 *Changes in color (from green to purple) indicate increases in geographic expansion and*
 3 *intensity. The diagram demonstrates the increasing geographic expansion and intensity of*
 4 *drivers that have impacted the natural environment. Figure original to The Nature Record.*

5 **Figure 9.2. Historical Waves of Colonization in North America**

Map Showing Initial Waves of Colonization



6

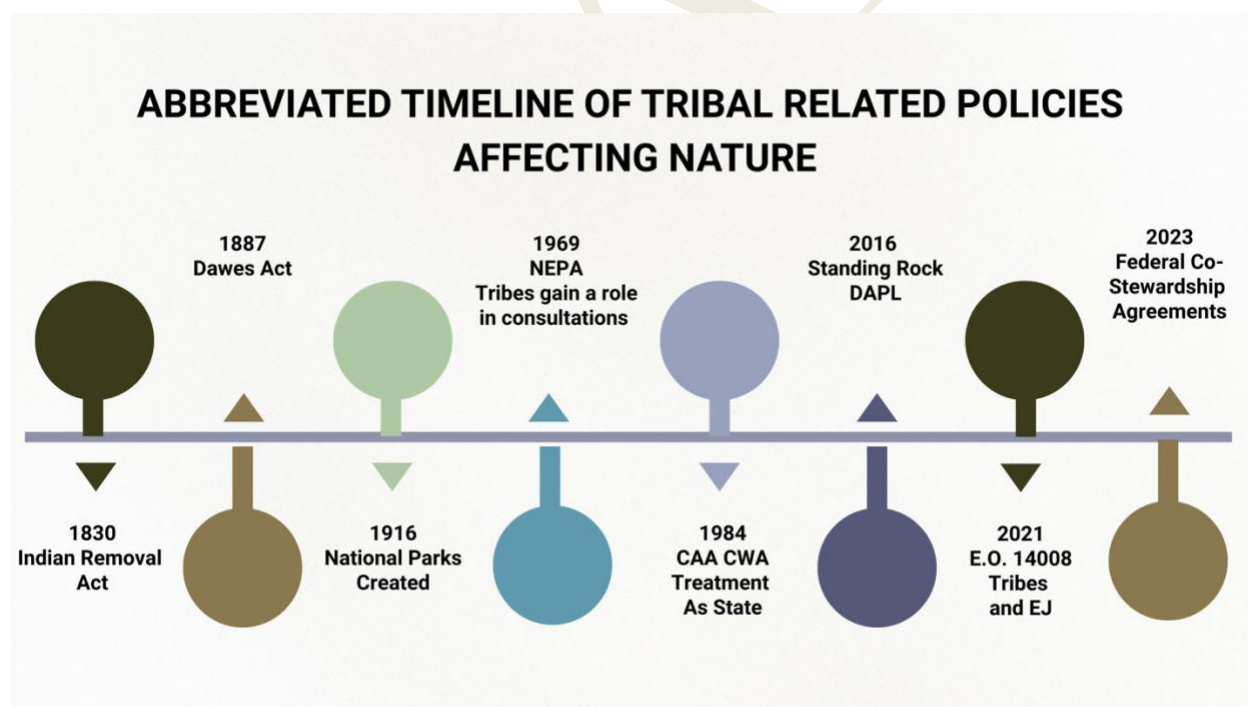
7 **Three waves of colonization led to the displacement of enslaved Africans and forced**
 8 **removal of Indigenous Peoples in North America.**

9 *The map of the US shows the general locations and timing of three key waves of*
 10 *colonization. First, The Spanish colonization occurred in Mexico during 1492–1832.*
 11 *Second, British colonization and settlement occurred in the US during 1585–1763. Third,*
 12 *French colonization occurred in Canada during 1534–1763. Taken together, these waves of*
 13 *European settlers killed 56 million Indigenous People over a 100-year period and*
 14 *dislocated 12.5 million enslaved people. Figure original to The Nature Record.*

15 The modern impacts of human activities on the climate system and on biodiversity were
 16 not realized by most Americans until many decades after the start of the Industrial

1 Revolution. Such recognition has now led to numerous efforts to protect and restore
 2 nature. Beginning in the 1970s, many environmental laws have been implemented in the
 3 US. **The Clean Air Act, Endangered Species Act, Safe Drinking Water Act,** and the
 4 **Surface Mining Control and Reclamation Act** are examples of federal laws that were
 5 introduced to implement ecological restoration and conservation. There is also growing
 6 acceptance of a pluralistic understanding of nature change that is inclusive of **Indigenous**
 7 **Knowledges (IK)** or **traditional ecological knowledge (TEK)** in scientific research and in
 8 institutional structures. Institutional mandates have been introduced to respect and
 9 promote the inclusion of IK/TEK in decision-making and programming (48). Such efforts
 10 promote IK/TEK to be on equal footing with mainstream scientific approaches and highlight
 11 the importance of aligning research with protocols for engagement with Indigenous
 12 Nations, urban populations, and other communities (e.g., (49)). Policy changes affecting
 13 Tribal Nations' relationships with nature (land, water, and natural resources) are critical for
 14 predicting future drivers of climate change. Indigenous peoples steward extensive
 15 ecologically significant lands, often using knowledge systems that have maintained
 16 ecosystem resilience for millennia. Existing policies governing Tribal sovereignty and
 17 environmental co-management directly influence how US lands will be protected or
 18 exploited (Figure 9.3). These changes help shape future drivers of climate change
 19 trajectories, such as effects on biodiversity and landscape-level climate feedback loops.

20 **Figure 9.3. Abbreviated Timeline of Tribal-Related Policies Affecting Nature**



21
 22 **Federal law has oscillated between dispossession, exclusion, and, more recently,**
 23 **efforts toward inclusion and co-stewardship with Tribes. These shifts have had**
 24 **profound implications for land management and climate resilience across the United**
 25 **States.**

1 *The historical pattern of dispossession and exclusion has gradually given way to*
2 *consultation, inclusion, and co-management of public and Tribal lands. If integrated more*
3 *fully, federal policies have the potential not only to advance Indigenous and environmental*
4 *justice but also strengthen ecological resilience and climate adaptation by restoring land-*
5 *management practices rooted in long-term stewardship for the betterment of our shared*
6 *environment. The 1830 Indian Removal Act authorized the forced relocation of tribes from*
7 *their ancestral homelands, uprooting tens of thousands Indigenous peoples and disrupting*
8 *centuries-old ecological relationships. The 1887 Dawes Act (General Allotment Act) broke*
9 *up communally held Tribal lands, declaring “surplus” lands open to non-Native*
10 *settlement, reducing Tribal landholdings by the 1930s. In 1916, the National Park Service*
11 *was created, marking the implementation of a federal conservation model that placed vast*
12 *landscapes under government control. Much of that land had long been stewarded by*
13 *Indigenous peoples, and the shift often excluded Tribal presence, access, and traditional*
14 *stewardship practices. The 1969 National Environmental Policy Act requires federal*
15 *agencies to assess environmental impacts before taking major actions. When those*
16 *actions affect federal Tribal lands, tribes are to be consulted, a procedural opportunity for*
17 *Tribal involvement. In 1984, the US Environmental Protection Agency issues its “Treatment*
18 *as State” under the Clean Air Act and the Clean Water Act. This policy formally*
19 *acknowledged Federally Recognized Tribes as appropriate entities to set environmental*
20 *standards, granting Tribes regulatory authority similar to that of states over air, water*
21 *quality, and other environmental protection programs. In 2016, the Dakota Access Pipeline*
22 *project triggered broad Indigenous and environmental opposition. Tribes argued that the*
23 *permitting process violated environmental law and failed to respect treaty rights and*
24 *cultural obligations to land and water. In 2021, Executive Order 14008 gestured a renewed*
25 *federal commitment to environmental justice, recognizing the disproportionate burdens on*
26 *Indigenous and other historically marginalized communities (this order was later*
27 *overturned). The 2023 Federal “co-stewardship” agreements under the US Department of*
28 *the Interior promoted agencies formally partnering with Tribal Nations to jointly oversee*
29 *federal lands, waters, wildlife, and cultural resources. Figure original to The Nature Record.*

30 **Key Message 9.1: A complex network of direct and indirect drivers**
31 **caused by human actions and value systems affect nature on an**
32 **ongoing basis**

33 *Direct drivers that are widely recognizing as affecting nature include habitat loss,*
34 *disturbance, and fragmentation; pollution; overharvest; the spread of invasive, non-*
35 *indigenous species; and climate change (virtually certain). Human activities also affect*
36 *nature through more complex, indirect pathways, based on the underlying economic,*
37 *social or political considerations driving direct factors (very well established). Drivers*
38 *manifest differently across different ecosystems, locations, and time periods (virtually*
39 *certain) and can occur separately from, in combination with, or through networks of*

1 *multiple chains of causation (very well established). These drivers ultimately trace back to*
2 *human actions motivated by cultural values and worldviews (well established), and*
3 *understanding these causal networks can reveal possible opportunities for beneficial*
4 *interventions (well established).*

5 State of Knowledge 9.1

6 Direct Drivers of Change

7 Some anthropogenic drivers of change in nature are direct, where human activities have an
8 immediate, direct effect on natural systems. For example, harvesting of fish, wildlife, or
9 trees for human consumption, or removal of undesirable predators or pests, are direct
10 drivers that can have a wide range of outcomes for biodiversity depending on location,
11 scale, frequency, duration, intensity, type, or other specific characteristics. Other direct
12 drivers include climate change (for example, the direct impacts of GHG emissions, shifting
13 temperatures and precipitation patterns, and related ocean acidification and hypoxia [low
14 oxygen level conditions]), pollution, and land conversion. The latter can take many forms,
15 such as deforestation or tillage of grasslands for agriculture, urban and industrial
16 development, wetland drainage, dam building for water storage or hydroelectric
17 generation that alters natural hydrology and river flow and floods adjoining riparian habitat,
18 and introduction of non-native species (including infectious disease agents) that may
19 dramatically alter the dynamics of native ecosystems and species. All result in loss,
20 degradation, and/or disruption of habitats and species interactions, leading to biodiversity
21 loss.

22 Drivers of change of nature vary in magnitude over time and space (see Key Message 9.2),
23 and they interact in complex ways (50). Direct drivers usually do not operate in isolation,
24 creating the possibility that the effect of one may depend on the operation of others,
25 leading to additive, antagonistic, or synergistic outcomes (see Key Message 9.3). For
26 example, climate change may operate both directly (e.g., through heat-induced mortality)
27 and indirectly (e.g., a warming climate can facilitate northward migration of species not
28 historically found in an area, leading to new competitors or predators for resident species
29 or even emerging pathogens (51–53). Ultimately, changes to ecosystems or their
30 constituent species depend on the interactive and compound effects of the ensemble of
31 all drivers, because the effect of any one driver depends on the combination of drivers in
32 action. A holistic understanding of the cause–effect and feedback mechanisms that affect
33 nature is necessary for assessing current drivers of change and projecting future drivers of
34 change.

35 Indirect Drivers Underlie Direct Drivers of Change

36 Previous reviews and assessments have emphasized direct drivers of change, with less
37 emphasis on indirect drivers such as economics, technology, law, political systems, and
38 policy, and ultimately human values and worldviews (54,55). All “**direct**” **drivers** have their
39 own underlying causes, often referred to as “**indirect drivers**,” (54,56). For example, land

1 conversion to agriculture (Figure 9.4) is the result of a series of actions, beginning with a
2 landowner's decision based on their view of their relationship to the land they control, the
3 economic circumstances they face (commodity prices, policies, alternative land uses,
4 e.g., livestock pasture versus row crop versus conservation or ecological value and
5 incentives), the technology they can deploy to work at broader spatial scales, and access
6 to materials required to operate. When farmers elect to convert prairie or drain wetlands to
7 increase crop acreage (a direct driver), they are typically making an economic decision (an
8 indirect driver or underlying cause) based on commodity markets and policies (which are
9 themselves indirect drivers) that incentivize certain crops or expanded acreage versus
10 policies and incentives (e.g. Farm Bill supported Conservation Reserve Program
11 enrollment) to preserve wildlife habitat (57–59). Alternatively, landowners or stewards may
12 voluntarily maintain lands and waters in a more “natural” state because they value that
13 condition as individuals or culturally (e.g., Indigenous stewardship) (60–62). At every
14 step—from worldview to economics to technology to the decision to convert land to crop
15 production—there are collateral consequences beyond simply destroying grassland or
16 creating crop land. For example, mechanization and increased productivity drive increased
17 use of fossil fuels, particularly in transportation. The results include increased greenhouse
18 gas emissions (63), increased chemical pollution that directly impacts natural ecosystems
19 (64,65), altered hydrology/groundwater (66,67), accelerated loss of topsoil (68), increased
20 spread of non-native species, and loss of natives. Many of these changes will influence the
21 ability of the land to sustain crop production (e.g., through degraded soil, loss of stored soil
22 moisture, loss of pollinators), which may alter the cost–benefit analysis of the landowner
23 in relation to future land-use decisions. Similar analyses of the network of drivers and their
24 interactions would apply for any other ecosystem type (see Chs. 6, 7, 8, and 10).

25 Categorizing drivers as direct or indirect builds on a conceptualization that has been used
26 in prior syntheses (54,56). The comprehensive analysis of drivers of change in nature that
27 we describe here encompasses the full network of indirect and direct factors. Whether a
28 driver is considered direct or indirect is simply a matter of its proximity to the aspect of
29 nature in question (Figure 9.4). Most critically, any ecological or evolutionary function may
30 be impacted through multiple branches of the highly interconnected causal network (69).
31 Moreover, drivers often interact (see Key Message 9.3)—for example, habitat loss by itself
32 will cause population declines, but the effect is exacerbated (an interactive effect) by, for
33 example, expanding populations of invasive species or climate change. Crafting effective
34 solutions thus requires consideration of the network of interacting drivers, and not drivers
35 in isolation; in other words, a **socioecological systems** approach (70,71).

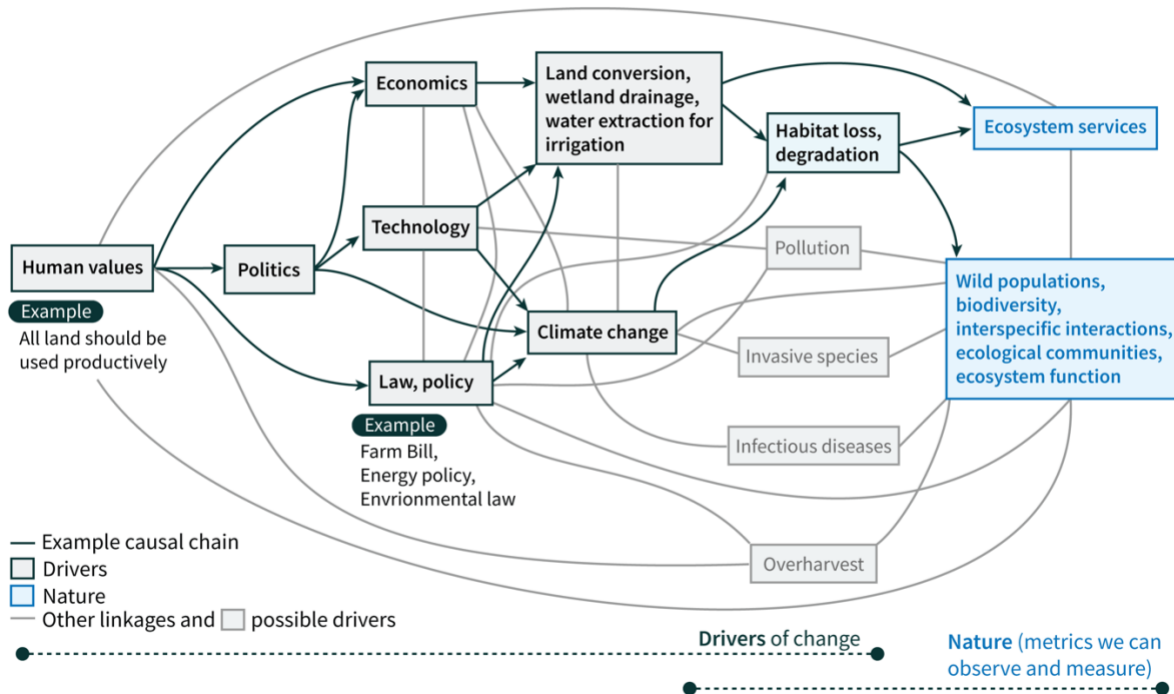
36 A robust understanding of system structure will improve our ability to foresee **tipping**
37 **points**, when systems rapidly and perhaps irreversibly change from a somewhat stable
38 state to an alternate state. Such transitions are—by definition—associated with loss of
39 system resilience—the capacity to withstand the effects of drivers pushing them away
40 from prior states. Maintaining biodiversity, including genetic diversity within species, and
41 ecological integrity (the functional network of species interactions and ecosystem

1 functionality) provides a buffer against perturbation and enhances system resilience (see
2 Ch. 14: Risk and Security) (72,73).

3 Most fundamentally, human values themselves underlie all indirect and direct drivers of
4 change in nature (Figure 9.4, (56)). Values guide the decision-making processes that shape
5 social, political, and economic policies, our actions, and their biodiversity outcomes. For
6 example, many Indigenous and African American cultures have belief systems rooted in
7 the natural world that value long-term stewardship rather than short-term capital, and
8 shared community benefits versus highly skewed individual benefits (48). Globally, areas
9 inhabited primarily by Indigenous communities retain higher biodiversity and ecosystem
10 function than those dominated by Western (Euro-American) cultures (62,74,75). Values
11 and social structures have substantial inertia, and it would be naive to suggest that change
12 is either simple or universally desired. Yet, history documents that change can and does
13 happen, including increasing interest in **Indigenous worldviews** (48,76–79). Within the
14 United States, an ongoing evolution of federal and state policies associated with
15 protecting the environment and species (listed, in part, in the Background) has also
16 produced substantial benefits to nature and humans. Resource management agency
17 culture is undergoing a further shift, both in growing acceptance of Indigenous Knowledges
18 as a valuable source of insight and in rethinking their longstanding mindset that previously
19 had not adequately accounted for ongoing environmental transformation (80–82).

1 **Figure 9.4. The Multiplicity of Interlinked, Interacting Causal Pathways Driving Change**
 2 **in Nature**

The Multiplicity of Interlinked, Interacting Causal Pathways Driving Change in Nature



3

4 **Interconnections between direct and indirect drivers cause terrestrial nature change**
 5 **through land conversion.**

6 *Building on the IPBES framework (56), this diagram highlights (in red) one important and*
 7 *widespread cause of nature change in terrestrial ecosystems—land conversion from forest*
 8 *or grassland to croplands—to illustrate the interconnections among drivers and multiple*
 9 *pathways that impact nature. Direct drivers of nature change are those immediately*
 10 *connected to and therefore identifiable as causes of nature change. They are designated*
 11 *as first degree drivers in this network. They are also commonly monitored and estimated,*
 12 *along with the attributes of nature they affect (both labeled Nature Metrics). Direct drivers*
 13 *are themselves the result of underlying causes—indirect drivers—which may involve a*
 14 *series of factors (causal chains). Indirect drivers may be separated by varying degrees from*
 15 *the attributes of nature they ultimately impact. At this time, the predominant causes of*
 16 *nature change can be traced to human activities that must be understood as*
 17 *consequences of human values and worldviews. Only some of the feedbacks (left-facing*
 18 *arrows) and none of the interactions among factors are illustrated. Collectively, these*
 19 *interconnected causal chains create a causal network (69). Figure original to The Nature*
 20 *Record.*

1 Description of Evidence Base

2 It is *virtually certain* that (a) categorizing drivers of nature change as direct or indirect and
3 that (b) the list of direct drivers includes habitat loss, disturbance, and fragmentation;
4 pollution; overharvest; the spread of invasive, non-indigenous species; and climate
5 change is widely used in peer-reviewed scientific literature and multiple high-profile
6 national or international reports, based on a substantial body of research that reveals
7 consistent observations of proximal causal factors of change. The list of indirect
8 drivers that includes political, social, and economic drivers is *very well established* in the
9 literature, based on a combination of published ecological and social science research
10 derived from a wide range of ecosystems and geographies. It is also *virtually*
11 *certain* that the specific combination of drivers and causal pathways is
12 understood to vary across ecosystem and historical factors. That cultural values and
13 worldviews lie at the center of decision-making, and that understanding such perspectives
14 is critical to effective decision-making, is *very well established* based on published social
15 science research in the “socioecological” and “human dimensions” literature.

16 Key Message 9.2: The main drivers of change in nature correspond 17 with trends in human population expansion, migration, and 18 resource extraction

19 *Population growth and westward migration in the late 19th and early 20th centuries drove*
20 *massive agricultural expansion and forest resource extraction for fuelwood and timber*
21 *(exceptionally likely, virtually certain). These trends were closely followed by*
22 *overharvesting of US fisheries and dam building that fragmented river systems (very likely,*
23 *very well established), patterns that have begun to reverse in many ecosystems in the 21st*
24 *century (likely, well established). Industrialization and technological development led to*
25 *growing fossil fuel extraction and mining impacts on ecosystems throughout the 20th*
26 *century (exceptionally likely, virtually certain). Introductions of exotic, invasive species*
27 *peaked in the 20th century, but their abundance and impact continue to grow (very likely,*
28 *well established). The Clean Air and Clean Water Acts resulted in marked reductions in*
29 *many air and water pollutants since the 1970s (very likely, very well established), although*
30 *pollutants such as nutrients and plastics remain a problem (very likely, well established).*

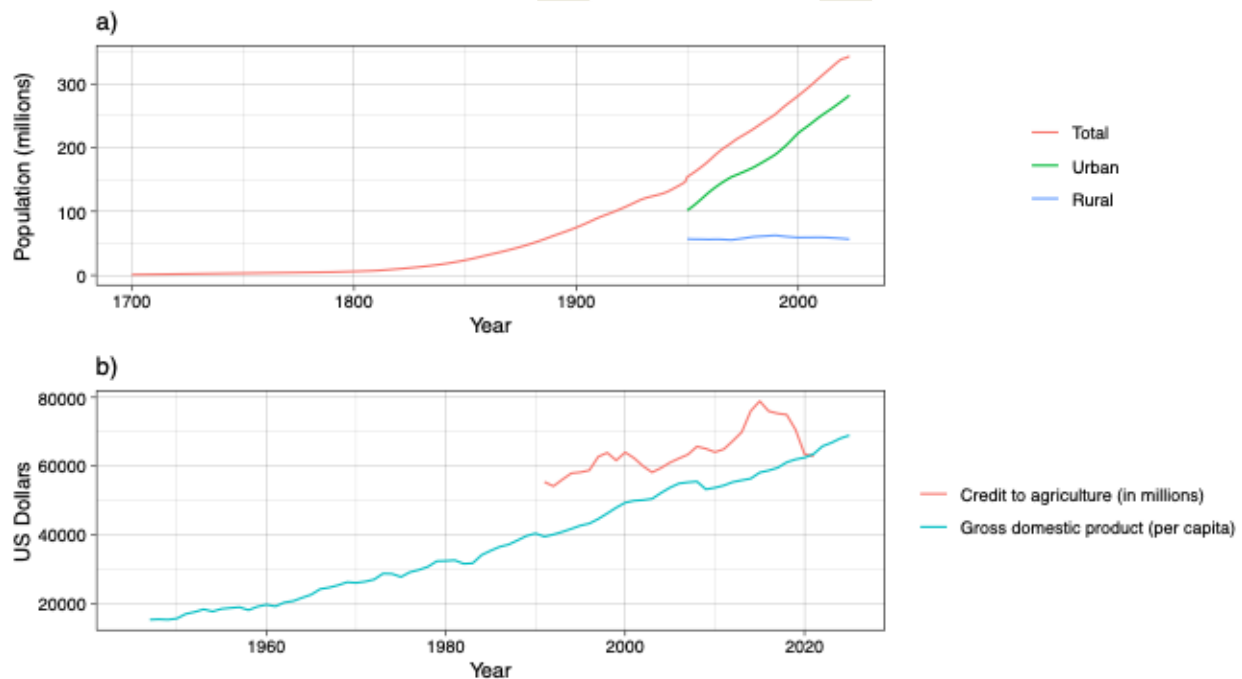
31 State of Knowledge 9.2

32 The US population grew from under one million people in 1700 to over 340 million today
33 (Figure 9.5a). As the population grew and expanded westward, demand for food, fuel, and
34 materials increased in parallel. These demands—along with economic and technological
35 development—have caused massive changes in US lands and waters over the past three
36 centuries. These impacts continue today as the economy continues to grow and people
37 move to urban areas reliant on industrial agriculture for food (Figure 9.5b). Many—though

1 not all—of the changes brought about by US population growth and economic
2 development have been detrimental for nature.

3 Historically, the US has experienced high rates of land-use and land-cover changes
4 associated with the expansion of agriculture (Figure 9.6). From 1800–2000, the area of
5 primary land (defined as land without land-use activity) declined by over 75% (more than
6 500 million hectares (Mha)) (83). Over the same period, the area of land converted to
7 cropland and pasture increased by more than 300 Mha, and the area of secondary land
8 (land recovering from harvesting, logging, or conversion) increased more than 100 Mha.
9 Today, primary land, defined as land not harvested, logged, or converted since the year
10 850, continues to decline in area, while secondary land and urban land continue to grow in
11 area (Figure 9.6). During the 19th and 20th centuries, the rise in agriculture, commerce,
12 and population size led to increasing extraction of fossil energy sources and new
13 environmental challenges, such as invasive species and pollution. US territories have
14 likewise experienced major land use and land cover changes, such as increasing
15 urbanization in Puerto Rico (84), though the trends are poorly documented due to
16 exclusion of the territories from many government databases.

17 **Figure 9.5. Growth in Population Size and Economic Activity in the US**



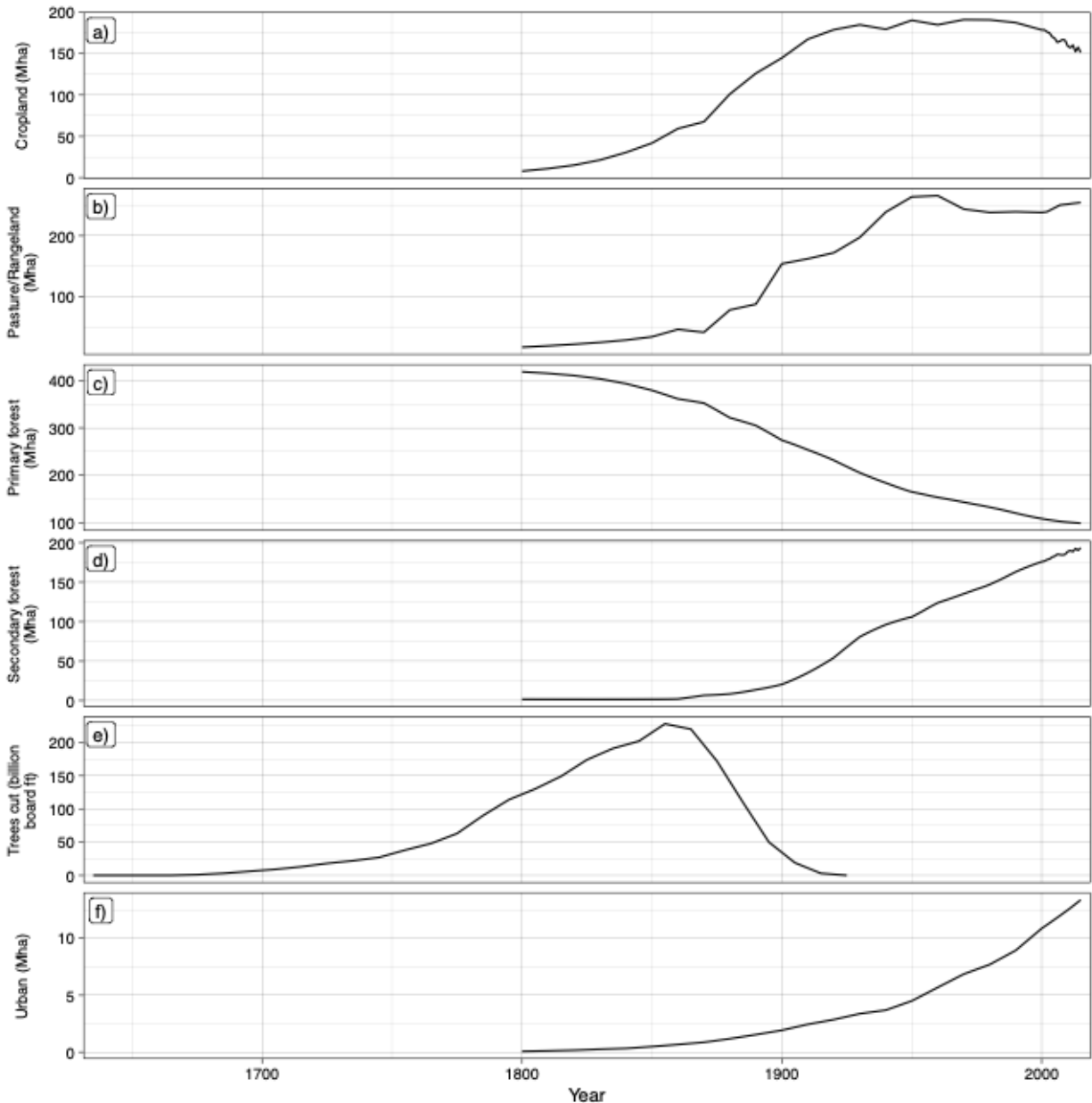
18

19 **US population size and economic activity have grown steadily, with most of the**
20 **population growth since 1950 occurring in urban areas.**

21 *(a) Total US population since 1700 is shown in the red line with urban (green line) and rural*
22 *(blue line) population sizes shown since 1950. (b) Credit to agriculture as bank loans and*
23 *advances in 2015 dollars since 1991 is shown in the red line. Gross domestic product (blue*

- 1 *line) is expressed per capita in chained 2017 dollars for quarter 1 of each year since 1947.*
- 2 *Figure original to The Nature Record. Data sources: Our World in Data (85), FAOSTAT*
- 3 *Population module (86), FAOSTAT Credit to Agriculture (87), US Bureau of Economic*
- 4 *Analysis (88).*

5 **Figure 9.6. Changes in Land Use Over Time in the 50 US States**



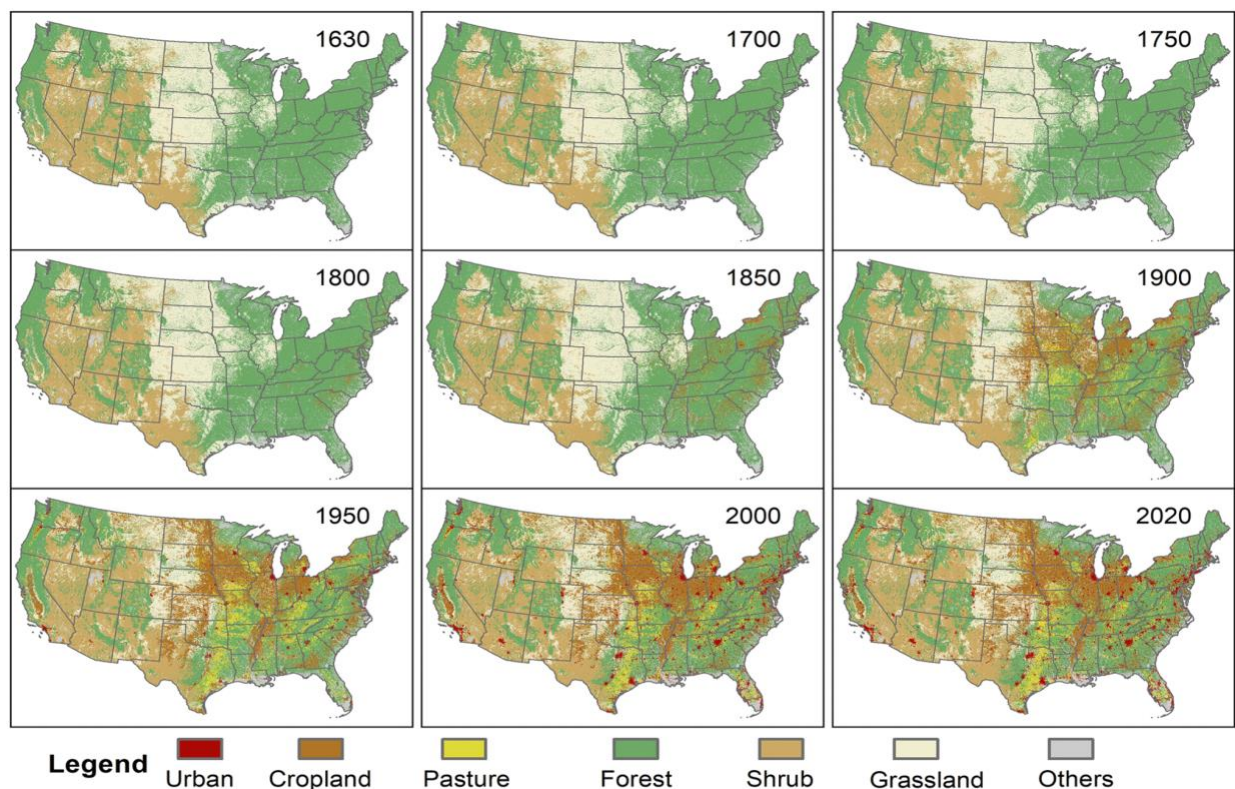
- 6
- 7 **Land uses have changed dramatically in the US since the 1700s, with cropland,**
- 8 **rangeland, pasture, and urban areas expanding.**
- 9 *Logging and forest clearing for crops and grazing increased cropland area (a) and pasture*
- 10 *and rangeland area (b), while reducing the area of primary (uncut) forest (c) since 1800.*

1 Secondary forest area increased after 1900 (d) as trees grew back and forest clearing for
 2 farms declined (e). Urban land area has grown at an increasing rate over the past century
 3 (f). Mha is one million hectares. Figure original to *The Nature Record*. Data sources: (a–d)
 4 University of Maryland Land-Use Harmonization (LUH2) (83); (e) from (89).

5 Cropland Expansion

6 Land conversion to grow crops intensified in the eastern US following colonization, with at
 7 least 24 million hectares (Mha) under cultivation by 1850 in the contiguous US (CONUS)
 8 (90). Croplands then spread westward throughout the midwestern states (Figure 9.7), with
 9 cultivated land area reaching 185 Mha by 1930 (Figure 9.6a). Prior to 1880, most cropland
 10 was converted from forest and shrubland, whereas subsequent conversion was mainly
 11 from grassland, corresponding to cropland expansion throughout the North American
 12 plains. After 1930, additional land area was converted to cropland in California and other
 13 western states. Cropland area rose in Alaska from 0.005 Mha in 1949 to 0.04 Mha in 1992
 14 before declining slightly since then, whereas in Hawai‘i, cropland area fell from 0.2 Mha in
 15 1959 to 0.03 Mha in 2017 (91). The need for cropland irrigation has driven freshwater
 16 withdrawals, particularly in arid and semi-arid regions of the western US (see Chapter 7:
 17 Inland Waters). Although total US withdrawals for irrigation have declined since 1980, the
 18 reliance on groundwater extraction has increased (92).

19 **Figure 9.7. Spatial Patterns in Major Land Uses in the Contiguous US (1630–2020)**



1 **Urban and agricultural land uses expanded westward in the contiguous US from 1630**
2 **to 2020.**

3 *Urban and agricultural land uses have expanded and spread westward across the*
4 *contiguous United States over the past four centuries, displacing forest, shrubland, and*
5 *grassland. These trends are based on integrating multi-source data, such as high-*
6 *resolution remote sensing image-based land-use and land cover (LULC) data, model-*
7 *based LULC products, and historical census data. Adapted from Li et al. 2023 (93). [CC-BY-](#)*
8 *[4.0](#). Data source: HISLAND-US.*

9 Contemporary rates of land-use and land-cover change have slowed markedly relative to
10 historical rates due to a slowdown in agricultural expansion. Agricultural abandonment
11 has reduced cropland in some areas, particularly in the eastern and midwestern US. By
12 2015, cropland area had declined to 151 Mha from its peak of 191 Mha in the 1970s. Total
13 cropland abandonment was about 65 Mha during the period from 1850 to 2016, with most
14 abandonment occurring in the central and southeastern US (90). Based on Landsat
15 imagery, 12.3 ± 2.9 Mha were abandoned between 1986 and 2018, mainly in the northern
16 and southern plains, the lower Mississippi, and the southeast (94). The USDA's Economic
17 Research Service Major Land Uses dataset indicates a decline in the national share of crop
18 land use from 23.7% in 1945 to 20.7% in 2012 (95).

19 However, recent trends in agriculture land area are complex, with evidence for cropland
20 expansion between 2008 and 2012. Over this time, 2.97 Mha were converted to cropland
21 while 1.76 Mha were removed from production for a net cropland expansion of 1.21 Mha
22 (96). Nearly 77% of the converted area was grassland, and the land was mainly used to
23 grow corn, wheat, and soybeans.

24 The proportion of land used for different crops has changed over the period from 1926 to
25 2019. While the proportion of cropland area planted in corn has remained stable over this
26 period, at around one-third, the proportion of soybeans has surged from almost zero to
27 nearly one-third, displacing other crops such as oats and cotton (95).

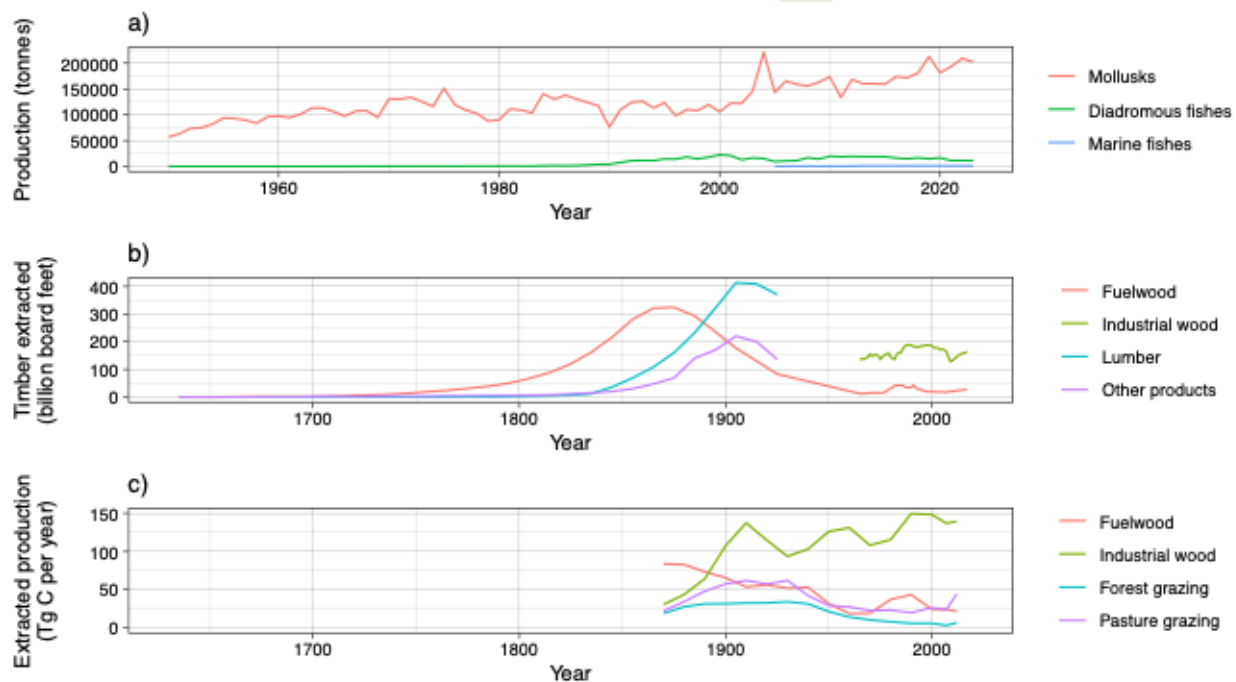
28 *Aquaculture*

29 Aquaculture has deep historical roots, beginning with early carp cultivation in China nearly
30 8,000 years ago, when farmers diverted river water into ponds to trap and raise fish (97). In
31 the Pacific, Native Hawaiians engineered *loko i'a*—sophisticated lava-rock fishponds that
32 harnessed tidal flows to cultivate mullet and milkfish—an Indigenous innovation that
33 shapes Hawai'i's contemporary role in aquaculture development, especially in the
34 aquarium trade (23). Over the past several decades, aquaculture has transformed into a
35 highly intensive global industry, expanding production while heightening concerns about
36 nutrient pollution, disease transmission, and escapes of farmed species; in the US, the
37 industry is growing slowly but steadily due to economic and nutritional demand (98).
38 Marine aquaculture (mariculture), a major component of this growth, has increased in US
39 coastal waters since 1950 (99), particularly for mollusks (Figure 9.8a), although production

1 data remain incomplete and regulations fragmented, leaving broad potential for future
2 development (100,101).

3 In freshwater environments, aquaculture can generate substantial ecological impacts:
4 uneaten feed and fish waste from ponds, cages, or net-pens can drive nutrient loading,
5 eutrophication, altered algal communities, and reduced dissolved oxygen, as documented
6 across multiple systems (102–104). Effluents may also contain pathogens, antibiotic-
7 resistant bacteria, and chemical contaminants that degrade water quality and threaten
8 wild fauna (105). Escapes of non-native or domesticated stocks pose additional risks,
9 including competition, hybridization, ecosystem disruption, and the introduction of
10 diseases or parasites to wild populations (106,107). Similar concerns apply to mariculture,
11 where environmental impacts depend heavily on species, location, and feeding practices;
12 documented effects include nutrient enrichment, pathogen and parasite transfer, habitat
13 alteration from infrastructure, and establishment of invasive or hybridizing escapees (108–
14 110).

15 **Figure 9.8. Extraction of Resources from Water- and Land-Based Ecosystems over**
16 **Time in the US**



17

18 **Aquaculture production has risen in recent decades, while forest harvesting and**
19 **grazing have declined over the past century.**

20 *(a) Aquaculture operations have produced an increasing quantity of mollusks (such as*
21 *oysters) from mainly coastal waters since 1950, while farming of diadromous fishes such*
22 *as salmon has declined slightly since 2000. (b) Wood extraction for fuel peaked in the mid-*
23 *1800s, whereas extraction for lumber and industrial uses peaked after the turn of the 20th*

1 century. “Industrial wood” includes lumber and some other products. (c) Wood extraction
2 and grazing in forests and rangelands has removed substantial amounts of plant carbon
3 (C) from land ecosystems; one Tg (teragram) equals one million tons. Figure original to *The*
4 *Nature Record*. Data sources: FAO Fisheries & Aquaculture (99); panel (b) from (89) prior to
5 1965 and from (111) after 1965; panel (c) from (112).

6 *Timber Extraction*

7 Changes in US forests have mainly been driven by domestic resource needs and economic
8 pressures (Figure 9.8b). Industrial wood imports made up less than 10% of total wood use,
9 reaching a high of 18% in 2007 (112). From 1630 to 1930, population growth and the need
10 for fuel and building materials led to heavy timber extraction across the country, beginning
11 in the East (89).

12 Forest clearing for agriculture reached its highest levels in the 1850s at 228 billion board
13 feet per decade (Figure 9.6e). Fuelwood extraction peaked in the 1870s at 324 billion board
14 feet per decade (Figure 9.8b) (89). Lumber extraction peaked in the early 1900s, between
15 1900 and 1909, with 413 billion board feet taken for timber and 220 billion board feet for
16 other wood products (Figure 9.8b). After 1930, harvesting for timber and wood products
17 continued to remove over 100 teragrams of carbon per year from US forests, while the
18 carbon removed by fuelwood harvesting continued to decline (Figure 9.8c). By the early
19 1900s, fossil fuels had begun replacing wood as the main energy source, a shift that
20 continued through the 20th century (112).

21 More recently, US timber production increased from 135 billion board feet in 1965 to a
22 peak of 189 billion board feet in 1989 (Figure 9.8b, “Industrial wood”). It then decreased to
23 192 billion board feet in 2005 (111). The housing market collapse and economic pressures
24 caused production to fall sharply to 128 billion board feet in 2009, followed by a rebound to
25 164 billion board feet by 2017. Timber production closely tracks wood product prices,
26 which rise or fall depending on demand for construction, lumber, pulpwood for paper,
27 fuelwood, and other industrial uses. Forest use land has declined in both Alaska and
28 Hawai'i since they became states in 1959, with a notable decline of 16 Mha in Alaska by
29 2017 (91).

30 *Grazing*

31 Grazing is the most extensive human land use in the contiguous United States. Indigenous
32 communities have long used fire to alter plant community composition and increase the
33 abundance of wild herbivores. Large-scale grazing by domestic livestock first emerged in
34 the southwestern United States, with grazers introduced by Coronado's expedition in
35 1540. Livestock density and distribution increased rapidly in the 1870s following the
36 subjugation of the Apache people (Figure 9.8c), with completion of the Southern Pacific
37 Railroad in 1881 enabling massive expansion of livestock numbers as a regional export
38 market developed (113). Domestic livestock were not present in the northwestern US until
39 the late 18th century but experienced similar rapid increases in numbers in the second half
40 of the 19th century with westward expansion (114). Large increases in livestock numbers,

1 coupled with severe weather (e.g., droughts in the Southwest and cold in the Northwest),
2 led to widespread degradation of rangelands by the early 20th century (113,114), with
3 consequences of degradation including soil erosion, decreased grass productivity, and
4 increased woody plant cover (115). Grazing intensity generally decreased following
5 adoption of the 1934 Taylor Grazing Act that implemented governmental regulation of
6 stocking rates in the public domain (113). Stocking rates in much of the western US
7 continued to drop for decades after the Taylor Grazing Act, as understanding of range
8 carrying capacities became more refined (116), with concomitant increases in rangeland
9 conditions in many locations (117). Forest lands were also subject to grazing pressure that
10 was most intense from 1890 to 1940 and then declined over 75% by 1990 (112). The total
11 area of grazing lands has remained steady over the past 60 years and now accounts for the
12 largest proportional land use area in the US (91).

13 *Urbanization*

14 Between 1630 and 1850, urban land increased by approximately 0.8 Mha in the US as the
15 population grew by 23 million (93). In the latter half of the 19th century, industrialization
16 and the availability of cheap land spurred rapid immigration and urban development, with
17 total urban land reaching 4.3 Mha by 1900. Throughout the 20th century, both population
18 growth and increasing urban land per capita accelerated land conversion. Urban land per
19 capita rose from 0.02 ha per person in 1900 to 0.14 ha per person by 2020, with the total
20 national urban land area expanding to 45.5 Mha (93). This area is considerably larger than
21 the last value shown in Figure 9.6g, possibly due to different definitions of urban land in
22 (83) versus (93), although both studies show rapid growth in urban land area. This growth
23 has been concentrated around major metropolitan areas, particularly in the eastern US
24 and along coastal regions, often replacing agricultural and forested lands and reshaping
25 hydrological, ecological, and climatic processes. Urbanization has altered hydrologic
26 regimes through increased impervious surface cover, leading to higher runoff, reduced
27 groundwater recharge, and degraded water quality in adjacent watersheds (118). Habitat
28 fragmentation and loss of green space have been extensive, contributing to local and
29 regional declines in biodiversity (119). Air pollution associated with vehicular emissions
30 and industrial activities has been mitigated in recent decades through Clean Air Act
31 regulations, yet urban areas remain hotspots for ozone, particulate matter, and heat island
32 effects (120). As of 2020, more than 80% of the US population resided in urban areas (121),
33 underscoring the expanding influence of cities on national patterns of resource demand,
34 waste generation, and climate-related vulnerability.

35 An increasing coastal population is a driver of change in ocean systems. From 1970 to
36 2020, the US population living near the coast grew by 46%, or 40.5 million people, leading
37 to impacts on nearshore marine habitats, including a 12% increase in coastal land
38 development since 1996 (122). Development and sea level rise have altered water cycles,
39 landforms, and plant ecology in coastal marshes and wetlands (123). Human alteration of
40 hydrology—such as wetland ditching and channelization of rivers (see Ch. 7: Inland
41 Waters)—and changing storm activity have interrupted the sediment delivery that sustains
42 many wetlands (124). Drivers of change can be a mixture of direct anthropogenic and

1 passive natural or anthropogenic. For example, in one New Jersey bay, the average net loss
2 rate of 0.35% per year of salt marsh from 1995 to 2015 was driven by excavations for
3 mosquito control (409 hectares), a direct driver, alongside edge erosion (303 ha) and
4 “ponding” (240 ha)—the creation of pools of water within the salt marsh, which may be a
5 function of sea level rise and nutrient pollution (125). Anthropogenic wetland restoration to
6 correct past environmental degradation can be a positive driver, enhancing biodiversity,
7 nutrient cycling, and carbon storage while providing resilience to environmental stressors
8 (126).

9 *Dam Construction*

10 Streams and rivers in the US have been subject to fragmentation by dam building since
11 European colonization (see Chapter 7: Inland Waters), with the oldest recorded dam in the
12 US being the Old Oaken Bucket Pond Dam in Scituate, MA, built in 1640 (127). Flow
13 modification in US freshwater systems, as expressed in reservoir storage capacity,
14 increased rapidly from 1950 to 1970, but has remained largely stable since. The density of
15 stream and river fragments attributed to the construction of 51,923 medium to large dams
16 in the continental US has increased over the period from 1920 to 2010, with most of the
17 increase occurring prior to 1980 (128). The National Inventory of Dams lists 92,521 dams
18 as of 2025, with an average age of 64 years. In total, including small and unlisted dams, the
19 National Aquatic Barrier Inventory has documented over 558,000 dams in the 50 US states,
20 Puerto Rico, and the US Virgin Islands (129). Since 1912, 2,119 dams have been removed in
21 the US, with the rate of removal stable at zero to 6 dams per year prior to 1980 and
22 increasing after that time (130). More than 100 dams per year have been removed in some
23 recent years, suggesting that threats from flow modification may be decreasing through
24 time (131). Some of these removals have already allowed fish populations to rebound,
25 such as the restoration of Chinook salmon runs in the Klamath River watershed within one
26 year after four dams were taken down (132).

27 *Fishing Pressure*

28 Harvesting of fisheries in US waters is an important driver of change in natural marine
29 systems. Fishing contributes to declines through direct harvest (e.g., oyster fisheries),
30 damage (e.g., trawling in seagrass beds), or food-web disruption (133–136). Fishing can
31 also harm non-target species and habitats through **bycatch** (unintended and unwanted
32 capture of marine animals during fishing) and seafloor damage. In some cases, bycatch
33 poses serious threats to endangered species, such as North Atlantic right whales (137).
34 Fishing gear that contacts the bottom can destroy seafloor habitat (138). Trawling annually
35 disturbs an estimated 1.4–7.9% of the continental shelves of the US West Coast and
36 Alaska (139). Impacts are generally worse and recovery times longer in deeper and more
37 complex habitats that experience less natural disturbance (140–142). From the 1960s to
38 1980s, bottom trawling and coral tangle net fishing on the Northwestern Hawaiian Ridge
39 and Emperor Seamounts removed over 200,000 metric tons of corals and 210,000 metric
40 tons of fish annually (143).

1 US federal fisheries management in the ocean, which typically spans marine fisheries from
2 3 to 200 nautical miles from shore, is regulated under the Magnuson–Stevens Fishery
3 Conservation and Management Act (MSA). Fisheries management decisions made under
4 this Act are supported by tools such as annual catch limits that consider risk of overfishing
5 based on the status of specific stocks and are underpinned by strong fishery-dependent
6 data (based on specifics of catch) and fishery-independent scientific monitoring.

7 Science-based policies, such as the MSA, have been a key driver of more sustainable
8 harvesting practices and fisheries recovery (see Chapter 6: Marine). Stocks are considered
9 “subject to overfishing” if they are harvested at a rate that is higher than the rate that would
10 produce maximum sustainable yield, or MSY. In 1999, 36% of federal fisheries stocks were
11 considered subject to overfishing. But from 2014 to 2023, the percentage of federally
12 managed fishery stocks subject to overfishing has remained under 10% (144), and as of
13 2023, it was just 6%. This success was enabled by the policy changes implemented in the
14 Magnuson–Stevens Fishery Conservation and Management Reauthorization Act of 2006,
15 which mandated for every federally managed fishery an end to overfishing and required
16 accountability measures, timelines, and science-based catch limits. This Amendment led
17 to management tools that better aligned conservation and economic incentives, such as
18 the rights-based approaches implemented in 2011 that enabled dramatic recovery of
19 groundfish fisheries along the US West Coast (145).

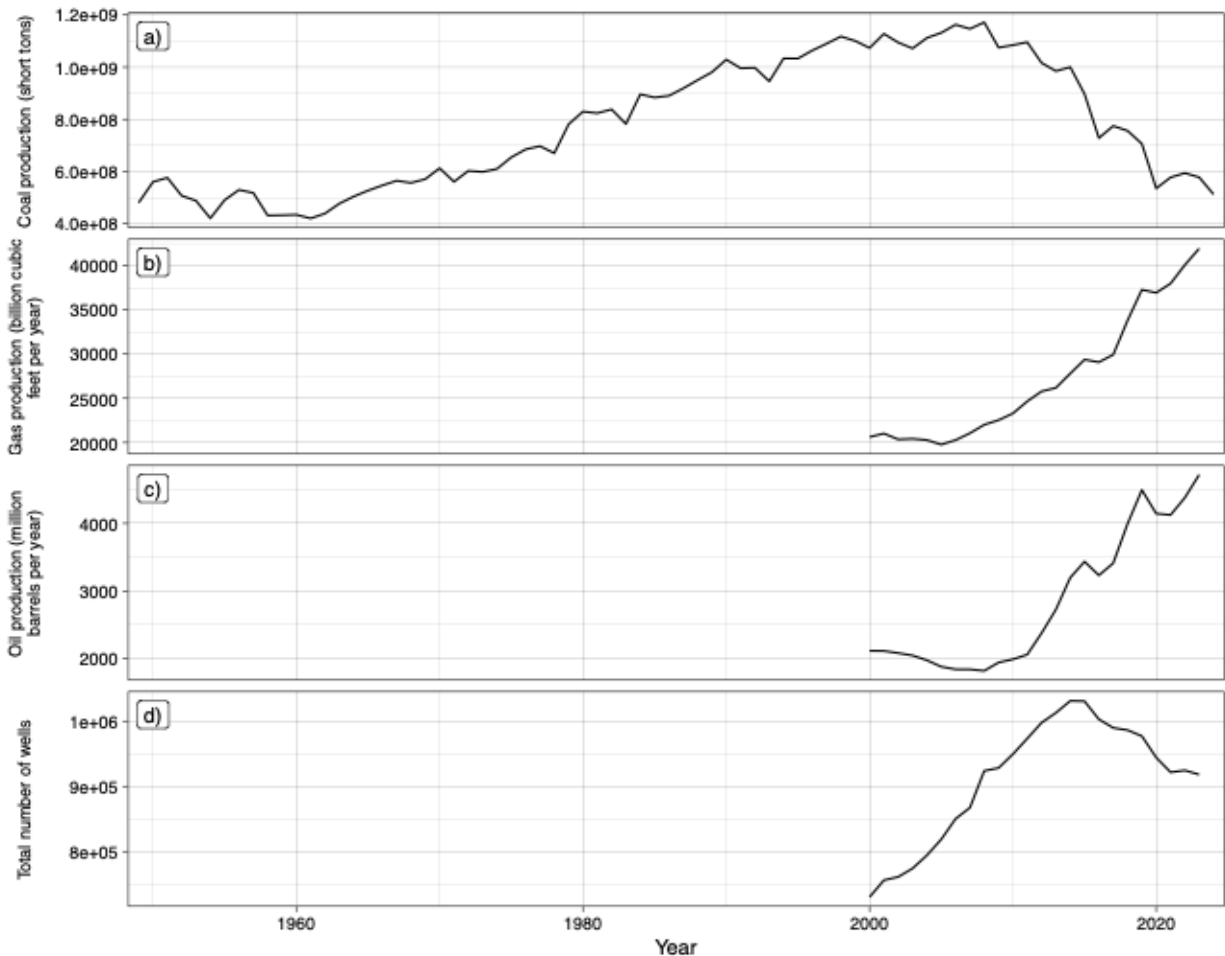
20 Even if not subject to overfishing, stocks may be designated as “overfished” if they are still
21 recovering from historical overfishing or if they face other environmental pressures that
22 limit population recovery. In 1999, 46% of federally managed stocks were considered
23 overfished (146,147). The percentage of overfished stocks of known status declined to
24 between 15% and 20% during 2014–2023, with a value of 18% in 2023. Still, a recent survey
25 of non-federal fisheries that are managed by states or territories or are unmanaged
26 estimated that only 19% had an acceptable stock status from which to base management
27 decisions (148). These fisheries include many commercially, recreationally, and culturally
28 important fish stocks and have significant impacts on nearshore ecosystems, which
29 harbor important marine biodiversity.

30 *Mining and Fossil Fuel Extraction*

31 Mining for minerals, metals, building materials, and coal intensified from the colonial era
32 through the 19th century, leaving a legacy of environmental impacts and costs. Colonial
33 settlers primarily engaged in surface mining activities, such as exploiting oysters for lime
34 and peat for iron. Underground mining accelerated throughout the latter part of the 19th
35 century along with the industrialization of the US. Large mining operations drove other
36 infrastructure development such as canals, roads, and railways. Demand for minerals and
37 materials escalated further with population growth, technology, and industrial activity
38 during the 20th century (149). Iron ore production, for example, grew three-fold from 1900
39 to 1950 before the US became more reliant on imported steel. Coal production quadrupled

1 to one billion tons over the 20th century, peaking at 1.17 billion tons in 2008 (Figure 9.9a).
 2 By 2023, production had declined to 578 million tons, a level last seen in 1969 (150). These
 3 mining activities are associated with environmental impacts such as heavy metal
 4 contamination and habitat loss through stream burial and water flow alteration, all of
 5 which can threaten species populations, such as salmon (151).

6 **Figure 9.9. Trends in Fossil Fuel Extraction in the US**



7
 8 **Fossil fuel extraction in the US has shifted away from coal and toward oil and gas in**
 9 **the last two decades.**

10 *(a) Coal production has decreased sharply since its peak in 2008, whereas gas and oil*
 11 *production has risen sharply since then (b, c) even as active gas and oil wells have*
 12 *declined in number recently (d). Figure original to The Nature Record. Data sources: US*
 13 *Energy Information Administration (150,152).*

14 US oil and gas extraction activities began in the late 19th century and expanded rapidly
 15 during the early to mid-20th century with shifts toward deep offshore oil production and
 16 natural gas fracking in recent decades (153). Drilling for oil began in 1859 in Pennsylvania.

1 The first wells were drilled in California and Texas seven years later, with commercial oil
2 production beginning in Texas in the 1890s. California and Oklahoma dominated oil
3 extraction through the 1920s before Texas became the largest oil-producing state
4 throughout most of the 20th century. Oil extraction activities in Alaska’s North Slope
5 ramped up in the late 1970s.

6 The first offshore oil well was drilled along the southern California coast in 1896 and in the
7 Gulf of Mexico in 1938. Offshore drilling in federal waters accelerated in the 1960s off
8 California’s coast and from the 1960s onward in the Gulf, expanding into deeper waters
9 during more recent decades. These offshore drilling activities cause damage to marine
10 ecosystems by disrupting marine mammal populations with seismic tests, disturbing the
11 ocean bottom with anchors and other infrastructure, and discharging pollutants into the
12 surrounding water (154). Accidental oil spills are common, and larger spills such as the
13 2010 Deepwater Horizon blowout have caused severed, lasting damage to marine and
14 coastal ecosystems.

15 US oil and natural gas production has surged over the last 20 years due to advances in
16 fracking and lateral drilling technology (Figure 9.9b–c). The natural gas boom has led to
17 new surface energy infrastructure development in landscapes overlying gas fields, such as
18 the Marcellus Shale. However, the total number of US oil and gas wells peaked at just over
19 one million in 2014 before declining to 918,000 in 2023 (Figure 9.9d) (152). In the Gulf,
20 natural gas production declined by 79% from 1997 to 2017, while oil production has shifted
21 toward very deep wells (more than 1,500 m) with associated impacts to the deep sea and
22 surrounding ecosystems during oil spills (155). Multiple moratoria on offshore drilling have
23 thus far limited its expansion outside the Gulf Coast region.

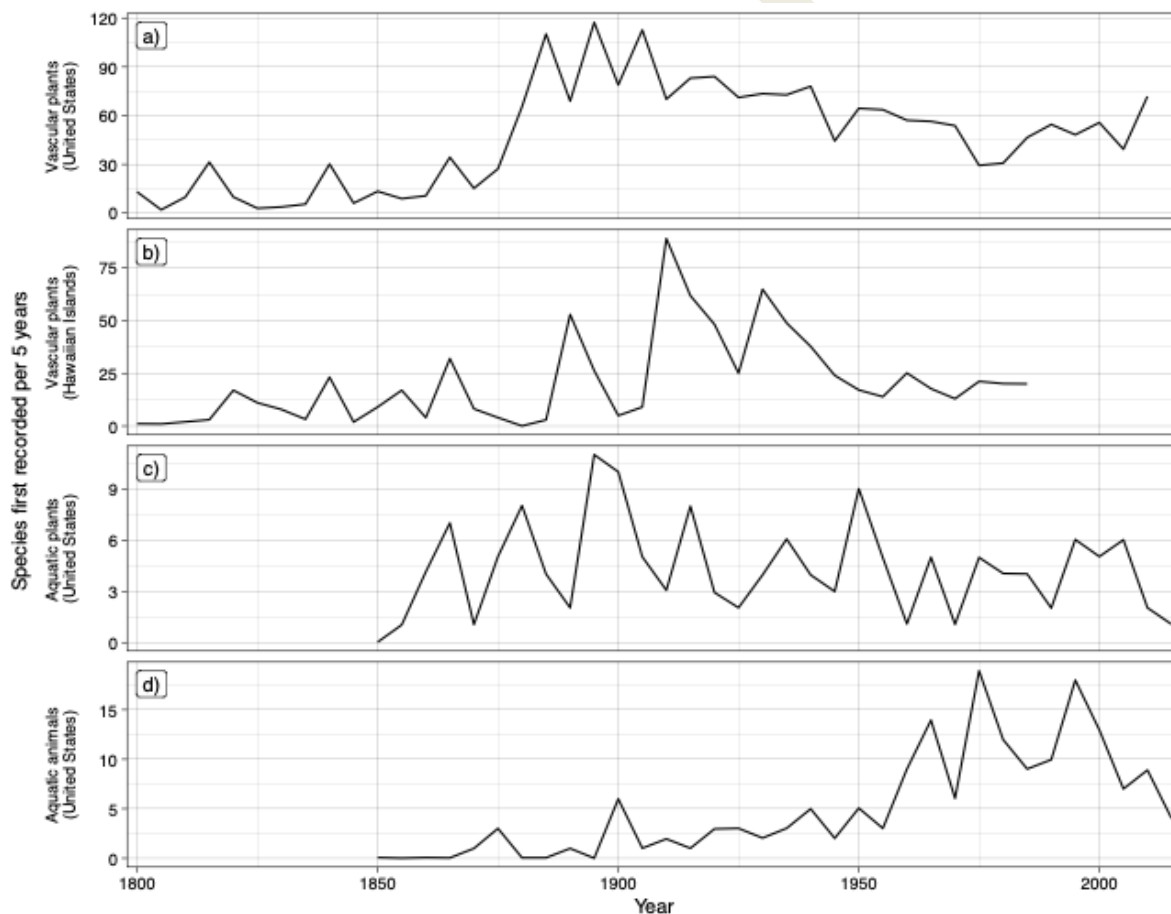
24 *Climate Drivers*

25 Detailed trends in climate drivers are available in the Fifth National Climate Assessment
26 (41) and in Chapter 10: Climate Change. Annual average US temperatures have been
27 rising, increasing by 2.5°F in the lower 48 states and 4.2°F in Alaska since 1970. Ocean
28 temperatures are also going up, especially near Alaska and the Northeast, and sea level
29 has risen about 11 inches on average along the contiguous US coast since 1920 (156),
30 although sea level changes at a particular location depends on variability in local climate,
31 hydrology, and geological subsidence. Higher CO₂ levels are making the ocean more
32 acidic, particularly in polar regions and upwelling systems, such as the California Current
33 system on the West Coast. These conditions can make it more difficult for some animals to
34 build shells and be corrosive to existing shells (157). Coastal hypoxia is also worsening
35 with climate change, putting sensitive species at greater risk to life-threatening conditions
36 (158). Seasonal summer hypoxia at the seafloor along the West Coast has been steadily
37 increasing from 2% spatial coverage in 1950 to an average of 24% in the last decade (159).
38 Rainfall patterns are shifting too—drier in Hawai’i and much of the West, wetter in most of
39 the East—and wildfire patterns have changed, with larger areas burning since 1983 even as
40 the number of fires has not shown a clear trend (160).

1 *Non-Indigenous Species*

2 Non-indigenous species introductions have occurred in what is now the CONUS since
 3 European colonization in the 1600s. Polynesians transported more than 30 plant and
 4 animal species on seafaring canoes that were introduced to the Hawaiian Islands 1500
 5 years ago. European colonists introduced additional species to the Hawaiian Islands
 6 starting in the late 1700s. Reliable records of introduction rates are available for the US
 7 and the Hawaiian Islands beginning in 1800 (Figure 9.10) (161). The typical unit of
 8 measurement for species introductions is the five-year first record rate, or the number of
 9 species recorded for the first time in a specific region during a five-year period. The median
 10 five-year first record rate for vascular plants rose from less than 15 in the early 1800s to
 11 over 100 just before the end of that century before declining toward 50 at the end of the
 12 20th century (Figure 9.10a). The Hawaiian Islands showed a similar trend, with median five-
 13 year first record rates around 10 in the early 1800s and rising to over 60 during the mid-
 14 1900s before declining to around 20 after 1950 (Figure 9.10b).

15 **Figure 9.10. Historical Patterns of Non-Indigenous Species Introductions Across**
 16 **Terrestrial and Aquatic Ecosystems in the US**



17

18 **Introductions of non-indigenous species are an ongoing driver of change in US aquatic**
 19 **and land ecosystems.**

1 (a) On land, introductions of non-indigenous plants peaked around 1900 in the contiguous
2 US, with rates remaining high until present, and (b) introductions peaked during the early
3 1900s in the Hawaiian Islands. (c) In aquatic ecosystems, introductions of non-indigenous
4 plant species have fluctuated, whereas introductions of exotic animal species (d) rose
5 after 1950. US territories, most of which are tropical islands, have also experienced
6 introductions of non-indigenous plant species. In Puerto Rico, forest composition has
7 shifted as a result of multiple tree species introductions (162). Alaska has historically
8 experienced low rates of species invasions, but more disturbance from climate warming,
9 wildfire, and development in recent decades has led to increasing non-indigenous species
10 establishment (163). For instance, plant species introductions have increased from one
11 per year prior to 1968 to three per year from 1968 to 2006 (164). Data are shown as the
12 number of non-indigenous species recorded for the first time over a five-year period. Figure
13 original to *The Nature Record*. Data sources: Terrestrial data = from (161) and aquatic data
14 from (165).

15 Similar trends are apparent for introductions of aquatic plant species in the CONUS (165).
16 Median five-year first record rates rose from 0–1 in 1850 to 7 in the early 1900s before
17 declining to less than 5 for the remainder of the 20th century (Figure 9.10c). However, the
18 pattern for non-indigenous aquatic animal species differs, with introduction rates
19 accelerating steadily from near zero in 1850 to over 10 by the year 2000 (Figure 9.10d).
20 These introductions have resulted in growing numbers, ranges, and impacts of non-
21 indigenous aquatic species (166). A similar trend has been observed in Puerto Rico where
22 80% of freshwater fish species are non-indigenous (167). In the ocean, the number of non-
23 indigenous species along the North American coast increased by more than 50% between
24 2000 and 2010, with 44–78% of initial introductions attributed to commercial shipping
25 (168). DNA surveys show that shipping is also leading to an exchange of pathogens and
26 parasites among regions and ocean basins (169,170).

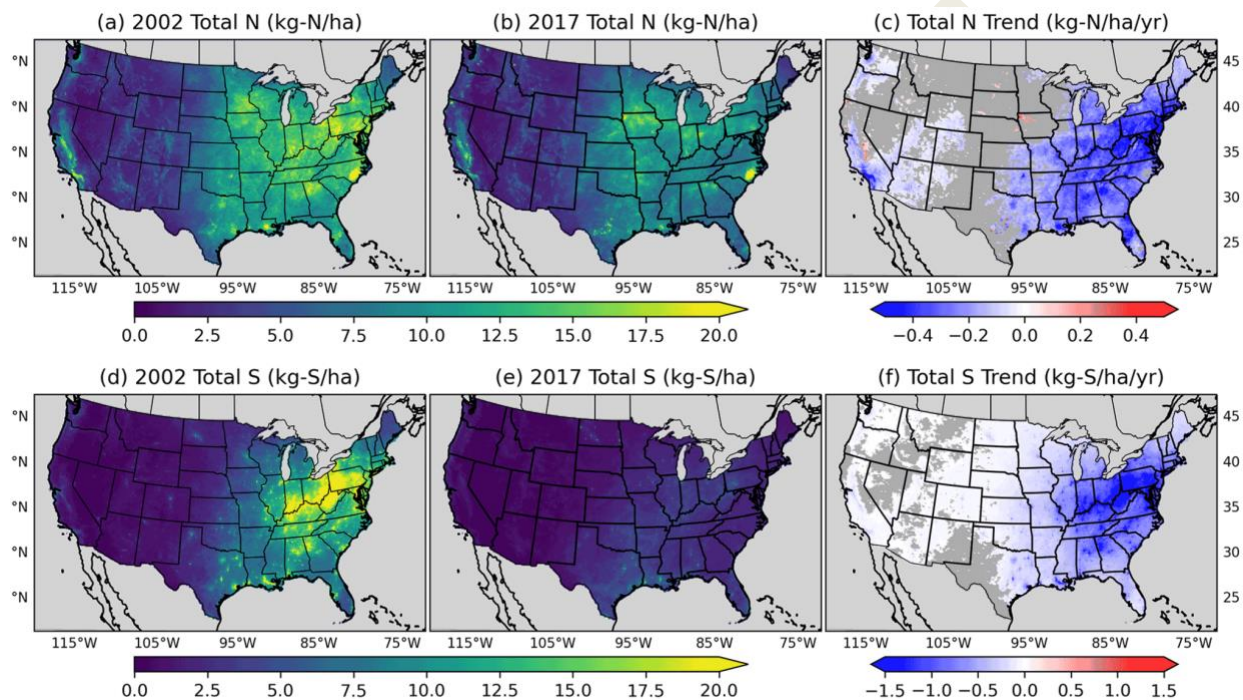
27 While new records of non-indigenous species declined during the late 20th century, their
28 numbers and impacts are increasing. Overall, nearly 50,000 non-indigenous species have
29 taken hold in the US with estimated economic damages over \$120 billion per year and their
30 spread responsible for 42% of the listings on the US Threatened and Endangered Species
31 List (171). Moreover, non-indigenous species continue to spread across the US. During the
32 period 2007–2018, 80% of surveyed national parks in the northeastern US showed rising
33 abundances of invasive plant species (172). More of the surveyed species were increasing
34 rather than decreasing in abundance, with Japanese stilt grass (*Microstegium vimineum*),
35 and several invasive shrubs showing particularly large increases.

36 *Pollution*

37 Atmospheric carbon dioxide concentrations, which directly impact plant photosynthesis
38 and surface ocean pH, have risen from 280 ppm before 1750 to over 425 ppm at present
39 (173,174). Emissions of air pollutants in the US have declined over the period 1980–2023
40 mainly as a result of regulation under the Clean Air Act (175). Declines range from 99% for

1 lead to 58% for volatile organic compounds. Emissions of sulfur dioxide have declined by
 2 94% and oxides of nitrogen have declined by 75%. Carbon monoxide emissions are down
 3 76% and emissions of particulate matter of 10 microns or less in size (PM₁₀) fell 62%.
 4 Emissions of particulate matter less than 2.5 microns in size (PM_{2.5}) are down 28% in 2023
 5 compared to 1990, although larger, more intense wildfires have contributed to a stagnation
 6 or even reversal of this improvement in the CONUS since 2016 (176).

7 **Figure 9.11. Spatial Patterns of Total Nitrogen and Sulfur Deposition (2002–2017)**

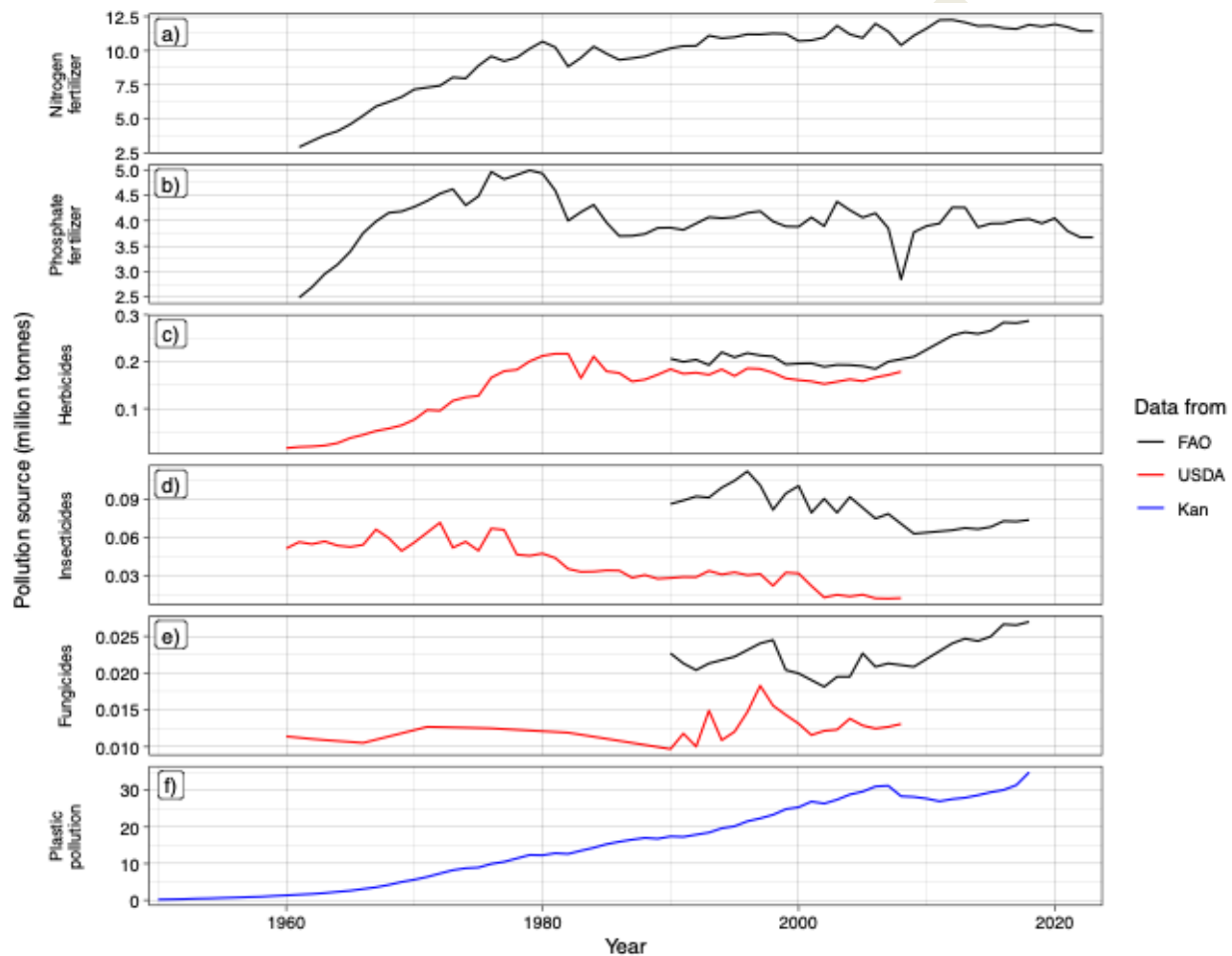


8
 9 **The deposition of atmospheric pollutants has declined dramatically since 2002,**
 10 **especially in the eastern US.**
 11 *(a,b) Spatial distribution of total nitrogen (N) deposition in 2002 (a) and 2017 (b) for the*
 12 *contiguous US in units of kilograms per hectare (kg ha⁻¹). (c) The change in deposition rate*
 13 *over the period from 2002 to 2017 in units of kilograms per hectare per year (kg ha⁻¹ yr⁻¹)*
 14 *with significance at the 95% confidence level based on a Wald statistical test. (d-f) The*
 15 *same results as (a-c) but for sulfur (S) deposition. Gray areas in panels (c) and (f) indicate a*
 16 *lack of data or no significant change. Adapted from Benish et al. 2022 (177). [CC-BY-4.0](#).*

17 Atmospheric nitrogen deposition has declined across the CONUS from 7.8 kg N ha⁻¹ yr⁻¹
 18 (kilograms of N per hectare per year) in 2002 to 6.3 kg N ha⁻¹ yr⁻¹ in 2017 (177). Most of this
 19 decline was driven by areas with historically high deposition, such as the Upper Midwest,
 20 Northeast, and Southeast (Figure 9.11). Declines in the West, with lower initial deposition
 21 rates in 2002, were more modest. Total sulfur deposition across the CONUS dropped
 22 sharply from 5.3 to 1.8 7.8 kg N ha⁻¹ yr⁻¹ over the 2002–2017 period. Geographic patterns in
 23 sulfur deposition and its reduction were similar to those for nitrogen deposition.

1 Deposition of nitrogen in precipitation is relatively low and stable in Alaska’s interior, with
 2 rates $<1 \text{ kg ha}^{-1} \text{ yr}^{-1}$ during 1980-2010 (178), although wildfires were associated with
 3 elevated levels of dry nitrogen deposition in the early 2000s (179). The tropical islands of
 4 Hawaii and the US territories typically receive low levels of pollutant deposition from the
 5 air, although there are local sources from vehicles, shipping, electricity generation, and
 6 wildfires which may be changing over time (180).

7 **Figure 9.12. Trends in Potential Pollution Sources in the US since 1950**



8

9 **Inputs of potential pollutants to the US environment have held steady or increased in**
 10 **recent years.**

11 *Fertilizer applications of nitrogen (a) and phosphate (b) to US agricultural fields increased*
 12 *through 1980, then held relatively steady. Pesticide inputs are dominated by herbicides,*
 13 *such as glyphosate, which have increased in use since the mid-2000s along with*
 14 *insecticides and fungicides (c–e). The data from the US Department of Agriculture (USDA,*
 15 *red lines) account for pesticide applications to 21 crop species—not all—which may help*
 16 *explain the lower numbers compared the Food and Agriculture Organization (FAO) data. (f)*
 17 *Plastic pollution has risen steadily since 1950. Figure original to The Nature Record. Data*

1 *sources: Food and Agriculture Organization, US Department of Agriculture (181); plastic*
2 *pollution data from (182).*

3 River and stream water pollutants in the CONUS have also decreased since the passage of
4 the Clean Water Act in 1972 and the Clean Air Act Amendments of 1970 (183). The
5 Resource Conservation and Recovery Act, passed by Congress in 1976, authorized the US
6 EPA to regulate hazardous waste from generation to disposal. Along with the Superfund
7 program enacted in 1980, this landmark environmental legislation has sharply reduced soil
8 and water pollution from toxic waste, generating nearly \$40 billion per year in economic
9 benefit along with ecological benefits that are more difficult to quantify (184).

10 Based on USGS monitoring of National Water Quality Network sites from 1972 to 2022, the
11 loads and concentrations of 10 water pollution indicators have declined, with the largest
12 declines occurring between 1972 and 1992 (185). The indicators include nutrients,
13 chloride, dissolved organic carbon, total dissolved solids, and suspended sediment. An
14 analysis of these indicators plus five more over the period 1982–2012 corroborated these
15 declines, suggesting improvement in water quality across much of the CONUS (186) (also
16 see Chapter 7: Inland Waters). Changes in watershed management were generally more
17 important than changes in streamflow for explaining improved water quality as measured
18 by pollutant concentrations. However, streamflow changes had a larger impact on trends
19 in pollutant loads. Still, nitrogen and phosphorus inputs have remained high due to
20 agricultural exemptions to the Clean Water Act (Figure 9.12a,b). Agricultural inputs of
21 pesticides have likewise increased or held steady over the past 20 years (Figure 9.12c–e).

22 Stormwater quality in the US has also improved substantially since 1980. Despite
23 increasing urbanization during this period, pollution control measures—mainly related to
24 the Clean Air Act—have reduced pollutants that build up on impervious surfaces and wash
25 into waterways during storms (187). Phasing out leaded gasoline and tightening emissions
26 standards for vehicles, power plants, and industry sharply reduced heavy metal
27 concentrations in stormwater by the 1990s. Suspended solids, such as soot, and nutrients
28 like nitrogen and phosphorus also declined in stormwater between 1980 and 2020, though
29 the declines were not as dramatic as for heavy metals.

30 Degraded water quality and altered water quantity (e.g. changes in freshwater and
31 groundwater inputs) have driven losses in marine systems, particularly of seagrasses and
32 corals (188–192). Nutrient loading into coastal waters has decreased from 2002 to 2012
33 from urban watersheds, but has not consistently decreased for agricultural watersheds,
34 with increases in undeveloped watersheds (193). However, these trends vary across US
35 regions and specific nutrients; for example, phosphorus loads into the Chesapeake Bay
36 have increased during that time, while nitrogen loads have decreased. Nutrient loading
37 into the Gulf from the Mississippi River has remained stable.

38 Even as water pollution from heavy metals—and, to a lesser extent, nutrients—has
39 declined, other pollution sources are growing. Plastic pollution (Figure 9.12f) has been
40 increasing in US waters in recent decades, from near zero at the advent of plastic in 1950

1 to a total plastic waste generation of 42 million metric tons in 2016, the highest per capita
2 rate in the world (194). The fastest increase was seen from 1980 to 2000 (195).
3 Approximately 1–2 million metric tons of US plastic waste leaks into the environment
4 annually (195). Much of this waste eventually enters the ocean via terrestrial runoff,
5 atmospheric deposition, and from human activities on boats or shorelines (196).
6 Increasingly, “forever chemicals” such as per- and poly-fluoroalkyl substances (PFAS) may
7 be entering waterways, although their levels have not yet been monitored extensively over
8 time (197). Their impacts on ecosystems have not been well studied, although these
9 emerging contaminants are known to have negative consequences, such as reducing the
10 growth of some aquatic species (198).

11 Harmful algal blooms (HABs) are an example of an increasingly frequent phenomenon that
12 are both the result of diverse direct drivers of change, including nutrient pollution, invasive
13 species, warming, and aquaculture activities, but also a driver of change, with important
14 implications for ocean biodiversity and human health (199). HABs are caused by many
15 different species and classes of algae and cyanobacteria across broad ecosystems, and
16 different types of HABs in the US show different trends in occurrence over time. Some
17 HABs show no increase in frequency over the past 30 years, including paralytic shellfish
18 toxin events; others have significantly increasing trends in frequency and/or geographic
19 extent (200). Overall, there has been an increasing trend for HABs in US waters from 1990
20 to 2019 (See Ch. 10: Climate Change). Regional increases in HAB toxins attributed to land-
21 based runoff, ocean warming and marine heat waves, changing ocean pH and nutrient
22 biogeochemistry, and lower oxygen, as well as better monitoring and alert systems over
23 the last three decades (200–202).

24 *Conservation Efforts*

25 Approximately 13% of US land and inland waters is recognized as protected by the United
26 Nations in their World Database on Protected and Conserved Areas (203). This percentage
27 has not changed substantially in recent decades. Approximately 26% of US ocean area is
28 counted as protected in marine protected areas (MPAs); however, over 96% of this
29 protected area is concentrated in the central Pacific (204). Less than 2% of other ocean
30 areas are protected in any kind of MPA, and many of these MPAs allow high levels of
31 extractive and destructive activities, leaving many ocean habitats and species vulnerable
32 (204). In December 2022, over 190 countries (not including the US) adopted the United
33 Nations Convention on Biological Diversity Kunming-Montreal Global Biodiversity
34 Framework. This framework includes the target of protecting at least 30% of land and
35 ocean area by 2030. Within the US, nine states have adopted this goal at the state level to
36 date (California, Hawai‘i, Maine, Maryland, Massachusetts, Nevada, New Mexico, New
37 York, and Vermont). Maryland has achieved this goal early for terrestrial protected areas
38 and is actively planting new trees to expand forest cover as part of the state’s 5 Million Tree
39 Initiative. As of October 2025, no states have achieved this goal for the ocean.

1 Description of Evidence Base

2 Trends in population growth, agricultural expansion, and resource extraction from US
3 forests are *virtually certain* based on US government and United Nations datasets as well
4 as scientific studies using re-analysis and remote sensing approaches. Likewise, US
5 government agencies maintain extensive, reliable records of dam building, drilling, and
6 mining activities, making it *very well established* that river fragmentation increased and
7 virtually certain that fossil fuel extraction and mining increased during the 20th century.
8 Extensive monitoring by NOAA makes it *very well established* that US fisheries were
9 overharvested in the 20th century and well established that many of those fisheries are
10 now recovering. Scientific studies, many of which are based on state and local databases,
11 support the *well established* finding that introductions of non-indigenous species peaked
12 in the 20th century for most of the US while their populations and impacts continue to
13 increase. Extensive monitoring data from the EPA along with many scientific studies
14 support a *very well established* trend toward reductions in many air and water pollutants
15 since the 1970s with recent scientific publications establishing that plastic and nutrient
16 pollution remain problematic.

17 Key Message 9.3: Drivers of change in nature rarely operate in 18 isolation, and interactions among drivers are complex

19 *Most ecosystems in the United States are affected by multiple, interacting drivers of*
20 *change (virtually certain). Direct and indirect drivers interact in complex ways, sometimes*
21 *amplifying or counteracting each other (established but incomplete). While it is clear that*
22 *drivers can interact, the net effects of interactions are at this point difficult to predict*
23 *(established but incomplete).*

24 State of Knowledge 9.3

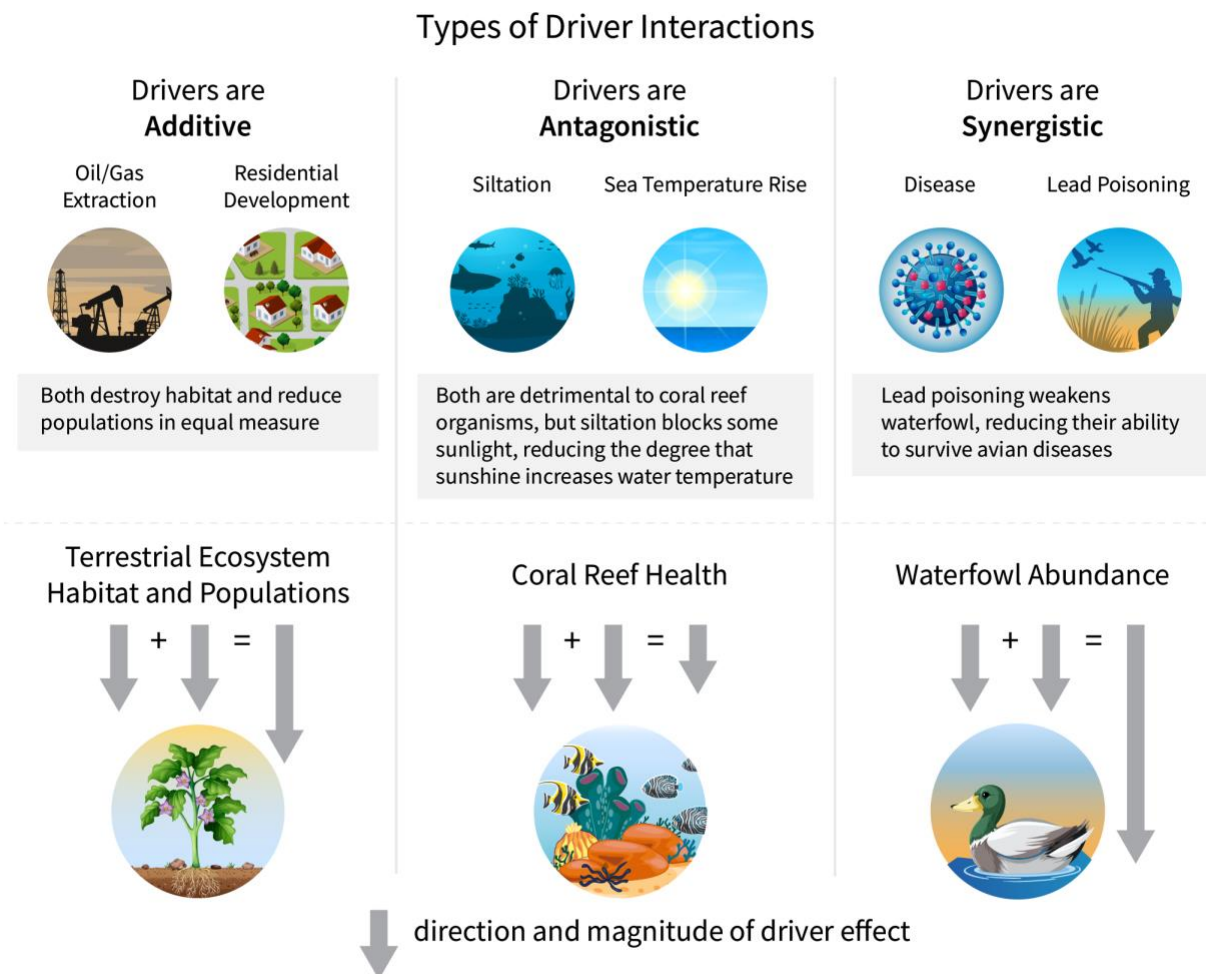
25 Additive, Antagonistic, and Synergistic Interactions Among Drivers

26 A challenge to interpreting and predicting how natural systems will respond to change is
27 that drivers of change rarely occur in isolation. When a single driver is acting, identifying
28 the consequences and, if desired, mitigating those consequences, can be straightforward.
29 For example, if residential development is destroying habitat for a rare plant, establishing a
30 conservation area can protect remaining individuals. However, systems are typically
31 affected by a complex and interacting suite of drivers that often co-occur. For example,
32 plant physiological processes can be affected by both increasing atmospheric CO₂
33 concentration and by rising temperatures driven by climate change (205).

34 When two drivers interact, there are three possible outcomes (Figure 9.13). The drivers
35 may be **additive** if they act independently. As an example, oil and gas extraction and
36 residential development could independently cause habitat loss for a rare plant. The
37 impact would be additive if the impact on the plant population is proportional to the sum of

1 the habitat area lost by the two drivers. Drivers are **antagonistic** when they are non-
 2 additive and one driver reduces the impact of another when they occur simultaneously. For
 3 example, coral reef organisms are sensitive to both siltation and sea temperature rise. An
 4 antagonistic interaction would occur if, in areas with low to moderate siltation, water
 5 temperature rise was moderated due to the siltation limiting solar radiation penetration
 6 into the water column (e.g., (206)). Drivers are **synergistic** if the overall effect is greater
 7 than the sum of the independent effects. For example, waterfowl can suffer both from lead
 8 poisoning caused by lead bullets and from disease. This would lead to a synergistic
 9 interaction if the effects of disease are more severe when the birds are already weakened
 10 by lead poisoning. As the number of drivers increases, their interactions and effects
 11 become much more complex and harder to predict.

12 **Figure 9.13. Interacting Drivers of Changes in Nature**



13

14 **Two interacting drivers can produce additive, antagonistic, or synergistic impacts.**

15 *Hypothetical examples with only two interacting drivers. The impact of the interaction is*
 16 *demonstrated by the direction of the arrows. The two drivers interact such that the net*

1 *impact is the sum of the two drivers (additive), smaller than the sum of the two drives*
2 *(antagonistic), or greater than the sum of the two drivers (synergistic). Figure original to The*
3 *Nature Record.*

4 Challenges with Predicting Interactions

5 It is difficult, if not impossible, to predict complex interactions among many drivers;
6 however, some higher-order interactions are detectable and interpretable. It has been
7 suggested that studying drivers individually may lead to overestimation of their effects
8 because combinations of effects may be in opposite directions or antagonistic (207).
9 However, a meta-analysis of more than 100 experiments found that community-level
10 responses occurred more often when three or more global change drivers were
11 simultaneously manipulated, consistent with either additive or synergistic effects of
12 multiple drivers, especially over long time periods (208). Experiments that manipulate
13 multiple global change drivers formally test for interactions among drivers. For example,
14 the TeRaCON experiment at Cedar Creek Ecosystem Science Reserve in Minnesota,
15 explored interactions of four drivers: temperature, rainfall, CO₂, and nitrogen. It detected a
16 three-way interaction between the effects of rainfall, CO₂, and nitrogen on total plant
17 biomass, indicating that low levels of any two resources limit the response to a third (209).
18 In other words, under experimental drought conditions and ambient nitrogen deposition,
19 plant biomass shows little response to increasing atmospheric CO₂.

20 The consequences of interacting drivers can change, and even reverse, through time. For
21 example, rising atmospheric CO₂ concentrations and nitrogen enrichment from air
22 pollution have co-occurred throughout the US for a century or more (210,211). Nitrogen
23 pollution often decreases terrestrial plant diversity (212), but it remains unclear whether or
24 how elevated CO₂ may amplify or dampen these effects. In a long-term experiment that
25 examined interactions of these two drivers, elevated CO₂ initially reduced plant species
26 loss resulting from nitrogen enrichment (213). However, over time this interaction
27 reversed, and elevated CO₂ later amplified the negative effects of nitrogen pollution,
28 tripling the species loss resulting from nitrogen enrichment (214). Long-term experiments
29 designed to test for interactions among drivers are rare; those that exist show that
30 interactions are not necessarily static but rather can substantially change over multiple
31 decades.

32 In a recent survey, 506 biodiversity experts in the US who have published scientific papers
33 on biodiversity responded to questions about interactions among multiple drivers. An
34 overwhelming majority of respondents (95%) indicated that there are synergistic
35 interactions between pairs of direct drivers of biodiversity loss, such that the combined
36 effects of multiple drivers are greater than the sum of their individual (positive or negative)
37 effects (215). Only 2% of experts reported antagonistic interactions in which the combined
38 effects are less than additive and the remaining 3% reported additive effects. When asked
39 about specific pairs of drivers, 90% reported synergistic interactions between climate
40 change and invasive alien species, whereas less than two thirds (64%) reported synergistic
41 interactions between overexploitation and pollution.

1 Actions to address drivers of change may not be effective unless these interactions and
2 the concomitant high degree of complexity are considered. For example, efforts to reduce
3 pollinator mortality via reduced use of pesticides or fertilizer could cause landowners to
4 respond to productivity losses on their current crop fields by conversion of conservation
5 grasslands to increased crop acreage. This shift could result in greater habitat loss or
6 fragmentation, leading to no net benefit or even a net cost to pollinator populations. The
7 effect of the drivers might be additive, but the changes are not independent. Similarly, the
8 effects of harvesting interact with other drivers, including disease, climate change, and
9 habitat loss. At some low levels of harvest, a species might be resilient to other factors but
10 may not survive under climatic conditions that are at the edge of its tolerances. Harvest
11 management needs to account for these other factors.

12 Description of Evidence Base

13 The existence of interactions between drivers are well documented in the scientific
14 literature, based on experimental and observational studies. While there is exceptionally
15 strong evidence that single drivers affect nature, relatively few studies have addressed two
16 or more drivers of change. It is well established based on measured data that systems are
17 rarely affected by single drivers in isolation. Evidence on the consequences of multiple
18 drivers comes largely from controlled studies where multiple drivers were manipulated
19 simultaneously. Results from experimental manipulations in plant communities make it
20 nearly certain that plant communities are altered by interacting drivers and that effects are
21 magnified over time. The scientific evidence is considered high quality in terms of
22 documenting possible outcomes of interacting drivers with transparent and well-
23 established scientific methods. However, there may be limitations in applying the results
24 of controlled scientific studies to real-world situations, particularly given that many drivers
25 may have sporadic or non-linear behavior. Interactions between drivers of nature are
26 considered a major research gap with a need for future studies.

27 Key Message 9.4: The future status of drivers of change in nature 28 depends on human policies, decisions, and actions

29 *Future drivers of change in nature are uncertain and depend on future human actions,*
30 *policies, and decisions (very well established). Future scenarios of change generally*
31 *project increases in population and economy activity (gross domestic product), a*
32 *slowdown in future land-use change, and an increase in climate change relative to*
33 *historical changes (well established). Future national-scale policies will have important*
34 *implications on the status of drivers of changes in nature in the US (very well established).*

35 State of Knowledge 9.4

36 Sophisticated strategies to project the future status of drivers of change in nature require
37 the development and analysis of scenarios—plausible descriptions of future conditions—

1 that account for complex socioeconomic interactions and physical constraints. This
2 approach has been used to provide consistent future scenarios of some of the most
3 important drivers, including population, gross domestic product (GDP), land use, and
4 climate. These have in turn been used as input for studies of projected future impacts on
5 biodiversity (216,217). For other variables, a less sophisticated extrapolation of historical
6 trends can be used as a basis to make projections and identify drivers of increasing or
7 decreasing concern and potential options for change.

8 Here we consider three formal scenarios—Shared Socioeconomic Pathways (SSPs)— that
9 describe possible future socioeconomic, geopolitical, and technological developments;
10 greenhouse gas concentration pathways; and changes in other climate drivers.
11 Resulting energy imbalances in the climate system (referred to as radiative forcing) under
12 various climate policy assumptions are also described. The scenarios discussed below
13 are:

- 14 1. SSP2-4.5 assumes a continuation of historical development trends combined with
15 a stabilizing climate pathway where greenhouse gas emissions peak around
16 midcentury and radiative forcing reaches about 4.5 Watts per square meter (W/m^2)
17 by 2100. This scenario assumes continuing moderate climate change and
18 biodiversity pressure.
- 19 2. SSP3-7.0 assumes a fragmented world with regional rivalries and weak global
20 cooperation, high population growth, slow economic development, and limited
21 technology transfer, producing high emissions and about 7.0 W/m^2 forcing by 2100.
22 This is a damaging pathway for nature, due to strong pressures from several direct
23 drivers, including land-use change, pollution, and climate change.
- 24 3. SSP5-8.5 assumes a world with rapid economic growth, energy-intensive lifestyles,
25 and abundant use of fossil fuels, leading to very high emissions and about 8.5 W/m^2
26 forcing by 2100. This scenario leads to severe impacts on biodiversity and nature's
27 contributions to people, not because of land-use pressure, but because of extreme
28 climate change.

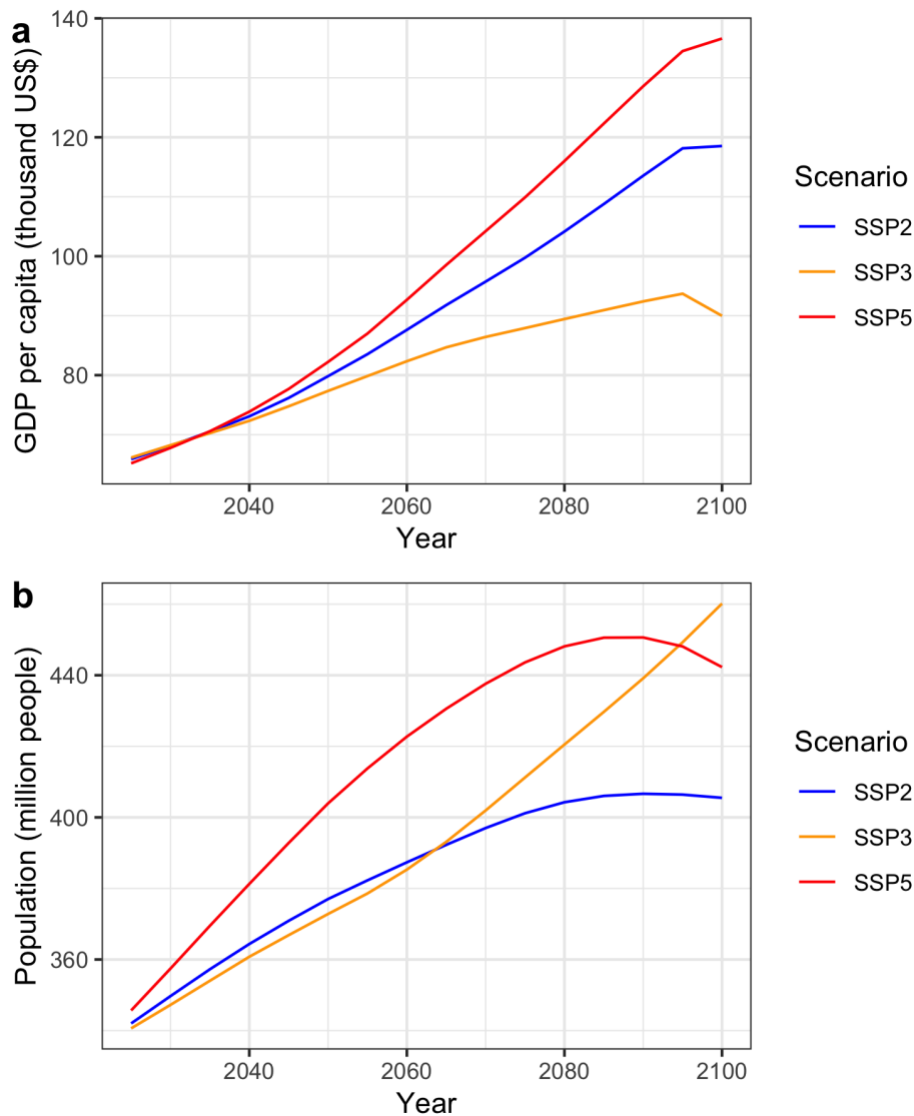
29 Socioeconomic Changes

30 Continued economic growth for the United States is expected through the end of the
31 century under all three SSPs considered. Per capita gross domestic product diverges
32 substantially across scenarios, with strong growth in SSP5-8.5, moderate growth in SSP2-
33 4.5, and slower growth in SSP3-7.0 (Figure 9.14a).

34 These scenarios span a wide range of possible demographic futures defined by differing
35 assumptions about education, health, inequality, and development trajectories.
36 Population growth is highest under SSP3 and SSP5, reflecting futures with either regional
37 rivalry or rapid economic expansion, and lower under SSP2, which assumes a middle of
38 the road continuation of historical trends (Figure 9.14b).

- 1 These socioeconomic futures serve as key indirect drivers influencing direct drivers such
 2 as land-use change, as well as other indirect drivers such as consumption patterns.

3 **Figure 9.14. Projected Trends in US Population and Per Capita GDP**



4

5 **US Population and per capita GDP are projected to rise over the coming century.**

- 6 *Projected future (a) per capita gross domestic product (GDP) and (b) population for the*
 7 *United States from 2025 to 2100 under three Shared Socioeconomic Pathway scenarios.*
 8 *The SSP5 scenario assumes a world with rapid economic and population growth, energy-*
 9 *intensive lifestyles, and abundant use of fossil fuels. SSP3 assumes a fragmented world*
 10 *with regional rivalries and weak global cooperation, with accelerating population growth,*
 11 *slow economic growth, and limited technology transfer. In SSP2, socioeconomic and*
 12 *technology developments continue on pathways similar to historical trends. Figure original*

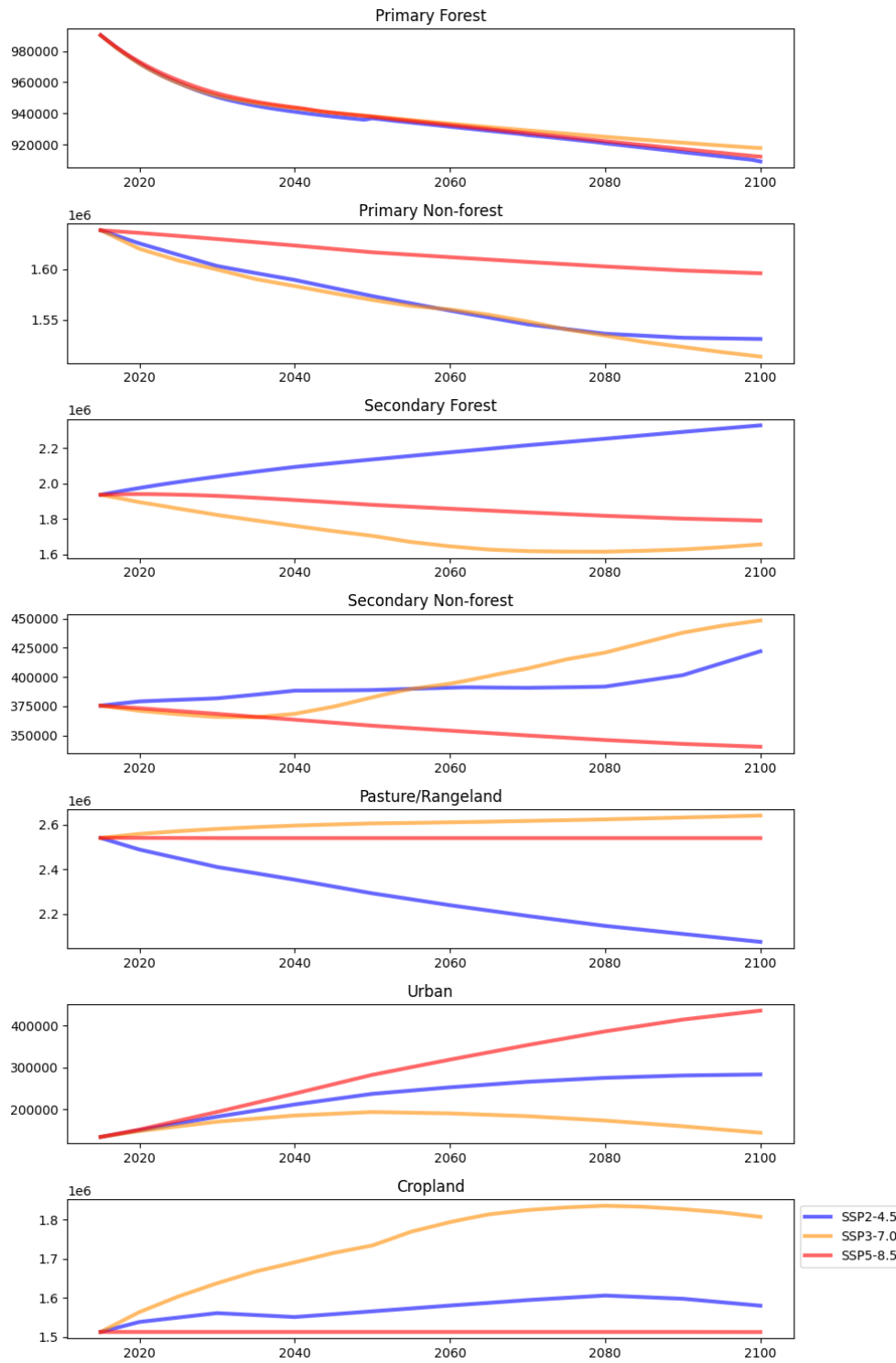
1 *to The Nature Record. Data sources: GDP and population data from the IIASA SSP*
2 *Database, with per capita GDP calculated directly from those series*

3 Land-Use Change

4 Scenarios of global land-use change developed for recent global climate change
5 assessments (Coupled Model Intercomparison Project (CMIP) are based on the same
6 socioeconomic assumptions presented above and are in that sense consistent with them
7 (83). Generally, these scenarios project a continued slowdown in future land-use changes
8 relative to historical rates, with potential decreases in primary land (i.e., non-disturbed
9 forest and non-forest) and pasture/rangeland, with increases in urban, cropland, and
10 secondary land. However, they also indicate a complex range of possible futures of land
11 use in the US, with potential consequences for nature (Figure 9.15).

12 Looking ahead to 2100, primary forest is projected to continue to decline by 8% (81,254
13 km²), with little variation between scenarios. Primary non-forest is projected to decline,
14 with more variation between scenarios, by 3–8% (–107,739 km² in SSP2-4.5, –42,644 km² in
15 SSP5-8.5). Pasture/rangeland will remain nearly constant or decrease by 18% (–467,184
16 km² in SSP2-4.5). Secondary forest is more uncertain and projected to change by
17 approximately +20% or –14% (392,567 km² in SSP2-4.5 and –280,386 in SSP3-7.0 km²,
18 respectively). Likewise, secondary non-forest is projected to change by similar amounts to
19 secondary forest (–35,233 km² in SSP5-8.5 or +73,027 km² in SSP3-7.0). Cropland will also
20 remain constant or increase up to 20% (+294,542 km² in SSP3-7.0). Urban land is projected
21 to have little change or nearly double (+302,778 km² in SSP5-8.5).

1 **Figure 9.15. Projected Future Land-Use Scenarios for the US (CONUS, AK, HI) from**
2 **2015 to 2100**



3
4 **Land use is projected to change in the future with potential consequences for nature.**

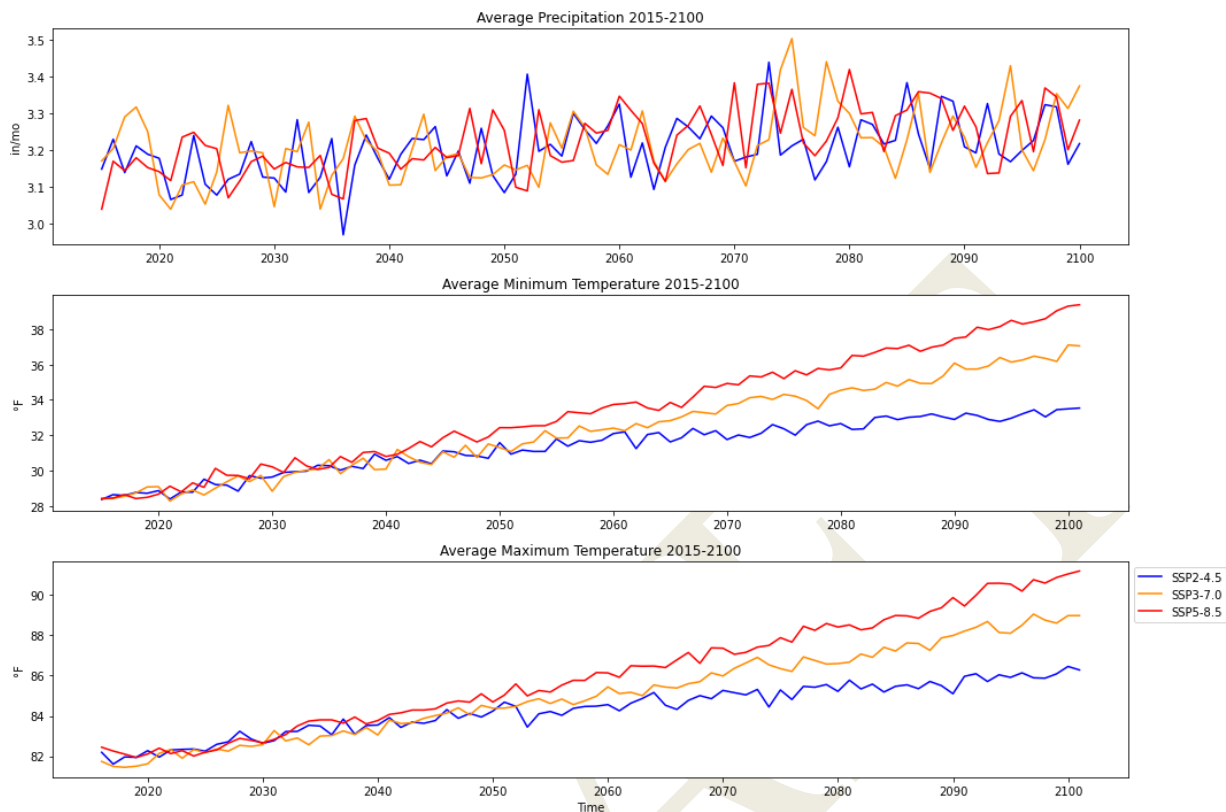
1 *Projected changes in land area are shown for 2015 to 2100 for seven categories of land*
2 *use: primary forest (a), primary non-forest (b), secondary forest (c), secondary non-forest*
3 *(d), pasture/rangeland (e), urban (f), and cropland (g). In each panel, changes are shown*
4 *for three socioeconomic development and climate change scenarios: SSP2-4.5 (blue*
5 *lines), SSP3-7.0 (red lines), and SSP5-8.5 (orange lines). Area units are in km². Figure*
6 *original to The Nature Record. Data from (83).*

7 Climate Change

8 Future scenarios of climate change for the United States have recently been assessed in
9 the Fifth National Climate Assessment (NCA5) (55). NCA5 included projections and
10 findings based on results from Coupled Model Intercomparison Program Phase 6 (CMIP6)
11 global climate models. In addition, two statistical downscaling techniques (LOCA2 and
12 STAR-ESDM) were applied to 16 CMIP6 models to provide higher-resolution projections at
13 national or subnational scales (218–220). Importantly, these climate model projections
14 were based on the same socioeconomic and land-use scenarios described above and are
15 thus consistent with them.

16 Climate changes are projected to continue in the future, with potential consequences for
17 nature (Figure 9.16). For example, from 2015 to 2100, average minimum and maximum
18 temperatures are projected to increase by 5°–11° and 4°–9° degrees Fahrenheit,
19 respectively, depending on scenario, with the smallest changes for SSP2-4.5 and the
20 largest changes for SSP5-8.5. Average annual precipitation had no significant trend (Figure
21 9.16). However, the results for temperature change are large compared to the historical
22 rate of change of about 2.5°F degrees since 1970 over the contiguous US (221).

1 **Figure 9.16. Future Climate Scenarios for 1950–2100 for the Contiguous United States**



2
3 **Climate is projected to change over the US, with potential consequences for nature.**

4 *Projected changes for the contiguous United States from 2015 to 2100 for three important*
5 *metrics: average annual precipitation (**top**), average minimum temperature (**center**),*
6 *average maximum temperature (**bottom**). For all panels, projections are shown for three*
7 *climate scenarios: SSP2-4.5 (blue), SSP3-7.0 (red), and SSP5-8.5 (orange). Figure original*
8 *to The Nature Record. Data from the CMIP6-LOCA2 dataset used in NCA5 (218,219).*

9 **Potential Consequences of Changes in Drivers**

10 The potential consequences of future climate change and land-use change on biodiversity
11 interact and have recently been quantified (216). Globally, the effects of future land-use
12 change on biodiversity loss were projected to slow and even reverse in some cases, while
13 the combined effects of future land-use and climate change were expected to increase
14 rates of biodiversity loss. Effective global climate mitigation was shown to reduce the
15 future negative effects on global biodiversity by 40–70%. The potential consequences of
16 future climate change on protected areas have also been assessed (217). Globally,
17 approximately 20% of protected areas are projected to experience a climate zone shift by
18 midcentury, with high climate change scenario (SSP5-8.5) impacting 40% of protected land
19 area by end of the century. Globally, under a high climate change scenario (RCP8.5),
20 approximately 30% of protected areas are projected to experience a climate zone shift by
21 midcentury and 50% by end of the century. Under a lower emissions scenario (RCP4.5),

1 25% of global protected land area is projected to undergo climate zone shifts by 2050 and
2 30% by end of the century (217, Table S2). Quantitative projections of the potential
3 consequences of changes in these drivers varied by scenario, location, and generally
4 applied to the United States.

5 National Policies Shaping Future Trends

6 Future US policies that align with the 2030 targets of the Kunming–Montreal Global
7 Biodiversity Framework (KMGBF) and Paris Agreement on climate could shape a more
8 nature-positive future. Although the United States is not a Party to the Convention on
9 Biological Diversity and has recently withdrawn from the Paris Agreement, past US
10 environmental statutes illustrate the capacity of federal policy to influence biodiversity
11 outcomes. For example, the Endangered Species Act and the
12 dichlorodiphenyltrichloroethane (DDT) ban under The Federal Insecticide, Fungicide, and
13 Rodenticide Act were central to the recovery of the bald eagle and other raptors; the Clean
14 Water Act substantially reduced point-source pollution, improving freshwater and
15 estuarine ecosystem condition; and the National Parks and broader public-lands network
16 have retained large areas of relatively intact habitat. At the same time, other policies, such
17 as commodity-linked agricultural subsidies and incentives for land conversion, have driven
18 habitat loss, nutrient enrichment, and biotic homogenization. New domestic policies
19 would likely be needed to achieve many of the KMGBF’s 2030 targets, including protecting
20 and restoring 30% of lands and waters by 2030; the systematic mainstreaming of
21 biodiversity across sectors; the management of incentives linked to biodiversity loss; and
22 the establishment of coordinated national systems for monitoring species, ecosystems,
23 and restoration trajectories, and climate change mitigation. Beyond the need for stronger
24 nature-supportive policies, reversing course on current beneficial policies would
25 exacerbate negative trends. United States policy has shaped biodiversity outcomes in the
26 past and will remain a central determinant of whether future trajectories more closely
27 resemble the ambitions articulated in global biodiversity targets.

28 Description of Evidence Base

29 Future changes in land use and climate change are inherently uncertain. The cases
30 evaluated here are based on *very well established* scenarios developed for the global
31 climate modeling community and have been used in prior national and international
32 assessments. Evaluation of the potential impact of these future changes in land use and
33 climate on nature is *well established* using multiple models and metrics for the response
34 of biodiversity and ecosystem function. The potential impact of national policies on
35 shaping future trends in nature has been *very well established* using historical precedents
36 of major US policies and associated outcomes.

1 **Key Message 9.5: Strategies that focus on core human values can**
2 **be effective at mitigating negative drivers of change and sustaining**
3 **the future benefits of nature**

4 *Decision-making that values multiple knowledge systems based on reciprocal*
5 *relationships with nature is expected to mitigate or reverse negative changes of nature*
6 *(well established). A framework of reciprocal benefit in which humans support and steward*
7 *foundational ecosystem goods and services enhances long-term sustainability*
8 *(established but incomplete). Co-management of nature that is holistic, inclusive, and*
9 *scales across jurisdictional boundaries is expected to provide widespread societal*
10 *benefits (very likely, established but incomplete).*

11 **State of Knowledge 9.5**

12 Drivers of change causing negative impacts to nature, and opportunities to address these
13 impacts, are tightly linked to the ways in which nature is valued in decision-making (see
14 Key Message 9.1) (222). Decision-making that emphasizes respectful, reciprocal
15 relationships and melds western science frameworks with Indigenous Knowledge and
16 other knowledge systems from marginalized communities may result in better policy
17 outcomes to protect nature's benefits and provide even more insight into ecosystems and
18 how they are changing due to drivers of changes of nature (see Key Message 9.1, 9.2) (223–
19 226). Most management and policy decisions have focused on a narrow set of values that
20 prioritize short-term profit and economic growth (222). Such policy decisions often do not
21 reflect public opinion about nature's value and benefits. Issues of inequity, power
22 imbalances, and lack of diverse perspectives in decision-making have been highlighted in
23 other assessments (222). Approaches to mitigating climate change that are focused on
24 inclusive governance and decision-making while valuing the perspectives and knowledge
25 of Indigenous Peoples, African Americans, other marginalized groups, and diverse local
26 communities provide enhanced understanding of the changes in nature and inform
27 biodiversity conservation and ecosystem management (56). Policies and decision-making
28 can support traditional and place-based knowledge of local communities, Tribal
29 sovereignty, and self-determination towards strengthening the possibility of achieving
30 holistic value-centric goals.

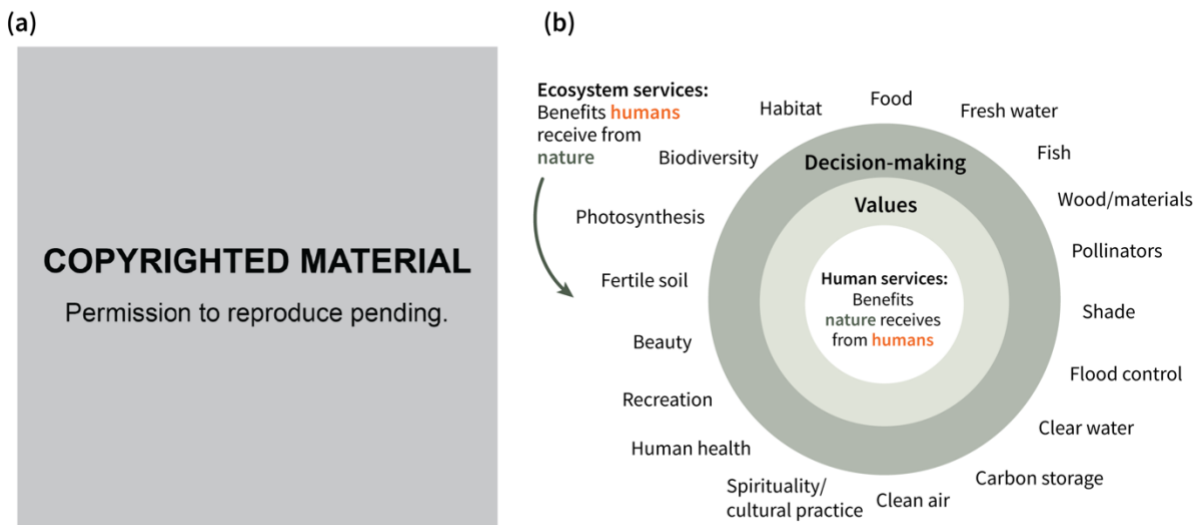
31 Valuation of nature is a critical consideration in the future of nature (see Ch.11: Culture),
32 perhaps *the* most critical consideration. For example, the prevalent concept of
33 **“ecosystem services”** with regards to nature commonly refers to the benefits humans
34 receive from natural systems or the functions that ecosystems confer that have monetary
35 or non-monetary value (40). A comprehensive overview of the supporting benefits humans
36 receive from ecosystems categorized these benefits into provisioning, regulating,
37 supporting, and cultural services (63). This standard method of categorizing ecosystem
38 services and their societal benefits is a unidirectional and instrumentalist viewpoint of
39 nature in which humans benefit from the final extractive endpoint. Alternative valuations of

1 nature include intrinsic and relational values. Further, a reimagined ecosystem services
 2 model might be multidirectional and cyclical, where ecosystems receive stewardship
 3 services from humans, which ultimately enhances the potential for humans to receive the
 4 full benefits of ecosystems in the future (Figure 9.17). Others have informed this
 5 framework, such as through a reciprocity restoration framework (227) and the “human
 6 services for ecosystems” framework (228).

7 The original ecosystem services framework used in assessments (63) include services
 8 such as aesthetics, recreation, clean water and air, and biodiversity. Several of these
 9 services are foundational and can lead to access to all other services. Thus, by making
 10 conservation and management decisions that support and/or improve these foundational
 11 ecosystem services, such as clean water, clean air, biodiversity, and soil health, the full
 12 list of benefits can be realized. In this reimagined model, the services (values) shift from
 13 the standard short-term goals of economic growth to new long-term goals of sustainable
 14 healthy ecosystems (Figure 9.17). This process includes an important point in the decision-
 15 making timeline that ensures different ways of knowing and holistic viewpoints are not just
 16 incorporated but serve as the foundation guiding decision-making processes (79,229,230).
 17 In order to support nature and receive benefits, humans can implement strategic adaptive
 18 management strategies that seek to understand and overcome the challenges and barriers
 19 (i.e., views, structures, and practices) to transformative change by addressing the
 20 underlying causes of biodiversity loss and nature’s decline (56).

21 **Figure 9.17. A Shift in the Ecosystem Goods and Services Model**

Re-Imagining Ecosystem Goods and Services



22

23 **In contrast to the traditional ecosystem services models, a framework of reciprocal**
 24 **benefit in which human actions support the sustainability of natural systems and**
 25 **nature’s benefits support future humanity is a strategic choice.**

1 *(a) The wide-ranging ecosystem services that benefit humans, including supporting,*
2 *provisioning, regulating, and cultural services (63). (b) A reimagined model where humans*
3 *provide services that support foundational goods and services, such as clean water, clean*
4 *air, biodiversity, and soil health. In this new multidirectional model, making decisions that*
5 *support the health of these foundational services will sustain the benefits that humans*
6 *derive from these services. (a) Adapted from MetroVancouver 2018 (231); (b) original to The*
7 *Nature Record.*

8 Studies Supporting the New Model

9 If humans value nature as a foundational ecosystem service, then policies and decision-
10 making that enhance it will lead to more goods and services received. For example, the
11 Clean Air Act has reduced air pollution and acid rain and improved visibility and the ozone
12 layer (221,232). The Clean Water Act has reduced water pollution, restored and improved
13 habitat for fish and wildlife, and provided safer drinking water (183). The Endangered
14 Species Act has prevented the extinction of roughly 291 species since passage in 1973,
15 and has to date saved more than 99% of species (233). Protecting terrestrial habitats for
16 wildlife will increase the generation of services, such as food, beauty, recreation, and
17 tourism. Policies and decisions that seek to increase biodiversity in terrestrial ecosystems
18 will increase photosynthesis and carbon storage (56), and thus, ability to receive other
19 services such as wood, shading, food security, and human health.

20 The influence and benefits of biodiversity on ecosystem productivity have been well-
21 established through various studies and reports (56,234–242). Supporting biodiversity can
22 further increase resistance to climate extremes and resilience to change (243). Taken
23 together, this increases the ability of nature to provide other services such as wood,
24 shading, and human health to name a few. Thus, by refocusing the values in the ecosystem
25 services model, decision-making can lead to healthier ecosystems.

26 Inclusive and sustainable management practices that enhance fundamental services can
27 prolong ecosystem services over the long term. For example, the Swinomish Tribal
28 community uses nonphysical, noneconomic Indigenous health indicators (community
29 connection, cultural use, education, self-determination, natural resource security, and
30 resilience) to prioritize their decision-making that builds resilience to climate change
31 impacts (244,245).

32 The role of Indigenous Knowledge and local knowledge is often ignored in solutions-based
33 thinking toward environmental challenges (246) and applied sporadically in assessments
34 and reports (247). Partnerships with different knowledge systems can be transformative
35 when respected as whole bodies of knowledge, practices, values, and worldviews (248).

36 Case Study: Sustainable Agriculture and Soil Health

37 Regenerative agriculture (a holistic and sustainable agricultural approach that may lessen
38 or improve environmental and/or social impacts) has received considerable attention in

1 recent years, especially as it is posited to have overall positive environmental impacts and
2 social benefits (249), and such an approach is necessary to meet food security and
3 environmental sustainability (250). Positive impacts of regenerative farming include
4 improving soil health, enhancing biodiversity, mitigating climate change, and supporting
5 ecosystem function (251). While the specific practices that encompass regenerative
6 agriculture are broad (249,251–253), Indigenous and local communities have been using
7 these methods for centuries and millennia (48,251). For example, enslaved peoples from
8 Africa brought knowledge of rice to the US, which informed its initial cultivation in South
9 Carolina (32). Small-scale efforts that focus on regenerative farming, such as the Jubilee
10 Justice Black Farmers’ Rice Project, support healthy ecosystems by using less water and
11 agro-chemicals and reducing methane emissions while improving soil health (254).

12 Case Study: Dams and Salmon

13 The health of inland waters is vital to supporting culturally important organisms, such as
14 salmon, for many tribes in the US. Tribes in the Pacific Northwest have relied on salmon for
15 their cultural and spiritual traditions and as an essential food source for millennia. Salmon
16 serve as key indicators of ecosystem health as they provide marine-derived nutrients in
17 marine, inland water, and terrestrial systems (255–257), are sensitive to rising
18 temperatures (258), and have been devastated by implementation of dams (259–261).
19 Tribes of the upper Columbia Basin have been working collaboratively for the past several
20 years on anadromous salmon reintroduction to their traditional waters for the first time in
21 110 years (262). This reintroduction effort exemplifies supporting a cultural keystone
22 species (Chinook Salmon) and finding ways to successfully bypass and negotiate dams
23 and reservoirs in blocked areas of the Chief Joseph Dam and Grand Coulee Dam. The
24 reintroduction of salmon in areas affected by dams restores cultural and spiritual
25 traditions and relationships in addition to improving the ecological health of these waters.

26 In California, 45 percent of California’s salmonids, including 11 of 21 anadromous species
27 (52%) and 3 of 10 inland species (30%), are likely to be extinct in the next 50 years under
28 current policy (263). If present conditions continue, 23 of the remaining 31 species (74%)
29 will likely go extinct within 100 years under current policy (263). One way to reverse course
30 on such trends is through the removal of dams. The Yurok Tribal Fisheries Program found
31 one of the four dams on the Klamath River was responsible for a massive die-off of salmon
32 due to its impact on water temperature and quality. The tribe saw their Chinook salmon
33 numbers decline by 98% with the installation of the dams. The dam removals reopened
34 over 400 miles of the river and the return of nearly 10,000 salmon (up 30% from 2024), as
35 well as a return to normal temperatures, improved water quality and reduced algal blooms
36 and their toxins, with multiple co-benefits for wildlife and humans (findings based on early
37 estimates from The Klamath River Salmon Monitoring program and The Klamath Basin
38 Monitoring Program, (132)).

1 Case Study: Fire

2 Cultural burning differs from prescribed burning and is the intentional application of low-
3 intensity fire by Indigenous Peoples to specific places at particular times of year for
4 defined cultural, ecological, and subsistence purposes (264). It is guided by long-term,
5 place-specific relationships with the land, governed by Indigenous protocol and place-
6 based knowledge systems (265–267), and historically practiced for millennia (268–270).
7 Cultural burning has been viewed by many Indigenous practitioners as a stewardship
8 practice that upholds their relationship and responsibilities to the land and in turn will
9 benefit the communities that depend on the gifts of these ecosystems (271). The purpose
10 of cultural burning goes beyond reducing fuels in the ecosystem, as it has been
11 documented as regulating and supporting biodiversity, pollination, soil health, regulating
12 pests and diseases, and increasing nutrient cycling and water resources (15,272). These
13 practices can improve ecosystem function by increasing biodiversity and productivity
14 while also providing cultural keystone species that provide food for communities, such as
15 camas, tarweed, and other roots and bulbs (271,273,274). Currently, cultural burning
16 practices are being revived across the west and worldwide in efforts to restore ecosystem
17 processes disrupted by fire exclusion, to buffer climate-driven changes, and to reduce
18 catastrophic wildfire risk (275,276).

19 Co-Management

20 There is increased understanding that when a diversity of multilevel values and concepts is
21 acknowledged in collective action, conservation initiatives are more likely to succeed
22 (277–279). Human values underlie the decision-making that results in societal shifts that
23 lead to policymaking and the management of resources that shape nature and biodiversity
24 (280). A relational understanding of worldviews, human–nature relationships, and value
25 concepts can be more holistic, inclusive, and transformative for policymaking and
26 decision-making. The weighting of diverse values of nature in decision-making can result in
27 sustainable outcomes (281). Co-management as a process and a non-static network of
28 multiple interests and worldviews that shift as human–nature relationships evolve can be
29 more effective in achieving policy change, with more equitable and sustainable outcomes.
30 Co-management frameworks result in better outcomes for addressing ecosystem
31 dynamics at the intersection of multiple scales and uncertainties, especially when
32 management outcomes include input from people directly impacted by decisions being
33 made on resources and by relationships to those resources (282). The structures and
34 dimensions of co-management can vary in their goals to operationalize the management
35 and conservation of natural and cultural resources across jurisdictional boundaries for
36 widespread societal benefits. With the increasing complexity of direct and indirect drivers
37 of changes in nature, power-sharing and knowledge generation under various co-
38 management frameworks will likewise need to change by representing diverse interests
39 and crossing different scales (283).

1 Description of Evidence Base

2 The finding that acknowledging and identifying how human values underpin decision
3 making and thus drive changes in nature in positive and negative ways is assessed to be
4 *well established*, based on published studies and evaluated in national and international
5 assessments and reports. A suite of successful environmental policies that have improved
6 or enhanced nature combined with many ecological restoration studies make it *very likely*
7 that humans can reduce or reverse negative impacts. It is *very likely* that extracting goods
8 and services from nature for short-term benefits will not sustain benefits to humans over
9 the long term. Efforts to reverse this outcome are *established but incomplete* since there
10 are limited examples of holistic frameworks for ecosystem goods and services that provide
11 a multidirectional relationship with humans supporting nature in order to sustain the
12 benefits that are received from nature. It is *very likely* that effective management and
13 decision-making can support long-term sustainable benefits as demonstrated through a
14 well-established collection of examples, which includes sustainable stewardship from
15 Indigenous Peoples and other communities since time immemorial. Additionally, there are
16 many published studies that highlight reciprocal human–nature relationships emphasizing
17 values as drivers of change.

18 Environmental Justice and Equity Highlights

19 **Highlight 1: Anthropogenic drivers of change in nature are rooted in decisions made**
20 **by those in power and by other social influencers, while marginalized communities**
21 **are most impacted by those changes.**

22 Historical racial and ethnic injustice imposed primarily by European colonists and settlers
23 against the original inhabitants of the land and subsequently against enslaved Africans and
24 their descendants have led to substantial inequities in whose values and interests drive
25 decision-making and policies (284). Historically marginalized and underserved
26 communities experience greater hazards from environmental degradation and climate
27 change, while nature benefits and conservation are targeted outside those marginalized
28 communities (285). Communities that depend on nature to maintain traditional lifeways
29 and food sovereignty may not have the means to resist or relocate and are highly
30 vulnerable to further change (48). Yet, some accepted policies and laws today have
31 precedents rooted in long-standing grassroots Black, Indigenous, and People of Color
32 community advocacy, demonstrating the value of continued community engagement
33 (285).

34 **Highlight 2: Sustainability and policy efforts are influenced by inclusive versus**
35 **noninclusive local, national, and global governance structures.**

36 Marginalized communities still have agency to resist harmful policies and identify and take
37 actions to reduce their vulnerability. There are opportunities for policymakers and
38 decision-makers to engage and work with marginalized communities to understand and

1 co-develop solutions to address the inequities of drivers of change at various spatial
2 scales (e.g., rural, urban). Examples include policy and climate incentives that aim to
3 reduce wealth inequality, increase human and nature well-being, improve access to
4 resources, and support cultural practices. Multifaceted governance practices (local to
5 global levels) influence laws, regulations, and climate and environmental policy, impacting
6 local-to-national adaptation planning and mitigation action (286). Exclusive policymaking
7 and sustainability initiatives have policy implications in other nations/countries, often
8 affecting marginalized communities facing the most environmental degradation. Policy
9 and sustainability initiatives inclusive of multiple knowledge systems (e.g., Indigenous and
10 local knowledge) and multisectoral participation inform effective decision-making that
11 impacts natural and cultural resources. Co-management of natural resources is becoming
12 increasingly more complex as land stewardship and jurisdictional controls (i.e., Tribal,
13 state, federal, etc.), laws, and regulations are converging and changing as land is being
14 considered for preservation, conservation, and development (287).

15 **Highlight 3: Indigenous and marginalized communities—often most impacted by**
16 **drivers of change in nature—offer expertise in effective stewardship and**
17 **sustainable practices to mitigate their impacts.**

18 Indigenous Peoples and other marginalized communities are often the most threatened by
19 the major drivers of change in nature. These drivers affect not only the ecosystems these
20 communities depend on but also their cultural practices, livelihoods, and long-standing
21 relationships with the land and water. For thousands of years, Indigenous Peoples have
22 shaped and cared for landscapes through cultural, spiritual, and land-stewardship
23 traditions. These practices reflect a holistic and reciprocal view of nature, connecting
24 values, beliefs, and responsibilities with the plants, animals, and ecosystems around
25 them. Likewise, African American communities have out of necessity been pioneers of
26 sustainable agriculture, water stewardship, circular economies, and community resilience
27 strategies (288). Colonization severely disrupted these relationships. It restricted access
28 to traditional lands, damaged environments, and undermined cultural and ecological
29 knowledge. This history has contributed to today's environmental vulnerabilities, as well as
30 to broader losses of biodiversity and ecosystem health. Many current drivers of change
31 intensify these harms, creating unequal impacts on Indigenous and marginalized
32 communities. At the same time, there is a growing recognition that Indigenous and local
33 stewardship practices offer sustainable and effective ways to respond to modern
34 environmental pressures.

35 Emerging Issues

36 New drivers of change in nature are emerging, many of which mirror earlier forces but
37 manifest at different scales and intensity, with the potential to rapidly transform
38 ecosystems. Existing drivers of change are also continually co-evolving, with the same
39 transformation potential. For example, the accelerating energy and water demands of data
40 centers and artificial intelligence infrastructure are intensifying stressors on the

1 environment (289). Data center cooling systems will affect multiple drivers, including
2 hydromodification from surface and groundwater withdrawals and pollution as discharges
3 may contain per- and polyfluoroalkyl substances (PFAS) used in two-phase cooling
4 (289,290). Energy demands of data centers may also impact land cover; lands currently
5 used primarily for grazing are optimal areas for implementing utility-scale renewable
6 energy projects and data centers, with the potential for major changes in land use in
7 upcoming decades (291,292). Meanwhile, global decarbonization efforts and the transition
8 to cleaner and renewable energy necessitates intensive extraction of critical minerals
9 (293), potentially decreasing climate drivers while simultaneously increasing drivers
10 related to land- and ocean-use change. Increased ecological disruption and global
11 connectivity heighten the risks of emerging infectious diseases (180), while climate-
12 induced migration may intensify urban expansion, habitat loss, and ecological
13 fragmentation in receiving regions. Rapid human population growth from migration can
14 intensify resource overuse, environmental degradation, and pollution, as existing
15 infrastructure and governance systems may be unprepared to accommodate the
16 increased population pressures. Collectively, these emerging drivers, including climate
17 change, e-commerce, biological invasions, new contaminants, engineered nanomaterials,
18 microplastic pollution, and increased light and noise, pose significant threats to
19 biodiversity (294) and highlight the interconnected and accelerating nature of
20 environmental change. Rapidly changing technologies, economies, and environmental
21 policies make it more difficult to project trajectories of the complex suite of drivers of
22 change of nature.

23 Novel governance approaches to co-management of natural systems are emerging; these
24 have the potential for significant changes to how nature and the drivers of change in nature
25 in the US will be managed in the future. Indigenous Peoples across North America are
26 demonstrating innovation and creativity in confronting disproportionate climate change
27 impacts through the revitalization of land- and maritime-based stewardship practices
28 through the expansion of co-management governance (295). Cultural and prescribed
29 burning led by Tribes in California, Montana, and the Great Lakes region has been widely
30 documented as an effective strategy for reducing catastrophic wildfire risk while restoring
31 culturally important ecosystems (296–298). In California, the passage of Senate Bill 310
32 now enables Federally Recognized Tribes to conduct cultural burns through agreements
33 with the California Natural Resources Agency and local air districts, marking a significant
34 policy shift toward sovereignty (49). Along the California coast, the Chumash Tribes have
35 become central partners in the first designated Indigenous-led Heritage National Marine
36 Sanctuary, which protects 4,543 square miles of Central California’s marine ecosystems
37 while supporting research, education, and cultural revitalization (299). Similarly, co-
38 management agreements at Bears Ears National Monument in Utah and Katmai National
39 Park and Preserve in Alaska illuminate how federal–Tribal partnerships are transforming
40 conservation governance. In a landmark 2022 agreement, the Bureau of Land Management
41 and US Forest Service formally committed to shared management of Bears Ears with five
42 Federally Recognized Tribes: the Hopi, Navajo, Ute Mountain Ute, Ute Indian Tribe of the
43 Uintah and Ouray Reservation, and Pueblo of Zuni. This partnership advances Tribal

1 authority over ancestral lands (300,301). In Alaska, Tribal co-management of marine
2 mammals has promoted full and equal participation of Alaska Native communities in
3 subsistence governance while enhancing conservation outcomes under rapid climate-
4 driven ecosystem change (302). Collectively, initiative such as these demonstrate that
5 Indigenous governance systems are not only culturally vital but also among the most
6 effective and adaptive responses to drivers of climate and biodiversity crises.

7

DRAFT

1 References

- 2 1. Clark PU, Dyke AS, Shakun JD, Carlson AE, Clark J, Wohlfarth B, et al. The Last Glacial
3 Maximum. *Science*. 2009 Aug 7;325(5941):710–4.
4 <https://doi.org/10.1126/science.1172873>
- 5 2. Omernik JM, Griffith GE. Ecoregions of the Conterminous United States: Evolution of a
6 Hierarchical Spatial Framework. *Environ Manage*. 2014 Dec 1;54(6):1249–66.
7 <https://doi.org/10.1007/s00267-014-0364-1>
- 8 3. Walker JD, Geissman JW, Bowring SA, Babcock LE. The Geological Society of America
9 Geologic Time Scale. *GSA Bull*. 2013 Mar 1;125(3–4):259–72.
10 <https://doi.org/10.1130/B30712.1>
- 11 4. Laird KR, Fritz SC, Cumming BF, Grimm EC. Early-Holocene limnological and climatic
12 variability in the Northern Great Plains. *The Holocene*. 1998 Apr;8(3):275–85.
13 <https://doi.org/10.1191/095968398673895438>
- 14 5. Laird KR, Fritz SC, Grimm EC, Mueller PG. Century scale paleoclimatic reconstruction
15 from Moon Lake, a closed-basin lake in the northern Great Plains. *Limnol Oceanogr*.
16 1996;41(5):890–902. <https://doi.org/10.4319/lo.1996.41.5.0890>
- 17 6. Williams JW, Jackson ST. Novel climates, no-analog communities, and ecological
18 surprises. *Front Ecol Environ*. 2007 Nov;5(9):475–82. <https://doi.org/10.1890/070037>
- 19 7. Klein Goldewijk K, Beusen A, van Drecht G, de Vos M. The HYDE 3.1 spatially explicit
20 database of human-induced global land-use change over the past 12,000 years. *Glob*
21 *Ecol Biogeogr*. 2011;20(1):73–86. <https://doi.org/10.1111/j.1466-8238.2010.00587.x>
- 22 8. Ingram S, Patrick S. Human securities, sustainability, and migration in the ancient
23 U.S. Southwest and Mexican Northwest. *Ecol Soc* [Internet]. 2021 Apr 26 [2025 Oct
24 30];26(2). <https://doi.org/10.5751/ES-12312-260209>
- 25 9. Nevle RJ, Bird DK. Effects of syn-pandemic fire reduction and reforestation in the
26 tropical Americas on atmospheric CO₂ during European conquest. *Palaeogeogr*
27 *Palaeoclimatol Palaeoecol*. 2008 Jul;264(1–2):25–38.
28 <https://doi.org/10.1016/j.palaeo.2008.03.008>
- 29 10. Lowder SK, Skoet J, Raney T. The Number, Size, and Distribution of Farms,
30 Smallholder Farms, and Family Farms Worldwide. *World Dev*. 2016 Nov 1;87:16–29.
31 <https://doi.org/10.1016/j.worlddev.2015.10.041>
- 32 11. Rick TC, Lockwood R. Integrating Paleobiology, Archeology, and History to Inform
33 Biological Conservation. *Conserv Biol*. 2013 Feb;27(1):45–54.
34 <https://doi.org/10.1111/j.1523-1739.2012.01920.x>

- 1 12. Armstrong CG, Shoemaker AC, McKechnie I, Ekblom A, Szabó P, Lane PJ, et al.
2 Anthropological contributions to historical ecology: 50 questions, infinite prospects.
3 PLOS ONE. 2017 Feb 24;12(2):e0171883.
4 <https://doi.org/10.1371/journal.pone.0171883>
- 5 13. McClenachan L, Rick T, Thurstan RH, Trant A, Alagona PS, Alway HK, et al. Global
6 research priorities for historical ecology to inform conservation. *Endanger Species*
7 *Res.* 2024 Jun 27;54:285–310. <https://doi.org/10.3354/esr01338>
- 8 14. Miller RJ, Ruru J. *An Indigenous Lens into Comparative Law: The Doctrine of Discovery*
9 *in the United States and New Zealand* [Internet]. Rochester, NY: Social Science
10 Research Network; 2008 [2025 Oct 30]. <https://papers.ssrn.com/abstract=1099574>
- 11 15. Anderson MK. The Use of Fire by Native Americans in California. In: van Wagendonk
12 JW, editor. *Fire in California's Ecosystems* [Internet]. University of California Press;
13 2018 [2024 Dec 27]. p. 381–98. <https://doi.org/10.1525/9780520961913-022>
- 14 16. Lightfoot K, Parrish O. *California Indians and Their Environment* [Internet]. University
15 of California Press; 2009 [2025 Dec 5]. [https://www.ucpress.edu/books/california-](https://www.ucpress.edu/books/california-indians-and-their-environment/paper)
16 [indians-and-their-environment/paper](https://www.ucpress.edu/books/california-indians-and-their-environment/paper)
- 17 17. McCune JL, Pellatt MG, Vellend M. Multidisciplinary synthesis of long-term human–
18 ecosystem interactions: A perspective from the Garry oak ecosystem of British
19 Columbia. *Biol Conserv.* 2013 Oct 1;166:293–300.
20 <https://doi.org/10.1016/j.biocon.2013.08.004>
- 21 18. Lepofsky D, Armstrong CG. Foraging New Ground: Documenting Ancient Resource
22 and Environmental Management in Canadian Archaeology. *Can J Archaeol J Can*
23 *Archéologie.* 2018;42(1):57–73.
- 24 19. Armstrong CG, Miller J, McAlvay A, Ritchie PM, Lepofsky D. Historical Indigenous
25 Land-Use Explains Plant Functional Trait Diversity. *Ecol Soc* [Internet]. 2021 Apr 22
26 [2025 Oct 30];26(2). <https://doi.org/10.5751/ES-12322-260206>
- 27 20. Motzkin G, Foster DR. Grasslands, heathlands and shrublands in coastal New
28 England: historical interpretations and approaches to conservation. *J Biogeogr.*
29 2002;29(10–11):1569–90. <https://doi.org/10.1046/j.1365-2699.2002.00769.x>
- 30 21. Foster DR, Motzkin G. Interpreting and conserving the openland habitats of coastal
31 New England: insights from landscape history. *For Ecol Manag.* 2003 Nov
32 3;185(1):127–50. [https://doi.org/10.1016/S0378-1127\(03\)00251-2](https://doi.org/10.1016/S0378-1127(03)00251-2)
- 33 22. Toniello G, Lepofsky D, Lertzman-Lepofsky G, Salomon AK, Rowell K. 11,500 y of
34 human–clam relationships provide long-term context for intertidal management in the
35 Salish Sea, British Columbia. *Proc Natl Acad Sci.* 2019 Oct 29;116(44):22106–14.
36 <https://doi.org/10.1073/pnas.1905921116>

- 1 23. Innes-Gold AA, Madin EMP, Stokes K, Ching C, Kawelo H, Kotubetey K, et al.
2 Restoration of an Indigenous aquaculture system can increase reef fish density and
3 fisheries harvest in Hawai'i. *Ecosphere*. 2024;15(3):e4797.
4 <https://doi.org/10.1002/ecs2.4797>
- 5 24. Artelle KA, Reynolds JD, Treves A, Walsh JC, Paquet PC, Darimont CT. Hallmarks of
6 science missing from North American wildlife management. *Sci Adv*. 2018 Mar
7 7;4(3):eaao0167. <https://doi.org/10.1126/sciadv.aao0167>
- 8 25. Thompson MSA, Couce E, Webb TJ, Grace M, Cooper KM, Schratzberger M. What's
9 hot and what's not: Making sense of biodiversity 'hotspots.' *Glob Change Biol*.
10 2021;27(3):521–35. <https://doi.org/10.1111/gcb.15443>
- 11 26. Salomon AK, Okamoto DK, Wilson Kii'iljuus Barbara J., Tommy Happynook
12 hiininaasim, Wickaninnish null, Mack wiicuckum A, et al. Disrupting and diversifying
13 the values, voices and governance principles that shape biodiversity science and
14 management. *Philos Trans R Soc B Biol Sci*. 2023 May 29;378(1881):20220196.
15 <https://doi.org/10.1098/rstb.2022.0196>
- 16 27. Farrell J, Burow PB, McConnell K, Bayham J, Whyte K, Koss G. Effects of land
17 dispossession and forced migration on Indigenous peoples in North America.
18 *Science*. 2021 Oct 29;374(6567):eabe4943. <https://doi.org/10.1126/science.abe4943>
- 19 28. Whyte K. *Settler Colonialism, Ecology, and Environmental Injustice*. *Environ Soc*. 2018
20 Sep 1;9:125–44. <https://doi.org/10.3167/ares.2018.090109>
- 21 29. Moore JW. *Sugar and the Expansion of the Early Modern World-Economy: Commodity
22 Frontiers, Ecological Transformation, and Industrialization*. *Rev Fernand Braudel
23 Cent*. 2000;23(3):409–33.
- 24 30. Reusser L, Bierman P, Rood D. Quantifying human impacts on rates of erosion and
25 sediment transport at a landscape scale. *Geology*. 2015 Feb 1;43(2):171–4.
26 <https://doi.org/10.1130/G36272.1>
- 27 31. McNeill JR. *Something new under the sun: an environmental history of the twentieth-
28 century world*. First published as a Norton paperback. New York: W. W. Norton; 2001.
- 29 32. Carney JA. *Black Rice* [Internet]. Harvard University Press; 2009 [2025 Dec 8].
30 <https://doi.org/10.2307/j.ctvjz837d>
- 31 33. Cunfer G. *On the Great Plains: agriculture and environment* / Geoff Cunfer ; foreword
32 by Dan L. Flores. 1st ed. College Station: Texas A&M University Press; 2005. 292 p.
33 (Environmental history series).

- 1 34. Silkenat D. Scars on the Land: An Environmental History of Slavery in the American
2 South [Internet]. 1st ed. Oxford University Press New York; 2022 [2026 Jan 7].
3 <https://doi.org/10.1093/oso/9780197564226.001.0001>
- 4 35. Cochran L, Murray EJ, Gougeon RA, Schweickart E, Filoromo S. Implications of
5 Historic Landscape Modification to Modern Crisis Management. *Int J Hist Archaeol*
6 [Internet]. 2025 Oct 14 [2026 Jan 7]; <https://doi.org/10.1007/s10761-025-00804-7>
- 7 36. Morgan PD. *Slave counterpoint: black culture in the eighteenth-century Chesapeake*
8 *and Lowcountry*. Chapel Hill: Univ. of North Carolina Press; 1999. 703 p.
- 9 37. Rose NH, Badolo A, Sylla M, Akorli J, Otoo S, Gloria-Soria A, et al. Dating the origin and
10 spread of specialization on human hosts in *Aedes aegypti* mosquitoes. *eLife*. 2023
11 Mar 10;12:e83524. <https://doi.org/10.7554/eLife.83524>
- 12 38. Powell JR, Gloria-Soria A, Kotsakiozi P. Recent History of *Aedes aegypti*: Vector
13 Genomics and Epidemiology Records. *BioScience*. 2018 Nov 1;68(11):854–60.
14 <https://doi.org/10.1093/biosci/biy119>
- 15 39. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working*
16 *Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate*
17 *Change*. 2021. <https://doi.org/10.1017/9781009157896>
- 18 40. IPCC. *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II*
19 *Contribution to the Sixth Assessment Report of the Intergovernmental Panel on*
20 *Climate Change*. 1st ed. Cambridge University Press; 2023.
21 <https://doi.org/10.1017/9781009325844>
- 22 41. Marvel K, Su W, Delgado R, Aarons S, Chatterjee A, Garcia ME, et al. Chapter 2 :
23 *Climate Trends*. *Fifth National Climate Assessment* [Internet]. U.S. Global Change
24 *Research Program*; 2023 [2025 Oct 22]. <https://doi.org/10.7930/NCA5.2023.CH2>
- 25 42. IPCC, editor. *The Earth’s Energy Budget, Climate Feedbacks and Climate Sensitivity*.
26 *In: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution*
27 *to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*
28 [Internet]. Cambridge: Cambridge University Press; 2021 [2025 Oct 30]. p. 923–1054.
29 <https://doi.org/10.1017/9781009157896.009>
- 30 43. Thornton PE, Reed BC, Xian GZ, Chini L, East AE, Field JL, et al. Chapter 6 : *Land Cover*
31 *and Land-Use Change*. *Fifth National Climate Assessment* [Internet]. U.S. Global
32 *Change Research Program*; 2023 [2025 Oct 30].
33 <https://doi.org/10.7930/NCA5.2023.CH6>
- 34 44. Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, et al. Global
35 consequences of land use. *Science*. 2005;309(5734):570–4.
36 <https://doi.org/10.1126/science.1111772>

- 1 45. Bashir I, Lone FA, Bhat RA, Mir SA, Dar ZA, Dar SA. Concerns and Threats of
2 Contamination on Aquatic Ecosystems. In: Hakeem KR, Bhat RA, Qadri H, editors.
3 Bioremediation and Biotechnology [Internet]. Cham: Springer International
4 Publishing; 2020 [2025 Oct 29]. p. 1–26. https://doi.org/10.1007/978-3-030-35691-0_1
- 5 46. Gill SE, Handley JF, Ennos AR, Pauleit S. Adapting Cities for Climate Change: The Role
6 of the Green Infrastructure. *Built Environ.* 2007 Mar 13;33(1):115–33.
7 <https://doi.org/10.2148/benv.33.1.115>
- 8 47. Chazdon RL. Beyond Deforestation: Restoring Forests and Ecosystem Services on
9 Degraded Lands. *Science.* 2008 Jun 13;320(5882):1458–60.
10 <https://doi.org/10.1126/science.1155365>
- 11 48. Status of Tribes and Climate Change Working Group. The Status of Tribes and Climate
12 Change, Vol. 2, (B. M. Panek, Ed.) [Internet]. Institute for Tribal Environmental
13 Professionals, Northern Arizona University; 2025 [2025 Oct 30].
14 <http://nau.edu/staccreport>
- 15 49. CA SB310. 2025.
- 16 50. Schulte To Bühne H, Tobias JA, Durant SM, Pettorelli N. Improving Predictions of
17 Climate Change–Land Use Change Interactions. *Trends Ecol Evol.* 2021 Jan;36(1):29–
18 38. <https://doi.org/10.1016/j.tree.2020.08.019>
- 19 51. McCluney KE, Belnap J, Collins SL, González AL, Hagen EM, Nathaniel Holland J, et al.
20 Shifting species interactions in terrestrial dryland ecosystems under altered water
21 availability and climate change. *Biol Rev.* 2012 Aug;87(3):563–82.
22 <https://doi.org/10.1111/j.1469-185X.2011.00209.x>
- 23 52. Hamann E, Blevins C, Franks SJ, Jameel MI, Anderson JT. Climate change alters plant–
24 herbivore interactions. *New Phytol.* 2021 Feb;229(4):1894–910.
25 <https://doi.org/10.1111/nph.17036>
- 26 53. Fusco EJ, Finn JT, Balch JK, Nagy RC, Bradley BA. Invasive grasses increase fire
27 occurrence and frequency across US ecoregions. *Proc Natl Acad Sci.* 2019 Nov
28 19;116(47):23594–9. <https://doi.org/10.1073/pnas.1908253116>
- 29 54. IPBES. Global assessment report on biodiversity and ecosystem services of the
30 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
31 [Internet]. Brondizio ES, Settele J, Díaz S, Ngo HT, editors. Bonn, Germany: Secretariat
32 of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem
33 Services; 2019 [2024 May 18]. <https://doi.org/10.5281/zenodo.6417333>
- 34 55. USGCRP. Fifth National Climate Assessment [Internet]. Crimmins AR, Avery CW,
35 Easterling DR, Kunkel KE, Maycock TK, editors. Fifth National Climate Assessment.

- 1 Washington, DC: U.S. Global Change Research Program; 2023 [2024 Apr 29].
2 <https://doi.org/10.7930/NCA5.2023>
- 3 56. IPBES. Summary for Policymakers of the Thematic Assessment Report on the
4 Underlying Causes of Biodiversity Loss and the Determinants of Transformative
5 Change and Options for Achieving the 2050 Vision for Biodiversity of the
6 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
7 [Internet]. Bonn, Germany: IPBES secretariat; 2024 [2025 Oct 31].
8 <https://doi.org/10.5281/zenodo.17099400>
- 9 57. Chaudhary AK, Mook A, Dwivedi P. Factors Influencing Reenrollment in the
10 Conservation Reserve Program. *Soc Nat Resour*. 2025 Nov 30;1–21.
11 <https://doi.org/10.1080/08941920.2025.2589243>
- 12 58. Barnes JC, Sketch M, Gramza AR, Sorice MG, Iovanna R, Dayer AA. Land use decisions
13 after the Conservation Reserve Program: Re-enrollment, reversion, and persistence in
14 the southern Great Plains. *Conserv Sci Pract*. 2020 Sep;2(9):e254.
15 <https://doi.org/10.1111/csp2.254>
- 16 59. Feng H, Hennessy DA, Miao R. The Effects Of Government Payments On Cropland
17 Acreage, Conservation Reserve Program Enrollment, And Grassland Conversion In
18 The Dakotas. *Am J Agric Econ*. 2013 Jan;95(2):412–8.
19 <https://doi.org/10.1093/ajae/aas112>
- 20 60. Kemink KM, Diedrich A, Adams VM, Pressey RobertL. Exploring motives for
21 participation in a perpetual easement program: Going beyond financial incentives.
22 *Biol Conserv*. 2023 Aug;284:110193. <https://doi.org/10.1016/j.biocon.2023.110193>
- 23 61. Dawson NM, Coolsaet B, Sterling EJ, Loveridge R, Gross-Camp ND, Wongbusarakum
24 S, et al. The role of Indigenous peoples and local communities in effective and
25 equitable conservation. *Ecol Soc*. 2021;26(3):art19. [https://doi.org/10.5751/ES-
26 12625-260319](https://doi.org/10.5751/ES-12625-260319)
- 27 62. Waller DM, Reo NJ. First stewards: ecological outcomes of forest and wildlife
28 stewardship by indigenous peoples of Wisconsin, USA. *Ecol Soc*. 2018;23(1):art45.
29 <https://doi.org/10.5751/ES-09865-230145>
- 30 63. Bolster CH, Mitchell R, Kitts A, Campbell A, Cosh M, Farrigan TL, et al. Chapter 11 :
31 Agriculture, Food Systems, and Rural Communities. Fifth National Climate
32 Assessment [Internet]. U.S. Global Change Research Program; 2023 [2025 Oct 29].
33 <https://doi.org/10.7930/NCA5.2023.CH11>
- 34 64. National Academy of Sciences, The Royal Society. The Challenge of Feeding the World
35 Sustainably: Summary of the US-UK Scientific Forum on Sustainable Agriculture

- 1 [Internet]. Washington, D.C.: National Academies Press; 2021 [2025 Dec 7].
2 <https://doi.org/10.17226/26007>
- 3 65. McLaughlin A, Mineau P. The impact of agricultural practices on biodiversity. *Agric*
4 *Ecosyst Environ.* 1995 Oct;55(3):201–12. [https://doi.org/10.1016/0167-](https://doi.org/10.1016/0167-8809(95)00609-V)
5 [8809\(95\)00609-V](https://doi.org/10.1016/0167-8809(95)00609-V)
- 6 66. Gordon LJ, Peterson GD, Bennett EM. Agricultural modifications of hydrological flows
7 create ecological surprises. *Trends Ecol Evol.* 2008 Apr;23(4):211–9.
8 <https://doi.org/10.1016/j.tree.2007.11.011>
- 9 67. Skaggs RW, Brevé MA, Gilliam JW. Hydrologic and water quality impacts of
10 agricultural drainage*. *Crit Rev Environ Sci Technol.* 1994 Jan;24(1):1–32.
11 <https://doi.org/10.1080/10643389409388459>
- 12 68. Thaler EA, Larsen IJ, Yu Q. The extent of soil loss across the US Corn Belt. *Proc Natl*
13 *Acad Sci.* 2021 Feb 23;118(8):e1922375118.
14 <https://doi.org/10.1073/pnas.1922375118>
- 15 69. Niemeijer D, De Groot RS. Framing environmental indicators: moving from causal
16 chains to causal networks. *Environ Dev Sustain.* 2008 Feb;10(1):89–106.
17 <https://doi.org/10.1007/s10668-006-9040-9>
- 18 70. Polhill JG, Filatova T, Schlüter M, Voinov A. Modelling systemic change in coupled
19 socio-environmental systems. *Environ Model Softw.* 2016 Jan 1;75:318–32.
20 <https://doi.org/10.1016/j.envsoft.2015.10.017>
- 21 71. Zare F, Jakeman AJ, Elsayah S, Guillaume JHA. Bridging practice and science in socio-
22 environmental systems research and modelling: A design science approach. *Ecol*
23 *Model.* 2024 Jun 1;492:110719. <https://doi.org/10.1016/j.ecolmodel.2024.110719>
- 24 72. Razgour O, Forester B, Taggart JB, Bekaert M, Juste J, Ibáñez C, et al. Considering
25 adaptive genetic variation in climate change vulnerability assessment reduces
26 species range loss projections. *Proc Natl Acad Sci.* 2019 May 21;116(21):10418–23.
27 <https://doi.org/10.1073/pnas.1820663116>
- 28 73. Sæther B, Engen S, Solbu EB. Assessing the sensitivity and resistance of communities
29 in a changing environment. *J Anim Ecol.* 2024 Jan;93(1):8–20.
30 <https://doi.org/10.1111/1365-2656.14003>
- 31 74. Fernández-Llamazares Á, Fa JE, Brockington D, Brondízio ES, Cariño J, Corbera E, et
32 al. No basis for claim that 80% of biodiversity is found in Indigenous territories.
33 *Nature.* 2024 Sep;633(8028):32–5. <https://doi.org/10.1038/d41586-024-02811-w>
- 34 75. Riley K, Nguyen B, Jorgensen M, Mills M. Experts, not Obstacles: Indigenous
35 Conservation Excellence and the Trap of Conservation at any Cost. *Landback Policy*

- 1 Brief [Internet]. Harvard Project on Indigenous Governance & Native Nations Institute;
2 2025 [2025 Oct 30]. [https://ash.harvard.edu/resources/experts-not-obstacles-](https://ash.harvard.edu/resources/experts-not-obstacles-indigenous-conservation-excellence-and-the-trap-of-conservation-at-any-cost/)
3 [indigenous-conservation-excellence-and-the-trap-of-conservation-at-any-cost/](https://ash.harvard.edu/resources/experts-not-obstacles-indigenous-conservation-excellence-and-the-trap-of-conservation-at-any-cost/)
- 4 76. Nikolakis W, Hotte N. Implementing “ethical space”: An exploratory study of
5 Indigenous-conservation partnerships. *Conserv Sci Pract*. 2022 Jan;4(1):e580.
6 <https://doi.org/10.1111/csp2.580>
- 7 77. Redvers N, Celidwen Y, Schultz C, Horn O, Githaiga C, Vera M, et al. The determinants
8 of planetary health: an Indigenous consensus perspective. *Lancet Planet Health*.
9 2022 Feb 1;6(2):e156–63. [https://doi.org/10.1016/S2542-5196\(21\)00354-5](https://doi.org/10.1016/S2542-5196(21)00354-5)
- 10 78. Stein S, Ahenakew C, Valley W, Sherpa PY, Crowson E, Robin T, et al. Toward more
11 ethical engagements between Western and Indigenous sciences. *FACETS*. 2024
12 Jan;9:1–14. <https://doi.org/10.1139/facets-2023-0071>
- 13 79. David-Chavez DM, Gavin MC, Ortiz N, Valdez S, Carroll SR. A values-centered
14 relational science model: supporting Indigenous rights and reconciliation in research.
15 *Ecol Soc* [Internet]. 2024 May 31 [2025 Oct 30];29(2). [https://doi.org/10.5751/ES-](https://doi.org/10.5751/ES-14768-290211)
16 [14768-290211](https://doi.org/10.5751/ES-14768-290211)
- 17 80. Wilkening JL, Magness DR, Thompson LM, Lynch AJ. A Brave New World: Managing for
18 Biodiversity Conservation under Ecosystem Transformation. *Land*. 2023
19 Aug;12(8):1556. <https://doi.org/10.3390/land12081556>
- 20 81. Siegel KJ, Cavanaugh KC, Dee LE. Balancing multiple management objectives as
21 climate change transforms ecosystems. *Trends Ecol Evol*. 2024 Apr 1;39(4):381–95.
22 <https://doi.org/10.1016/j.tree.2023.11.003>
- 23 82. Williams BK, Brown ED. Managing ecosystems with resist–accept–direct (RAD).
24 *Methods Ecol Evol*. 2024 May;15(5):796–805. [https://doi.org/10.1111/2041-](https://doi.org/10.1111/2041-210X.14309)
25 [210X.14309](https://doi.org/10.1111/2041-210X.14309)
- 26 83. Hurtt GC, Chini L, Sahajpal R, Frohking S, Bodirsky BL, Calvin K, et al. Harmonization of
27 global land use change and management for the period 850–2100 (LUH2) for CMIP6.
28 *Geosci Model Dev*. 2020 Nov 10;13(11):5425–64. [https://doi.org/10.5194/gmd-13-](https://doi.org/10.5194/gmd-13-5425-2020)
29 [5425-2020](https://doi.org/10.5194/gmd-13-5425-2020)
- 30 84. Gould WA, Wadsworth FH, Quiñones M, Fain SJ, Álvarez-Berrios NL. Land Use,
31 Conservation, Forestry, and Agriculture in Puerto Rico. *Forests* [Internet]. 2017 Jul 6
32 [2026 Jan 21];8(7). <https://doi.org/10.3390/f8070242>
- 33 85. HYDE (2023); Gapminder (2022); UN WPP (2024) – with major processing by Our
34 World in Data. Population – HYDE, Gapminder, UN – Long-run data [Internet]. 2025
35 [2026 Jan 8]. [https://archive.ourworldindata.org/20250929-](https://archive.ourworldindata.org/20250929-103213/grapher/population.html)
36 [103213/grapher/population.html](https://archive.ourworldindata.org/20250929-103213/grapher/population.html)

- 1 86. FAO. FAOSTAT Population module [Internet]. 2024 [2025 Dec 7].
2 <https://www.fao.org/faostat/en/#data/OA>
- 3 87. FAO. FAOSTAT Credit to Agriculture [Internet]. 2024 [2026 Jan 8].
4 <https://www.fao.org/faostat/en/#data/IC>
- 5 88. U.S. Bureau of Economic Analysis. Real gross domestic product per capita
6 [A939RX0Q048SBEA] [Internet]. FRED, Federal Reserve Bank of St. Louis; 2025 [2025
7 Dec 7]. <https://fred.stlouisfed.org/series/A939RX0Q048SBEA>
- 8 89. Birdsey R, Pregitzer K, Lucier A. Forest Carbon Management in the United States. *J*
9 *Environ Qual.* 2006;35(4):1461–9. <https://doi.org/10.2134/jeq2005.0162>
- 10 90. Yu Z, Lu C. Historical cropland expansion and abandonment in the continental U.S.
11 during 1850 to 2016. *Glob Ecol Biogeogr.* 2018;27(3):322–33.
12 <https://doi.org/10.1111/geb.12697>
- 13 91. USDA Economic Research Service. Land Use, Land Value & Tenure - Major Land Uses
14 [Internet]. 2024 [2025 Oct 27]. [https://www.ers.usda.gov/data-products/major-land-](https://www.ers.usda.gov/data-products/major-land-uses)
15 [uses](https://www.ers.usda.gov/data-products/major-land-uses)
- 16 92. Dieter CA, Maupin MA, Caldwell RR, Harris MA, Ivahnenko TI, Lovelace JK, et al.
17 Estimated use of water in the United States in 2015 [Internet]. Circular. U.S.
18 Geological Survey; 2018 [2025 Nov 30]. Report No.: 1441.
19 <https://doi.org/10.3133/cir1441>
- 20 93. Li X, Tian H, Lu C, Pan S. Four-century history of land transformation by humans in the
21 United States (1630–2020): annual and 1km grid data for the HIStory of LAND changes
22 (HISLAND-US). *Earth Syst Sci Data.* 2023 Mar 3;15(2):1005–35.
23 <https://doi.org/10.5194/essd-15-1005-2023>
- 24 94. Xie Y, Spawn-Lee SA, Radeloff VC, Yin H, Robertson GP, Lark TJ. Cropland
25 abandonment between 1986 and 2018 across the United States: spatiotemporal
26 patterns and current land uses. *Environ Res Lett.* 2024 Mar;19(4):044009.
27 <https://doi.org/10.1088/1748-9326/ad2d12>
- 28 95. Spangler K, Burchfield EK, Schumacher B. Past and Current Dynamics of U.S.
29 Agricultural Land Use and Policy. *Front Sustain Food Syst* [Internet]. 2020 Jul 21 [2025
30 Oct 16];4. <https://doi.org/10.3389/fsufs.2020.00098>
- 31 96. Lark TJ, Meghan Salmon J, Gibbs HK. Cropland expansion outpaces agricultural and
32 biofuel policies in the United States. *Environ Res Lett.* 2015 Apr;10(4):044003.
33 <https://doi.org/10.1088/1748-9326/10/4/044003>

- 1 97. Nakajima T, Hudson MJ, Uchiyama J, Makibayashi K, Zhang J. Common carp
2 aquaculture in Neolithic China dates back 8,000 years. *Nat Ecol Evol.* 2019
3 Oct;3(10):1415–8. <https://doi.org/10.1038/s41559-019-0974-3>
- 4 98. NOAA Fisheries. Fisheries of the United States, 2020 [Internet]. U.S. Department of
5 Commerce; 2022. Report No.: NOAA Current Fishery Statistics No. 2020.
6 [https://www.fisheries.noaa.gov/national/sustainable-fisheries/fisheries-united-
8 states](https://www.fisheries.noaa.gov/national/sustainable-fisheries/fisheries-united-
7 states)
- 8 99. FAO. FAO Fisheries & Aquaculture - Global aquaculture production Quantity (1950 -
9 2023) [Internet]. 2025 [2025 Oct 31]. [https://www.fao.org/fishery/statistics-
11 query/en/aquaculture/aquaculture_quantity](https://www.fao.org/fishery/statistics-
10 query/en/aquaculture/aquaculture_quantity)
- 11 100. Lester SE, Gentry RR, Lemoine HR, Froehlich HE, Gardner LD, Rennick M, et al.
12 Diverse state-level marine aquaculture policy in the United States: Opportunities and
13 barriers for industry development. *Rev Aquac.* 2022;14(2):890–906.
14 <https://doi.org/10.1111/raq.12631>
- 15 101. Froehlich HE, Gentry RR, Lester SE, Rennick M, Lemoine HR, Tapia-Lewin S, et al.
16 Piecing together the data of the U.S. marine aquaculture puzzle. *J Environ Manage.*
17 2022 Apr 15;308:114623. <https://doi.org/10.1016/j.jenvman.2022.114623>
- 18 102. Guo L, Li Z. Effects of nitrogen and phosphorus from fish cage-culture on the
19 communities of a shallow lake in middle Yangtze River basin of China. *Aquaculture.*
20 2003 Oct 31;226(1):201–12. [https://doi.org/10.1016/S0044-8486\(03\)00478-2](https://doi.org/10.1016/S0044-8486(03)00478-2)
- 21 103. Findlay DL, Podemski CL, Kasian SEM. Aquaculture impacts on the algal and bacterial
22 communities in a small boreal forest lake This paper is part of the series “Forty Years
23 of Aquatic Research at the Experimental Lakes Area”. *Can J Fish Aquat Sci.* 2009
24 Nov;66(11):1936–48. <https://doi.org/10.1139/F09-121>
- 25 104. Paterson MJ, Podemski CL, Findlay WJ, Findlay DL, Salki AG. The response of
26 zooplankton in a whole-lake experiment on the effects of a cage aquaculture
27 operation for rainbow trout (*Oncorhynchus mykiss*). *Can J Fish Aquat Sci.* 2010
28 Nov;67(11):1852–61. <https://doi.org/10.1139/F10-106>
- 29 105. Liu X, Wang Y, Liu H, Zhang Y, Zhou Q, Wen X, et al. A systematic review on
30 aquaculture wastewater: Pollutants, impacts, and treatment technology. *Environ Res.*
31 2024 Dec 1;262:119793. <https://doi.org/10.1016/j.envres.2024.119793>
- 32 106. Krkošek M, Ford JS, Morton A, Lele S, Myers RA, Lewis MA. Declining Wild Salmon
33 Populations in Relation to Parasites from Farm Salmon. *Science.* 2007 Dec
34 14;318(5857):1772–5. <https://doi.org/10.1126/science.1148744>
- 35 107. Naylor R, Hindar K, Fleming IA, Goldburg R, Williams S, Volpe J, et al. Fugitive Salmon:
36 Assessing the Risks of Escaped Fish from Net-Pen Aquaculture. *BioScience.* 2005

- 1 May 1;55(5):427–37. <https://doi.org/10.1641/0006->
2 [3568\(2005\)055%255B0427:FSATRO%255D2.0.CO;2](https://doi.org/10.1641/0006-3568(2005)055%255B0427:FSATRO%255D2.0.CO;2)
- 3 108. Sarà G, Lo Martire M, Sanfilippo M, Pulicanò G, Cortese G, Mazzola A, et al. Impacts of
4 marine aquaculture at large spatial scales: Evidences from N and P catchment
5 loading and phytoplankton biomass. *Mar Environ Res.* 2011 Jun 1;71(5):317–24.
6 <https://doi.org/10.1016/j.marenvres.2011.02.007>
- 7 109. Lulijwa R, Rupia EJ, Alfaro AC. Antibiotic use in aquaculture, policies and regulation,
8 health and environmental risks: a review of the top 15 major producers. *Rev Aquac.*
9 2020;12(2):640–63. <https://doi.org/10.1111/raq.12344>
- 10 110. Sellars L, Franks B. How mariculture expansion is dewilding the ocean and its
11 inhabitants. *Sci Adv.* 2024 Oct 16;10(42):eadn8943.
12 <https://doi.org/10.1126/sciadv.adn8943>
- 13 111. Howard JL, Liang S. U.S. timber production, trade, consumption, and price statistics,
14 1965-2017. *Res Pap FPL-RP-701 Madison WI US Dep Agric For Serv For Prod Lab 96 P.*
15 2019;701:1–96. <https://doi.org/10.2737/FPL-RP-701>
- 16 112. Magerl A, Matej S, Kaufmann L, Noë JL, Erb K, Gingrich S. Forest carbon sink in the
17 U.S. (1870–2012) driven by substitution of forest ecosystem service flows. *Resour*
18 *Conserv Recycl.* 2022 Jan 1;176:105927.
19 <https://doi.org/10.1016/j.resconrec.2021.105927>
- 20 113. Bahre CJ, Shelton ML. Rangeland Destruction: Cattle and Drought in Southeastern
21 Arizona at the Turn of the Century. *J Southwest.* 1996;38(1):1–22.
- 22 114. Galbraith WA, Anderson EW. Grazing History of the Northwest. *J Range Manag.* 1971
23 Jan 1;24:6–12. <https://doi.org/10.2307/3896056>
- 24 115. Fredrickson E, Havstad KrisM, Estell R, Hyder P. Perspectives on desertification:
25 south-western United States. *J Arid Environ.* 1998 Jun 1;39(2):191–207.
26 <https://doi.org/10.1006/jare.1998.0390>
- 27 116. Borman MM. Forest Stand Dynamics and Livestock Grazing in Historical Context.
28 *Conserv Biol.* 2005;19(5):1658–62. <https://doi.org/10.1111/j.1523-1739.2005.00115.x>
- 29 117. Holechek JL. A Brief History of Range Management in the United States. *Rangelands.*
30 1981;3:16–8.
- 31 118. Paul MJ, Meyer JL. Streams in the Urban Landscape. *Annu Rev Ecol Evol Syst.* 2001
32 Nov 1;32(Volume 32, 2001):333–65.
33 <https://doi.org/10.1146/annurev.ecolsys.32.081501.114040>

- 1 119. Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, et al. Global change
2 and the ecology of cities. *Science*. 2008;319(February):756–60.
3 <https://doi.org/10.1126/science.1150195>
- 4 120. US EPA OAR. Accomplishments and Successes of Reducing Air Pollution from
5 Transportation in the United States [Internet]. 2015 [2025 Oct 27].
6 [https://www.epa.gov/transportation-air-pollution-and-climate-](https://www.epa.gov/transportation-air-pollution-and-climate-change/accomplishments-and-successes-reducing-air)
7 [change/accomplishments-and-successes-reducing-air](https://www.epa.gov/transportation-air-pollution-and-climate-change/accomplishments-and-successes-reducing-air)
- 8 121. US Census Bureau. *Census.gov*. 2023 [2025 Oct 27]. 2020 Census Urban Areas Facts.
9 [https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-](https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural/2020-ua-facts.html)
10 [rural/2020-ua-facts.html](https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural/2020-ua-facts.html)
- 11 122. NOAA Office for Coastal Management. Economics and Demographics [Internet]. 2025
12 [2025 Dec 8]. [https://coast.noaa.gov/states/fast-facts/economics-and-](https://coast.noaa.gov/states/fast-facts/economics-and-demographics.html)
13 [demographics.html](https://coast.noaa.gov/states/fast-facts/economics-and-demographics.html)
- 14 123. Morris JT, Sundareshwar PV, Nietch CT, Kjerfve B, Cahoon DR. Responses of Coastal
15 Wetlands to Rising Sea Level. *Ecology*. 2002;83(10):2869–77.
16 <https://doi.org/10.2307/3072022>
- 17 124. Day JW, Boesch DF, Clairain EJ, Kemp GP, Laska SB, Mitsch WJ, et al. Restoration of
18 the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science*. 2007 Mar
19 23;315(5819):1679–84. <https://doi.org/10.1126/science.1137030>
- 20 125. Krause JR, Oczkowski AJ, Watson EB. Improved mapping of coastal salt marsh habitat
21 change at Barnegat Bay (NJ, USA) using object-based image analysis of high-
22 resolution aerial imagery. *Remote Sens Appl Soc Environ*. 2023 Jan 1;29:100910.
23 <https://doi.org/10.1016/j.rsase.2022.100910>
- 24 126. Zedler JB, Kercher S. WETLAND RESOURCES: Status, Trends, Ecosystem Services,
25 and Restorability. *Annu Rev Environ Resour*. 2005 Nov 21;30(1):39–74.
26 <https://doi.org/10.1146/annurev.energy.30.050504.144248>
- 27 127. US Army Corp of Engineers. National Inventory of Dams & Low-Head Dams Inventory
28 [Internet]. 2025 [2025 Oct 20]. <https://nid.sec.usace.army.mil/>
- 29 128. Spinti RA, Condon LE, Zhang J. The evolution of dam induced river fragmentation in
30 the United States. *Nat Commun*. 2023 Jun 28;14(1):3820.
31 <https://doi.org/10.1038/s41467-023-39194-x>
- 32 129. National Aquatic Connectivity Collaborative. National Aquatic Barrier Inventory
33 [Internet]. 2026 [2026 Jan 21]. <https://aquaticbarriers.org/inventory/>
- 34 130. American Rivers. American Rivers Dam Removal Database [Internet]. figshare; 2025
35 [2025 Oct 16]. <https://doi.org/10.6084/m9.figshare.5234068.v12>

- 1 131. Bellmore RJ, Duda JJ, Craig LS, Greene SL, Torgersen CE, Collins MJ, et al. Status and
2 trends of dam removal research in the United States. *WIREs Water*. 2017 Mar
3 1;4(2):e1164. <https://doi.org/10.1002/wat2.1164>
- 4 132. California Department of Fish and Wildlife. ‘Salmon Everywhere’ One Year After
5 Klamath Dam Removal [Internet]. 2025 [2026 Jan 5].
6 [https://wildlife.ca.gov/News/Archive/salmon-everywhere-one-year-after-klamath-](https://wildlife.ca.gov/News/Archive/salmon-everywhere-one-year-after-klamath-dam-removal)
7 [dam-removal](https://wildlife.ca.gov/News/Archive/salmon-everywhere-one-year-after-klamath-dam-removal)
- 8 133. Sotka EE, Hay ME. Effects of herbivores, nutrient enrichment, and their interactions on
9 macroalgal proliferation and coral growth. *Coral Reefs*. 2009 Sep 1;28(3):555–68.
10 <https://doi.org/10.1007/s00338-009-0529-1>
- 11 134. Schulte DM. History of the Virginia Oyster Fishery, Chesapeake Bay, USA. *Front Mar*
12 *Sci* [Internet]. 2017 May 9 [2025 Nov 12];4. <https://doi.org/10.3389/fmars.2017.00127>
- 13 135. Nordlund LM, Unsworth RKF, Gullström M, Cullen-Unsworth LC. Global significance
14 of seagrass fishery activity. *Fish Fish*. 2018;19(3):399–412.
15 <https://doi.org/10.1111/faf.12259>
- 16 136. Shantz AA, Ladd MC, Burkepile DE. Overfishing and the ecological impacts of
17 extirpating large parrotfish from Caribbean coral reefs. *Ecol Monogr*.
18 2020;90(2):e01403. <https://doi.org/10.1002/ecm.1403>
- 19 137. Knowlton AR, Clark JS, Hamilton PK, Kraus SD, Pettis HM, Rolland RM, et al. Fishing
20 gear entanglement threatens recovery of critically endangered North Atlantic right
21 whales. *Conserv Sci Pract*. 2022;4(8):e12736. <https://doi.org/10.1111/csp2.12736>
- 22 138. Kaiser MJ, Collie JS, Hall SJ, Jennings S, Poiner IR. Modification of marine habitats by
23 trawling activities: prognosis and solutions. *Fish Fish*. 2002 Jun;3(2):114–36.
24 <https://doi.org/10.1046/j.1467-2979.2002.00079.x>
- 25 139. Amoroso RO, Pitcher CR, Rijnsdorp AD, McConnaughey RA, Parma AM, Suuronen P,
26 et al. Bottom trawl fishing footprints on the world’s continental shelves. *Proc Natl*
27 *Acad Sci* [Internet]. 2018 Oct 23 [2025 Nov 13];115(43).
28 <https://doi.org/10.1073/pnas.1802379115>
- 29 140. Hourigan TF, Etnoyer PJ, Cairns SD, United States, National Marine Fisheries Service,
30 Office of Habitat Conservation (U.S.), United States, National Oceanic and
31 Atmospheric Administration, Coral Reef Conservation Program. The state of deep-sea
32 coral and sponge ecosystems of the United States. 2017 [2025 Nov 7];
33 <https://doi.org/10.25923/WJ31-G055>
- 34 141. Baco AR, Roark EB, Morgan NB. Amid fields of rubble, scars, and lost gear, signs of
35 recovery observed on seamounts on 30- to 40-year time scales. *Sci Adv*. 2019 Aug
36 7;5(8):eaaw4513. <https://doi.org/10.1126/sciadv.aaw4513>

- 1 142. Pitcher CR, Hiddink JG, Jennings S, Collie J, Parma AM, Amoroso R, et al. Trawl
2 impacts on the relative status of biotic communities of seabed sedimentary habitats
3 in 24 regions worldwide. *Proc Natl Acad Sci*. 2022 Jan 11;119(2):e2109449119.
4 <https://doi.org/10.1073/pnas.2109449119>
- 5 143. Koslow JA, Boehlert GW, Gordon JDM, Haedrich RL, Lorange P, Parin N. Continental
6 slope and deep-sea fisheries: implications for a fragile ecosystem. *ICES J Mar Sci*.
7 2000 Jun 1;57(3):548–57. <https://doi.org/10.1006/jmsc.2000.0722>
- 8 144. NOAA Fisheries. NOAA. 2025 [2025 Oct 23]. Status of Stocks 2023.
9 <https://www.fisheries.noaa.gov/national/sustainable-fisheries/status-stocks-2023>
- 10 145. Barner AK, Lubchenco J, Costello C, Gaines SD, Leland A. Solutions for Recovering
11 and Sustaining the Bounty of the Ocean: Combining Fishery Reforms, Rights-Based
12 Fisheries Management, and Marine Reserves | *Oceanography*. [2026 Jan 7];
13 [https://tos.org/oceanography/article/solutions-for-recovering-and-sustaining-the-](https://tos.org/oceanography/article/solutions-for-recovering-and-sustaining-the-bounty-of-the-ocean-combining-fi)
14 [bounty-of-the-ocean-combining-fi](https://tos.org/oceanography/article/solutions-for-recovering-and-sustaining-the-bounty-of-the-ocean-combining-fi)
- 15 146. National Marine Fisheries Service. Our living oceans: report on the status of U.S. living
16 marine resources [Internet]. Silver Spring, Maryland, USA: US Department of
17 Commerce; 1999 [2025 Oct 27]. Report No.: NOAA Technical Memorandum NMFS-
18 F/SPO-41. <https://repository.library.noaa.gov>
- 19 147. Dell’Apa A, Schiavinato L, Rulifson RA. The Magnuson–Stevens act (1976) and its
20 reauthorizations: Failure or success for the implementation of fishery sustainability
21 and management in the US? *Mar Policy*. 2012 May 1;36(3):673–80.
22 <https://doi.org/10.1016/j.marpol.2011.11.002>
- 23 148. Melnychuk MC, Ashbrook CE, Bell RJ, Bellquist L, Kauer K, Wilson JR, et al.
24 Characterizing state-managed and unmanaged fisheries in coastal marine states and
25 territories of the United States. *Fish Fish*. 2023;24(5):711–29.
26 <https://doi.org/10.1111/faf.12756>
- 27 149. Vrtis G, Elsass K. Mining and the Environment. In: *Oxford Research Encyclopedia of*
28 *American History* [Internet]. 2023 [2025 Oct 30].
29 <https://oxfordre.com/americanhistory/display/10.1093/acrefore/9780199329175.001>
30 [.0001/acrefore-9780199329175-e-419](https://oxfordre.com/americanhistory/display/10.1093/acrefore/9780199329175.001)
- 31 150. U.S. Energy Information Administration. U.S. production of all types of coal has
32 declined over the past two decades [Internet]. 2025 Apr [2025 Oct 30].
33 <https://www.eia.gov/todayinenergy/detail.php?id=64924>
- 34 151. Sergeant CJ, Sexton EK, Moore JW, Westwood AR, Nagorski SA, Ebersole JL, et al.
35 Risks of mining to salmonid-bearing watersheds. *Sci Adv*. 2022 Jul;8(26):eabn0929.
36 <https://doi.org/10.1126/sciadv.abn0929>

- 1 152. U.S. Energy Information Administration. US Oil and Gas Wells by Production Rate
2 [Internet]. 2025 Dec [2026 Jan 25]. <https://www.eia.gov/petroleum/wells/index.php>
- 3 153. Cleveland C. The history of oil production in the United States [Internet]. 2024 [2025
4 Oct 30]. [https://visualizingenergy.org/the-history-of-oil-production-in-the-united-
5 states-2/](https://visualizingenergy.org/the-history-of-oil-production-in-the-united-states-2/)
- 6 154. Cordes EE, Jones DOB, Schlacher TA, Amon DJ, Bernardino AF, Brooke S, et al.
7 Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide
8 Management Strategies. *Front Environ Sci* [Internet]. 2016 Sep 16 [2025 Nov 29];4.
9 <https://doi.org/10.3389/fenvs.2016.00058>
- 10 155. Murawski SA, Hollander DJ, Gilbert S, Gracia A. Deepwater Oil and Gas Production in
11 the Gulf of Mexico and Related Global Trends. In: Murawski SA, Ainsworth CH, Gilbert
12 S, Hollander DJ, Paris CB, Schlüter M, et al., editors. *Scenarios and Responses to
13 Future Deep Oil Spills: Fighting the Next War* [Internet]. Cham: Springer International
14 Publishing; 2020 [2025 Oct 30]. p. 16–32. [https://doi.org/10.1007/978-3-030-12963-
15 7_2](https://doi.org/10.1007/978-3-030-12963-7_2)
- 16 156. May CL, Osler MS, Stockdon HF, Barnard PL, Callahan JA, Collini RC, et al. Chapter 9 :
17 Coastal Effects. *Fifth National Climate Assessment* [Internet]. U.S. Global Change
18 Research Program; 2023 [2024 Dec 2]. <https://doi.org/10.7930/NCA5.2023.CH9>
- 19 157. Ma D, Gregor L, Gruber N. Four Decades of Trends and Drivers of Global Surface
20 Ocean Acidification. *Glob Biogeochem Cycles*. 2023;37(7):e2023GB007765.
21 <https://doi.org/10.1029/2023GB007765>
- 22 158. Siedlecki SA, Banas NS, Davis KA, Giddings S, Hickey BM, MacCready P, et al.
23 Seasonal and interannual oxygen variability on the Washington and Oregon
24 continental shelves. *J Geophys Res Oceans*. 2015 Feb 1;120(2):608–33.
25 <https://doi.org/10.1002/2014JC010254>
- 26 159. Barth JA, Pierce SD, Carter BR, Chan F, Erofeev AY, Fisher JL, et al. Widespread and
27 increasing near-bottom hypoxia in the coastal ocean off the United States Pacific
28 Northwest. *Sci Rep*. 2024 Feb 15;14(1):3798. [https://doi.org/10.1038/s41598-024-
29 54476-0](https://doi.org/10.1038/s41598-024-54476-0)
- 30 160. National Interagency Fire Center. *Wildfires and Acres* | National Interagency Fire
31 Center [Internet]. 2025 [2025 Oct 22]. [https://www.nifc.gov/fire-
32 information/statistics/wildfires](https://www.nifc.gov/fire-information/statistics/wildfires)
- 33 161. Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, et al. No
34 saturation in the accumulation of alien species worldwide. *Nat Commun*. 2017 Feb
35 15;8(1):14435. <https://doi.org/10.1038/ncomms14435>

- 1 162. Lugo AE, Brandeis TJ. New mix of alien and native species coexists in Puerto Rico's
2 landscapes. In: In: Burslem, D F R P; Pinard, M A, and Hartley, S E, editors Biotic
3 interactions in the tropics: their role in the maintenance of species diversity [Internet].
4 Cambridge University Press; 2005 [2026 Jan 21]. p. 484–509.
5 <https://research.fs.usda.gov/treesearch/30252>
- 6 163. Wurtz TL, Schulz BK. Regional Summaries: Alaska Region. In: In: Poland, Therese M;
7 Patel-Weynand, Toral; Finch, Deborah M; Ford Miniati, Chelcy; Hayes, Deborah C;
8 Lopez, Vanessa M, eds Invasive Species in Forests and Rangelands of the United
9 States: A Comprehensive Science Synthesis for the United States Forest Sector
10 [Internet]. Springer International Publishing;; 2021 [2026 Jan 21]. p. 336–42.
11 <https://research.fs.usda.gov/treesearch/62015>
- 12 164. Carlson M, Shephard M. IS THE SPREAD OF NON-NATIVE PLANTS IN ALASKA
13 ACCELERATING? 2007 Jan. Report No.: PNW-GTR-694.
- 14 165. Mangiante MJ, Davis AJS, Panlasigui S, Neilson ME, Pflingsten I, Fuller PL, et al. Trends
15 in nonindigenous aquatic species richness in the United States reveal shifting spatial
16 and temporal patterns of species introductions. *Aquat Invasions*. 2018 Sep
17 1;13(3):323–38. <https://doi.org/10.3391/ai.2018.13.3.02>
- 18 166. Strayer DL. Alien species in fresh waters: ecological effects, interactions with other
19 stressors, and prospects for the future. *Freshw Biol*. 2010 Jan 1;55(s1):152–74.
20 <https://doi.org/10.1111/j.1365-2427.2009.02380.x>
- 21 167. Rodríguez-Barreras R, Zapata-Arroyo C, Falcón L. W, Olmeda MDL. An island invaded
22 by exotics: a review of freshwater fish in Puerto Rico. *Neotropical Biodivers*. 2020 Jan
23 1;6(1):42–59. <https://doi.org/10.1080/23766808.2020.1729303>
- 24 168. Ruiz GM, Fofonoff PW, Steves BP, Carlton JT. Invasion history and vector dynamics in
25 coastal marine ecosystems: A North American perspective. *Aquat Ecosyst Health*
26 *Manag*. 2015 Jul 3;18(3):299–311. <https://doi.org/10.1080/14634988.2015.1027534>
- 27 169. Pagenkopp Lohan KM, Darling JA, Ruiz GM. International shipping as a potent vector
28 for spreading marine parasites. *Divers Distrib*. 2022;28(9):1922–33.
29 <https://doi.org/10.1111/ddi.13592>
- 30 170. Lv B, Zhu G, Tian W, Guo C, Lu X, Han Y, et al. The prevalence of potential pathogens
31 in ballast water and sediments of oceangoing vessels and implications for
32 management. *Environ Res*. 2023 Feb 1;218:114990.
33 <https://doi.org/10.1016/j.envres.2022.114990>
- 34 171. Pimentel D, Zuniga R, Morrison D. Update on the environmental and economic costs
35 associated with alien-invasive species in the United States. *Ecol Econ*. 2005 Feb
36 15;52(3):273–88. <https://doi.org/10.1016/j.ecolecon.2004.10.002>

- 1 172. Miller KM, McGill BJ, Weed AS, Seirup CE, Comiskey JA, Matthews ER, et al. Long-term
2 trends indicate that invasive plants are pervasive and increasing in eastern national
3 parks. *Ecol Appl*. 2021;31(2):e02239. <https://doi.org/10.1002/eap.2239>
- 4 173. Keeling RF, Morgan EJ, Keeling CD. Atmospheric Monthly In Situ CO₂ Data - Mauna
5 Loa Observatory, Hawaii. Scripps CO₂ Program Data. UC San Diego Library Digital
6 Collections; 2017. <https://doi.org/10.6075/J08W3BHW>
- 7 174. Rubino M, Etheridge DM, Thornton DP, Howden R, Allison CE, Francey RJ, et al.
8 Revised records of atmospheric trace gases CO₂, CH₄, N₂O, and δ¹³C-CO₂ over the
9 last 2000 years from Law Dome, Antarctica. *Earth Syst Sci Data*. 2019 Apr
10 11;11(2):473–92. <https://doi.org/10.5194/essd-11-473-2019>
- 11 175. US EPA OAR. Air Quality - National Summary [Internet]. 2025 [2025 Oct 23].
12 <https://www.epa.gov/air-trends/air-quality-national-summary>
- 13 176. Burke M, Childs ML, de la Cuesta B, Qiu M, Li J, Gould CF, et al. The contribution of
14 wildfire to PM_{2.5} trends in the USA. *Nature*. 2023 Oct;622(7984):761–6.
15 <https://doi.org/10.1038/s41586-023-06522-6>
- 16 177. Benish SE, Bash JO, Foley KM, Appel KW, Hogrefe C, Gilliam R, et al. Long-term
17 regional trends of nitrogen and sulfur deposition in the United States from 2002 to
18 2017. *Atmospheric Chem Phys*. 2022 Sep 30;22(19):12749–67.
19 <https://doi.org/10.5194/acp-22-12749-2022>
- 20 178. Linder G, Brumbaugh W, Neitlich P, Little E. Atmospheric Deposition and Critical
21 Loads for Nitrogen and Metals in Arctic Alaska: Review and Current Status. *Open J Air*
22 *Pollut*. 2013 Dec 5;2(4):76–99. <https://doi.org/10.4236/ojap.2013.24010>
- 23 179. Nagano H, Iwata H. Evaluating the relationship between wildfire extent and nitrogen
24 dry deposition in a boreal forest in interior Alaska. *Polar Sci*. 2017 Mar 1;11:96–104.
25 <https://doi.org/10.1016/j.polar.2016.11.002>
- 26 180. Baker RE, Mahmud AS, Miller IF, Rajeev M, Rasambainarivo F, Rice BL, et al. Infectious
27 disease in an era of global change. *Nat Rev Microbiol*. 2022 Apr;20(4):193–205.
28 <https://doi.org/10.1038/s41579-021-00639-z>
- 29 181. Fernandez-Cornejo J, Nehring R, Osteen C, Wechsler S, Martin A, Vialou A. Pesticide
30 Use in U.S. Agriculture: 21 Selected Crops, 1960-2008 | Economic Research Service
31 [Internet]. 2014 [2025 Dec 7]. Report No.: Economic Information Bulletin Number 124.
32 <https://www.ers.usda.gov/publications/pub-details?pubid=43855>
- 33 182. Kan M, Wang C, Zhu B, Chen WQ, Liu Y, Ren Y, et al. Seven decades of plastic flows
34 and stocks in the United States and pathways toward zero plastic pollution by 2050. *J*
35 *Ind Ecol*. 2023;27(6):1538–52. <https://doi.org/10.1111/jiec.13427>

- 1 183. Shapiro JS. Pollution Trends and US Environmental Policy: Lessons from the Past Half
2 Century. *Rev Environ Econ Policy*. 2022 Jan 1;16(1):42–61.
3 <https://doi.org/10.1086/718054>
- 4 184. US EPA. Redevelopment Economics at Hazardous Waste Cleanup Facilities [Internet].
5 2022 [2026 Jan 6]. [https://www.epa.gov/hw/redevelopment-economics-hazardous-](https://www.epa.gov/hw/redevelopment-economics-hazardous-waste-cleanup-facilities)
6 [waste-cleanup-facilities](https://www.epa.gov/hw/redevelopment-economics-hazardous-waste-cleanup-facilities)
- 7 185. U.S. Geological Survey. NWQN [Internet]. 2025 [2025 Oct 23].
8 <https://nrtwq.usgs.gov/nwqn/#/MAPTREN>
- 9 186. Murphy J, Sprague L. Water-quality trends in US rivers: Exploring effects from
10 streamflow trends and changes in watershed management. *Sci Total Environ*. 2019
11 Mar 15;656:645–58. <https://doi.org/10.1016/j.scitotenv.2018.11.255>
- 12 187. Simpson IM, Schwartz JS, Hathaway JM, Winston RJ. Environmental regulations in the
13 United States lead to improvements in untreated stormwater quality over four
14 decades. *Water Res*. 2023 Sep 1;243:120386.
15 <https://doi.org/10.1016/j.watres.2023.120386>
- 16 188. Waycott M, Duarte CM, Carruthers TJB, Orth RJ, Dennison WC, Olyarnik S, et al.
17 Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proc*
18 *Natl Acad Sci*. 2009 Jul 28;106(30):12377–81.
19 <https://doi.org/10.1073/pnas.0905620106>
- 20 189. D’Angelo C, Wiedenmann J. Impacts of nutrient enrichment on coral reefs: new
21 perspectives and implications for coastal management and reef survival. *Curr Opin*
22 *Environ Sustain*. 2014 Apr 1;7:82–93. <https://doi.org/10.1016/j.cosust.2013.11.029>
- 23 190. Lefcheck JS, Orth RJ, Dennison WC, Wilcox DJ, Murphy RR, Keisman J, et al. Long-term
24 nutrient reductions lead to the unprecedented recovery of a temperate coastal region.
25 *Proc Natl Acad Sci*. 2018 Apr 3;115(14):3658–62.
26 <https://doi.org/10.1073/pnas.1715798115>
- 27 191. Lapointe BE, Brewton RA, Herren LW, Porter JW, Hu C. Nitrogen enrichment, altered
28 stoichiometry, and coral reef decline at Looe Key, Florida Keys, USA: a 3-decade
29 study. *Mar Biol*. 2019 Jul 15;166(8):108. <https://doi.org/10.1007/s00227-019-3538-9>
- 30 192. de Fouw J, Madden CJ, Furman BT, Hall MO, Verstijnen Y, Holthuijsen S, et al.
31 Reduced seagrass resilience due to environmental and anthropogenic effects may
32 lead to future die-off events in Florida Bay. *Front Mar Sci* [Internet]. 2024 Jul 15 [2025
33 Dec 4];11. <https://doi.org/10.3389/fmars.2024.1366939>
- 34 193. Oelsner GP, Stets EG. Recent trends in nutrient and sediment loading to coastal areas
35 of the conterminous U.S.: Insights and global context. *Sci Total Environ*. 2019 Mar
36 1;654:1225–40. <https://doi.org/10.1016/j.scitotenv.2018.10.437>

- 1 194. National Academies of Sciences, Engineering, and Medicine. Reckoning with the U.S.
2 Role in Global Ocean Plastic Waste [Internet]. Washington, D.C.: National Academies
3 Press; 2022 [2025 Oct 24]. <https://doi.org/10.17226/26132>
- 4 195. Law KL, Starr N, Siegler TR, Jambeck JR, Mallos NJ, Leonard GH. The United States'
5 contribution of plastic waste to land and ocean. *Sci Adv*. 2020 Oct 30;6(44):eabd0288.
6 <https://doi.org/10.1126/sciadv.abd0288>
- 7 196. NASEM. Reckoning with the U.S. Role in Global Ocean Plastic Waste [Internet].
8 Washington, D.C.: The National Academies of Sciences, Engineering, and Medicine.
9 National Academies Press; 2022 [2025 Oct 21]. <https://doi.org/10.17226/26132>
- 10 197. Salvatore D, Mok K, Garrett KK, Poudrier G, Brown P, Birnbaum LS, et al. Presumptive
11 Contamination: A New Approach to PFAS Contamination Based on Likely Sources.
12 *Environ Sci Technol Lett*. 2022 Nov 8;9(11):983–90.
13 <https://doi.org/10.1021/acs.estlett.2c00502>
- 14 198. Banyoi SM, Porseryd T, Larsson J, Grahn M, Dinnézt P. The effects of exposure to
15 environmentally relevant PFAS concentrations for aquatic organisms at different
16 consumer trophic levels: Systematic review and meta-analyses. *Environ Pollut*. 2022
17 Dec 15;315:120422. <https://doi.org/10.1016/j.envpol.2022.120422>
- 18 199. Vanderploeg HA, Liebig JR, Carmichael WW, Agy MA, Johengen TH, Fahnenstiel GL, et
19 al. Zebra mussel (*Dreissena polymorpha*) selective filtration promoted toxic
20 *Microcystis* blooms in Saginaw Bay (Lake Huron) and Lake Erie. *Can J Fish Aquat Sci*.
21 2001 Jun;58(6):1208–21. <https://doi.org/10.1139/f01-066>
- 22 200. Anderson DM, Fensin E, Gobler CJ, Hoeglund AE, Hubbard KA, Kulis DM, et al. Marine
23 harmful algal blooms (HABs) in the United States: History, current status and future
24 trends. *Harmful Algae*. 2021 Feb 1;102:101975.
25 <https://doi.org/10.1016/j.hal.2021.101975>
- 26 201. Griffith AW, Gobler CJ. Harmful algal blooms: A climate change co-stressor in marine
27 and freshwater ecosystems. *Harmful Algae*. 2020 Jan 1;91:101590.
28 <https://doi.org/10.1016/j.hal.2019.03.008>
- 29 202. Hallegraeff GM, Anderson DM, Belin C, Bottein MYD, Bresnan E, Chinain M, et al.
30 Perceived global increase in algal blooms is attributable to intensified monitoring and
31 emerging bloom impacts. *Commun Earth Environ*. 2021 Jun 8;2(1):117.
32 <https://doi.org/10.1038/s43247-021-00178-8>
- 33 203. UN Environment Programme World Conservation Monitoring Centre. Protected Area
34 Profile for United States of America from the World Database on Protected Areas,
35 January 2026 [Internet]. United Nations Environment Programme World Conservation
36 Monitoring Centre; 2026. <http://www.protectedplanet.net>

- 1 204. Sullivan-Stack J, Aburto-Oropeza O, Brooks CM, Cabral RB, Caselle JE, Chan F, et al. A
2 Scientific Synthesis of Marine Protected Areas in the United States: Status and
3 Recommendations. *Front Mar Sci* [Internet]. 2022 May 18 [2025 Oct 30];9.
4 <https://doi.org/10.3389/fmars.2022.849927>
- 5 205. Wang D, Heckathorn SA, Wang X, Philpott SM. A meta-analysis of plant physiological
6 and growth responses to temperature and elevated CO₂. *Oecologia*. 2012 May
7 1;169(1):1–13. <https://doi.org/10.1007/s00442-011-2172-0>
- 8 206. Fisher R, Bessell-Browne P, Jones R. Synergistic and antagonistic impacts of
9 suspended sediments and thermal stress on corals. *Nat Commun*. 2019 May
10 28;10(1):2346. <https://doi.org/10.1038/s41467-019-10288-9>
- 11 207. Leuzinger S, Luo Y, Beier C, Dieleman W, Vicca S, Körner C. Do global change
12 experiments overestimate impacts on terrestrial ecosystems? *Trends Ecol Evol*.
13 2011;26:236–41.
- 14 208. Komatsu KJ, Avolio ML, Lemoine NP, Isbell F, Grman E, Houseman GR, et al. Global
15 change effects on plant communities are magnified by time and the number of global
16 change factors imposed. *Proc Natl Acad Sci*. 2019 Sep 3;116(36):17867–73.
17 <https://doi.org/10.1073/pnas.1819027116>
- 18 209. Reich PB, Hobbie SE, Lee TD. Plant growth enhancement by elevated CO₂ eliminated
19 by joint water and nitrogen limitation. *Nat Geosci*. 2014;7:920–4.
- 20 210. Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, et al.
21 Nitrogen Cycles: Past, Present, and Future. *Biogeochemistry*. 2004 Sep 1;70(2):153–
22 226. <https://doi.org/10.1007/s10533-004-0370-0>
- 23 211. Gruber N, Galloway JN. An Earth-system perspective of the global nitrogen cycle.
24 *Nature*. 2008 Jan;451(7176):293–6. <https://doi.org/10.1038/nature06592>
- 25 212. Borer ET, Seabloom EW, Gruner DS, Harpole WS, Hillebrand H, Lind EM, et al.
26 Herbivores and nutrients control grassland plant diversity via light limitation. *Nature*.
27 2014 Apr 1;508(7497):517–20. <https://doi.org/10.1038/nature13144>
- 28 213. Reich PB. Elevated CO₂ Reduces Losses of Plant Diversity Caused by Nitrogen
29 Deposition. *Science*. 2009 Dec 4;326(5958):1399–402.
30 <https://doi.org/10.1126/science.1178820>
- 31 214. Reich PB, Mohanbabu N, Isbell F, Hobbie SE, Butler EE. High CO₂ dampens then
32 amplifies N-induced diversity loss over 24 years. *Nature*. 2024 Nov;635(8038):370–5.
33 <https://doi.org/10.1038/s41586-024-08066-9>

- 1 215. Isbell F, Balvanera P, Mori AS, He JS, Bullock JM, Regmi GR, et al. Expert perspectives
2 on global biodiversity loss and its drivers and impacts on people. *Front Ecol Environ.*
3 2023;21(2):94–103. <https://doi.org/10.1002/fee.2536>
- 4 216. Pereira HM, Martins IS, Rosa IMD, Kim H, Leadley P, Popp A, et al. Global trends and
5 scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050.
6 *Science.* 2024 Apr 26;384(6694):458–65. <https://doi.org/10.1126/science.adn3441>
- 7 217. Cui D, Frazier AE, Liang S, Roehrdanz PR, Hurtt GC, Zhu Z, et al. Projected climate
8 zone shifts could undermine the effectiveness of global protected areas for
9 biodiversity conservation by mid-to-late century. *Glob Environ Change Adv.* 2025
10 Sep;5:100017. <https://doi.org/10.1016/j.gecadv.2025.100017>
- 11 218. Alder JR. CMIP6-LOCA2 threshold and extreme event metric projections from 1950-
12 2100 for the Contiguous United States [Internet]. U.S. Geological Survey; [2025 Dec
13 7]. <https://doi.org/10.5066/P13OV6GY>
- 14 219. Basile S, Crimmins AR, Avery CW, Hamlington BD, Kunkel KE, Crimmins AR, et al.
15 Appendix A3 : Scenarios and Datasets. Fifth National Climate Assessment [Internet].
16 U.S. Global Change Research Program; 2023 [2025 Dec 7].
17 <https://doi.org/10.7930/NCA5.2023.A3>
- 18 220. Hayhoe K, Scott-Fleming I, Stoner A, Wuebbles DJ. STAR-ESDM: A Generalizable
19 Approach to Generating High-Resolution Climate Projections Through Signal
20 Decomposition. *Earths Future.* 2024;12(7):e2023EF004107.
21 <https://doi.org/10.1029/2023EF004107>
- 22 221. Su W, Marvel K, Delgado R, Aarons S, Chatterjee A, Garcia ME, et al. Climate Trends
23 [Internet]. Fifth National Climate Assessment. U.S. Global Change Research Program,
24 Washington, DC; 2023 Nov [2026 Jan 26]. <https://nca5.climate.us/chapter/2/>
- 25 222. IPBES. Methodological assessment of the diverse values and valuation of nature of
26 the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem
27 Services [Internet]. Zenodo; 2022 Apr [2025 Oct 31].
28 <https://doi.org/10.5281/zenodo.7687931>
- 29 223. Service CN, Adams MS, Artelle KA, Paquet P, Grant LV, Darimont CT. Indigenous
30 Knowledge and Science Unite to Reveal Spatial and Temporal Dimensions of
31 Distributional Shift in Wildlife of Conservation Concern. Festa-Bianchet M, editor.
32 *PLoS ONE.* 2014 Jul 23;9(7):e101595. <https://doi.org/10.1371/journal.pone.0101595>
- 33 224. Polfus JL, Manseau M, Simmons D, Neyelle M, Bayha W, Andrew F, et al.
34 Łeghągots’enetę ; (learning together): the importance of indigenous perspectives in
35 the identification of biological variation. *Ecol Soc.* 2016;21(2):art18.
36 <https://doi.org/10.5751/ES-08284-210218>

- 1 225. Whyte KP, Brewer JP, Johnson JT. Weaving Indigenous science, protocols and
2 sustainability science. *Sustain Sci*. 2016 Jan;11(1):25–32.
3 <https://doi.org/10.1007/s11625-015-0296-6>
- 4 226. Reo NJ, Whyte KP, McGregor D, Smith M (Peggy), Jenkins JF. Factors that support
5 Indigenous involvement in multi-actor environmental stewardship. *Altern Int J Indig*
6 *Peoples*. 2017 Jun;13(2):58–68. <https://doi.org/10.1177/1177180117701028>
- 7 227. Kimmerer R. Restoration and Reciprocity: The Contributions of Traditional Ecological
8 Knowledge. In: Egan D, Hjerpe EE, Abrams J, editors. *Human Dimensions of*
9 *Ecological Restoration* [Internet]. Washington, DC: Island Press/Center for Resource
10 Economics; 2011 [2025 Dec 5]. p. 257–76. [https://doi.org/10.5822/978-1-61091-039-](https://doi.org/10.5822/978-1-61091-039-2_18)
11 [2_18](https://doi.org/10.5822/978-1-61091-039-2_18)
- 12 228. Lake F. Indigenous fire stewardship: Federal/Tribal partnerships for wildland fire
13 research and management. *Fire Manag Today*. 2021;79(1):30–9.
- 14 229. Baena PA, Brunel A, Fernández-de-Larrinoa Y, Martínez-Cruz TE, Milbank C, Way M. In
15 Brief: The White/Wiphala Paper on Indigenous Peoples’ Food Systems. In: Von Braun
16 J, Afsana K, Fresco LO, Hassan MHA, editors. *Science and Innovations for Food*
17 *Systems Transformation* [Internet]. Cham: Springer International Publishing; 2023
18 [2026 Jan 9]. p. 229–59. https://doi.org/10.1007/978-3-031-15703-5_13
- 19 230. Sangha KK, Preece L, Villarreal-Rosas J, Kegamba JJ, Paudyal K, Warmenhoven T, et al.
20 An ecosystem services framework to evaluate indigenous and local peoples’
21 connections with nature. *Ecosyst Serv*. 2018 Jun;31:111–25.
22 <https://doi.org/10.1016/j.ecoser.2018.03.017>
- 23 231. Metro Vancouver. *Ecological Health Framework* [Internet]. 2018.
24 [https://metrovancover.org/services/regional-planning/Documents/ecological-](https://metrovancover.org/services/regional-planning/Documents/ecological-health-framework.pdf)
25 [health-framework.pdf](https://metrovancover.org/services/regional-planning/Documents/ecological-health-framework.pdf)
- 26 232. US EPA O. *National Air Quality: Status and Trends of Key Air Pollutants* [Internet]. 2014
27 [2026 Jan 26]. <https://www.epa.gov/air-trends>
- 28 233. Greenwald N, Suckling KF, Hartl B, A. Mehrhoff L. Extinction and the U.S. Endangered
29 Species Act. *PeerJ*. 2019 Apr 22;7:e6803. <https://doi.org/10.7717/peerj.6803>
- 30 234. Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, et al. Biodiversity
31 loss and its impact on humanity. *Nature*. 2012 Jun 7;486(7401):59–67.
32 <https://doi.org/10.1038/nature11148>
- 33 235. Tilman D, Reich PB, Isbell F. Biodiversity impacts ecosystem productivity as much as
34 resources, disturbance, or herbivory. *Proc Natl Acad Sci*. 2012 Jun 26;109(26):10394–
35 7. <https://doi.org/10.1073/pnas.1208240109>

- 1 236. Naeem S, Thompson LJ, Lawler SP, Lawton JH, Woodfin RM. Declining biodiversity can
2 alter the performance of ecosystems. *Nature*. 1994 Apr;368(6473):734–7.
3 <https://doi.org/10.1038/368734a0>
- 4 237. Hector A, Schmid B, Beierkuhnlein C, Caldeira MC, Diemer M, Dimitrakopoulos PG, et
5 al. Plant Diversity and Productivity Experiments in European Grasslands. *Science*.
6 1999 Nov 5;286(5442):1123–7. <https://doi.org/10.1126/science.286.5442.1123>
- 7 238. Tilman D, Reich PB, Knops J, Wedin D, Mielke T, Lehman C. Diversity and Productivity
8 in a Long-Term Grassland Experiment. *Science*. 2001 Oct 26;294(5543):843–5.
9 <https://doi.org/10.1126/science.1060391>
- 10 239. Reich PB, Knops J, Tilman D, Craine J, Ellsworth D, Tjoelker M, et al. Plant diversity
11 enhances ecosystem responses to elevated CO₂ and nitrogen deposition. *Nature*.
12 2001 Apr 12;410(6830):809–10. <https://doi.org/10.1038/35071062>
- 13 240. Hooper DU, Chapin FS, Ewel JJ, Hector A, Inchausti P, Lavorel S, et al. EFFECTS OF
14 BIODIVERSITY ON ECOSYSTEM FUNCTIONING: A CONSENSUS OF CURRENT
15 KNOWLEDGE. *Ecol Monogr*. 2005 Feb;75(1):3–35. <https://doi.org/10.1890/04-0922>
- 16 241. Balvanera P, Pfisterer AB, Buchmann N, He J, Nakashizuka T, Raffaelli D, et al.
17 Quantifying the evidence for biodiversity effects on ecosystem functioning and
18 services. *Ecol Lett*. 2006 Oct;9(10):1146–56. [https://doi.org/10.1111/j.1461-
19 0248.2006.00963.x](https://doi.org/10.1111/j.1461-0248.2006.00963.x)
- 20 242. Cardinale BJ, Matulich KL, Hooper DU, Byrnes JE, Duffy E, Gamfeldt L, et al. The
21 functional role of producer diversity in ecosystems. *Am J Bot*. 2011 Mar;98(3):572–92.
22 <https://doi.org/10.3732/ajb.1000364>
- 23 243. Isbell F, Craven D, Connolly J, Loreau M, Schmid B, Beierkuhnlein C, et al. Biodiversity
24 increases the resistance of ecosystem productivity to climate extremes. *Nature*. 2015
25 Oct;526(7574):574–7. <https://doi.org/10.1038/nature15374>
- 26 244. Donatuto J, Campbell L, Trousdale W. The “value” of values-driven data in identifying
27 Indigenous health and climate change priorities. *Clim Change*. 2020 Jan;158(2):161–
28 80. <https://doi.org/10.1007/s10584-019-02596-2>
- 29 245. Donatuto J, Campbell L, LeCompte JK, Rohlman D, Tadlock S. The Story of 13 Moons:
30 Developing an Environmental Health and Sustainability Curriculum Founded on
31 Indigenous First Foods and Technologies. *Sustainability*. 2020 Oct 27;12(21):8913.
32 <https://doi.org/10.3390/su12218913>
- 33 246. Lam DPM, Hinz E, Lang DJ, Tengö M, Wehrden HV, Martín-López B. Indigenous and
34 local knowledge in sustainability transformations research: a literature review. *Ecol
35 Soc*. 2020;25(1):art3. <https://doi.org/10.5751/ES-11305-250103>

- 1 247. Petzold J, Andrews N, Ford JD, Hedemann C, Postigo JC. Indigenous knowledge on
2 climate change adaptation: a global evidence map of academic literature. *Environ*
3 *Res Lett.* 2020 Nov 1;15(11):113007. <https://doi.org/10.1088/1748-9326/abb330>
- 4 248. Orlove B, Sherpa P, Dawson N, Adelekan I, Alangui W, Carmona R, et al. Placing
5 diverse knowledge systems at the core of transformative climate research. *Ambio.*
6 2023 Sep;52(9):1431–47. <https://doi.org/10.1007/s13280-023-01857-w>
- 7 249. Newton P, Civita N, Frankel-Goldwater L, Bartel K, Johns C. What Is Regenerative
8 Agriculture? A Review of Scholar and Practitioner Definitions Based on Processes and
9 Outcomes. *Front Sustain Food Syst.* 2020 Oct 26;4:577723.
10 <https://doi.org/10.3389/fsufs.2020.577723>
- 11 250. Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, et al.
12 Solutions for a cultivated planet. *Nature.* 2011 Oct;478(7369):337–42.
13 <https://doi.org/10.1038/nature10452>
- 14 251. Sands B, Machado MR, White A, Zent E, Gould R. Moving towards an anti-colonial
15 definition for regenerative agriculture. *Agric Hum Values.* 2023 Dec;40(4):1697–716.
16 <https://doi.org/10.1007/s10460-023-10429-3>
- 17 252. LaCanne CE, Lundgren JG. Regenerative agriculture: merging farming and natural
18 resource conservation profitably. *PeerJ.* 2018 Feb 26;6:e4428.
19 <https://doi.org/10.7717/peerj.4428>
- 20 253. Fenster TLD, LaCanne CE, Pecenka JR, Schmid RB, Bredeson MM, Busenitz KM, et al.
21 Defining and validating regenerative farm systems using a composite of ranked
22 agricultural practices. *F1000Research.* 2021 Feb 15;10:115.
23 <https://doi.org/10.12688/f1000research.28450.1>
- 24 254. Black farmers are taking the lead in regenerative, organic specialty rice | CALS
25 [Internet]. 2024 [2025 Dec 8]. [https://cals.cornell.edu/news/2024/03/black-farmers-](https://cals.cornell.edu/news/2024/03/black-farmers-are-taking-lead-regenerative-organic-specialty-rice)
26 [are-taking-lead-regenerative-organic-specialty-rice](https://cals.cornell.edu/news/2024/03/black-farmers-are-taking-lead-regenerative-organic-specialty-rice)
- 27 255. Williams R, Krkošek M, Ashe E, Branch TA, Clark S, Hammond PS, et al. Competing
28 Conservation Objectives for Predators and Prey: Estimating Killer Whale Prey
29 Requirements for Chinook Salmon. O'Connor M, editor. *PLoS ONE.* 2011 Nov
30 9;6(11):e26738. <https://doi.org/10.1371/journal.pone.0026738>
- 31 256. Helfield JM, Naiman RJ. EFFECTS OF SALMON-DERIVED NITROGEN ON RIPARIAN
32 FOREST GROWTH AND IMPLICATIONS FOR STREAM PRODUCTIVITY. *Ecology.* 2001
33 Sep;82(9):2403–9. [https://doi.org/10.1890/0012-](https://doi.org/10.1890/0012-9658(2001)082%255B2403:EOSDNO%255D2.0.CO;2)
34 [9658\(2001\)082%255B2403:EOSDNO%255D2.0.CO;2](https://doi.org/10.1890/0012-9658(2001)082%255B2403:EOSDNO%255D2.0.CO;2)

- 1 257. Field RD, Reynolds JD. Ecological links between salmon, large carnivore predation,
2 and scavenging birds. *J Avian Biol.* 2013 Jan;44(1):009–16.
3 <https://doi.org/10.1111/j.1600-048X.2012.05601.x>
- 4 258. Marsha AL, Steel EA, Fullerton AH. Modeling thermal metrics of importance for native
5 vs non-native fish across stream networks to provide insight for watershed-scale
6 fisheries management. *Freshw Sci.* 2021 Mar 1;40(1):120–37.
7 <https://doi.org/10.1086/713038>
- 8 259. Church J, Ekechi CO, Hoss A, Larson AJ. Tribal Water Rights: Exploring Dam
9 Construction in Indian Country. *J Law Med Ethics.* 2015;43(S1):60–3.
10 <https://doi.org/10.1111/jlme.12218>
- 11 260. Lackey RT, Lach DH, Duncan SL, editors. *Salmon 2100: The Future of Wild Pacific*
12 *Salmon* [Internet]. American Fisheries Society; 2006 [2025 Dec 6].
13 <https://doi.org/10.47886/9781888569780>
- 14 261. Lawson M. *Dammed Indians Revisited.* South Dakota State Historical Society Press.;
15 2009.
- 16 262. Baldwin C, Giorgi C, Biladeau T. Cultural and educational releases of salmon in areas
17 blocked by major hydroelectric projects on the Columbia River. *Aquat Ecosyst Health*
18 *Manag.* 2022 Jan 1;25(1):16–26. <https://doi.org/10.14321/ae hm.025.01.16>
- 19 263. Moyle P, Lusardi R, Samuel P. *State of the Salmonids II: Fish in Hot Water Status,*
20 *threats, and solutions for California salmon, steelhead and trout.* 2017.
- 21 264. Goode RW, Beard SF, Oraftik C. Putting Fire on the Land: The Indigenous People
22 Spoke the Language of Ecology, and Understood the Connectedness and
23 Relationship Between Land, Water, and Fire. *J Calif Gt Basin Anthropol.* 2022 Jun
24 1;42(1):85.
- 25 265. Marks-Block T, Lake FK, Bliege Bird R, Curran LM. Revitalized Karuk and Yurok cultural
26 burning to enhance California hazelnut for basketweaving in northwestern California,
27 USA. *Fire Ecol.* 2021 Dec;17(1):6. <https://doi.org/10.1186/s42408-021-00092-6>
- 28 266. Tom E, Adams MM, Goode RW. Solastalgia to Soliphilia: Cultural Fire, Climate
29 Change, and Indigenous Healing. *Ecopsychology.* 2023 Dec 1;15(4):322–30.
30 <https://doi.org/10.1089/eco.2022.0085>
- 31 267. Fisk JJ, Leong KM, Berl REW, Long JW, Landon AC, Adams MM, et al. Evolving wildlife
32 management cultures of governance through Indigenous Knowledges and
33 perspectives. *J Wildl Manag.* 2024 Aug;88(6):e22584.
34 <https://doi.org/10.1002/jwmg.22584>

- 1 268. Lake FK, Christianson AC. Indigenous Fire Stewardship. In: Manzello SL, editor.
2 Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires [Internet]. Cham:
3 Springer International Publishing; 2019 [2025 Dec 8]. p. 1–9.
4 https://doi.org/10.1007/978-3-319-51727-8_225-1
- 5 269. Hankins DL. Climate resilience through ecocultural stewardship. Proc Natl Acad Sci.
6 2024 Aug 6;121(32):e2310072121. <https://doi.org/10.1073/pnas.2310072121>
- 7 270. Roos CI, Kaib JM, Laluk NC, Adams MM, Guiterman CH, Baisan CH, et al. Tree rings
8 reveal persistent Western Apache (Ndee) fire stewardship and niche construction in
9 the American Southwest. Proc Natl Acad Sci. 2025 Aug 12;122(32):e2509169122.
10 <https://doi.org/10.1073/pnas.2509169122>
- 11 271. Kimmerer RW, Lake FK. The Role of Indigenous Burning in Land Management. J For.
12 2001 Nov 1;99(11):36–41. <https://doi.org/10.1093/jof/99.11.36>
- 13 272. Native peoples' relationship to the California chaparral. In: Valuing Chaparral.
14 Springer;
- 15 273. Loscalzo AE. Tending the Wild: Native American Knowledge of California's Natural
16 Resources. J Ethnobiol. 2006 Sep;26(2):331–2. [https://doi.org/10.2993/0278-
17 0771\(2006\)26%255B331:TTWNAK%255D2.0.CO;2](https://doi.org/10.2993/0278-0771(2006)26%255B331:TTWNAK%255D2.0.CO;2)
- 18 274. Williams GW. Introduction to aboriginal fire use in North America. Fire Manag Today.
19 2000;60(3):8–12.
- 20 275. Kolden C. We're Not Doing Enough Prescribed Fire in the Western United States to
21 Mitigate Wildfire Risk. Fire. 2019 May 29;2(2):30. <https://doi.org/10.3390/fire2020030>
- 22 276. Stephens SL, Battaglia MA, Churchill DJ, Collins BM, Coppoletta M, Hoffman CM, et
23 al. Forest Restoration and Fuels Reduction: Convergent or Divergent? BioScience.
24 2020 Dec 2;biaa134. <https://doi.org/10.1093/biosci/biaa134>
- 25 277. Van Riper CJ, Thiel A, Penker M, Braitto M, Landon AC, Thomsen JM, et al. Incorporating
26 multilevel values into the social-ecological systems framework. Ecol Soc.
27 2018;23(3):art25. <https://doi.org/10.5751/ES-10047-230325>
- 28 278. Kenter JO, O'Brien L, Hockley N, Ravenscroft N, Fazey I, Irvine KN, et al. What are
29 shared and social values of ecosystems? Ecol Econ. 2015 Mar;111:86–99.
30 <https://doi.org/10.1016/j.ecolecon.2015.01.006>
- 31 279. Chan KMA, Guerry AD, Balvanera P, Klain S, Satterfield T, Basurto X, et al. Where are
32 Cultural and Social in Ecosystem Services? A Framework for Constructive
33 Engagement. BioScience. 2012 Aug;62(8):744–56.
34 <https://doi.org/10.1525/bio.2012.62.8.7>

- 1 280. Manfredo MJ, Teel TL, Dietsch AM. Implications of human value shift and persistence
2 for biodiversity conservation. *Conserv Biol.* 2016 Apr;30(2):287–96.
3 <https://doi.org/10.1111/cobi.12619>
- 4 281. Martin A, Balvanera P, Raymond C, Gómez-Baggethun E, Eser U, Gould R, et al.
5 Sustainability-aligned values: exploring the concept, evidence, and practice. *Ecol*
6 *Soc.* 2024;29(4):art18. <https://doi.org/10.5751/ES-15498-290418>
- 7 282. Natcher DC, Davis S, Hickey CG. Co-Management: Managing Relationships, Not
8 Resources. *Hum Organ.* 2005 Sep;64(3):240–50.
9 <https://doi.org/10.17730/humo.64.3.23yfnkr12ylapjxw>
- 10 283. Berkes. Navigating Social-Ecological Systems: Building Resilience for Complexity and
11 Change.
- 12 284. Folke C, Polasky S, Rockström J, Galaz V, Westley F, Lamont M, et al. Our future in the
13 Anthropocene biosphere. *Ambio.* 2021 Apr 1;50(4):834–69.
14 <https://doi.org/10.1007/s13280-021-01544-8>
- 15 285. US EPA. Climate Change and Social Vulnerability in the United States: A Focus on Six
16 Impacts [Internet]. 2021 Sep [2025 Oct 31].
17 <https://assessments.epa.gov/risk/document/&deid%3D352694>
- 18 286. Di Gregorio M, Fatorelli L, Paavola J, Locatelli B, Pramova E, Nurrochmat DR, et al.
19 Multi-level governance and power in climate change policy networks. *Glob Environ*
20 *Change.* 2019 Jan 1;54:64–77. <https://doi.org/10.1016/j.gloenvcha.2018.10.003>
- 21 287. Mills M, Nie M. Planning A New Paradigm: Tribal Co-Stewardship And Federal Public
22 Lands Planning. *Colo Environ Law J.* 2025 Jan 1;36(2):279.
- 23 288. Layman E, Civita N. Decolonizing agriculture in the United States: Centering the
24 knowledges of women and people of color to support relational farming practices.
25 *Agric Hum Values.* 2022;39(3):965–78. <https://doi.org/10.1007/s10460-022-10297-3>
- 26 289. Siddik MAB, Shehabi A, Marston L. The environmental footprint of data centers in the
27 United States. *Environ Res Lett.* 2021 May;16(6):064017.
28 <https://doi.org/10.1088/1748-9326/abfba1>
- 29 290. Alissa H, Nick T, Raniwala A, Arribas Herranz A, Frost K, Manousakis I, et al. Using life
30 cycle assessment to drive innovation for sustainable cool clouds. *Nature.* 2025
31 May;641(8062):331–8. <https://doi.org/10.1038/s41586-025-08832-3>
- 32 291. Hernandez RR, Hoffacker MK, Murphy-Mariscal ML, Wu GC, Allen MF. Solar energy
33 development impacts on land cover change and protected areas. *Proc Natl Acad Sci.*
34 2015 Nov 3;112(44):13579–84. <https://doi.org/10.1073/pnas.1517656112>

- 1 292. Briske DD, Archer SR, Burchfield E, Burnidge W, Derner JD, Gosnell H, et al. Supplying
2 ecosystem services on US rangelands. *Nat Sustain.* 2023 Dec;6(12):1524–32.
3 <https://doi.org/10.1038/s41893-023-01194-6>
- 4 293. Reich M, Simon AC. Critical Minerals. *Annu Rev Earth Planet Sci.* 2025 May
5 30;53(Volume 53, 2025):141–68. [https://doi.org/10.1146/annurev-earth-040523-
6 023316](https://doi.org/10.1146/annurev-earth-040523-023316)
- 7 294. Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, et al. Emerging threats
8 and persistent conservation challenges for freshwater biodiversity. *Biol Rev.*
9 2019;94(3):849–73. <https://doi.org/10.1111/brv.12480>
- 10 295. Kronk Warner EA, Salazar JA. Shared Stewardship. *SSRN Electron J [Internet].* 2024
11 [2025 Dec 7]; <https://doi.org/10.2139/ssrn.5046844>
- 12 296. Status of Tribes and Climate Change Working Group. Status of Tribes and Climate
13 Change, Vol. 2. Northern Arizona University.: Institute for Tribal Environmental
14 Professionals; 2025.
- 15 297. Lake FK, Wright V, Morgan P, McFadzen M, McWethy D, Stevens-Rumann C. Returning
16 Fire to the Land: Celebrating Traditional Knowledge and Fire. *J For.* 2017 Sep
17 20;115(5):343–53. <https://doi.org/10.5849/jof.2016-043R2>
- 18 298. Long JW, Hankins DL, Adams MM. Indigenous Fire Stewardship to Revitalize Disrupted
19 Ecosystems. *Glob Change Biol.* 2025 Aug;31(8):e70411.
20 <https://doi.org/10.1111/gcb.70411>
- 21 299. Wenzel L, Cannizzo Z, Stephenson F, Orchard S, Clarkson S, Wheeler E, et al.
22 Establishing marine protected areas in a changing climate [Internet]. IUCN,; 2025
23 [2025 Dec 7]. <https://doi.org/10.2305/KQCA8125>
- 24 300. Reed T. Restorative Justice for Indigenous Culture. *SSRN Electron J [Internet].* 2023
25 [2025 Dec 7]; <https://doi.org/10.2139/ssrn.4398314>
- 26 301. Wilson C, Noyes G. Indigenous Stewardship of Ancestral Lands Activates Land and
27 Culture: Will We Listen? *Parks Steward Forum [Internet].* 2025 Jan 15 [2025 Dec
28 7];41(1). <https://doi.org/10.5070/P5.42004>
- 29 302. Fay A. Fay, Alexandra, True Co-management: Critical Approaches to Indigenous Food
30 Sovereignty. *41 Yale Law Policy Rev.* 2023;233.

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