Chapter 8: Status, Trends, and Future Projections of Terrestrial Ecosystems in the US

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Date
February 23, 2026

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Summary

Terrestrial ecosystems in the United States include forests, grasslands, shrublands, deserts, and tundra, all of which provide places for people to enjoy, inhabit, steward, and use. All terrestrial ecosystems have been altered in some way by human activities through **land-use** and **land-cover** (**LULC**) **changes**, climate change, or some form of ecosystem degradation or restoration. LULC changes for forestry, agriculture, and urbanization benefit people in critical ways, yet typically these practices diminish the resources needed for the existence of plant, wildlife, and microbe species and cause declines in species abundances and ecosystem functioning. Habitat degradation can occur from changes in fire regimes, chemical pollutants, disease, invasive species, overharvest of species, and climate change. Climate change affects ecosystems directly by altering physical conditions, sometimes prompting species to shift their ranges. Climate change also interacts with other factors—such as habitat loss, fragmentation, intensive agricultural practices, degradation, overharvest, pollution, invasive species, and disease—often amplifying the effects of these existing stressors on individuals, populations, and ecosystems.

Ecosystem conservation and restoration efforts aim to reduce the negative impacts of LULC change, climate change, and ecosystem degradation. These efforts are most effective when they focus on landscapes with the ecological and cultural characteristics essential for supporting diverse ecosystems and that have the capacity to adapt in response to environmental change. Recent developments in analytical tools and the recognition of the value of Indigenous and local knowledge enable spatially targeted interventions that direct limited resources to priority ecosystems based on the goals of maximizing biodiversity benefits, strengthening resilience, and reducing greenhouse gas emissions or increasing carbon sequestration. In addition, there is growing recognition that working landscapes such as rangelands, agricultural areas, and urban greenspaces, when managed appropriately, can play a critical role in conserving biodiversity and promoting human well-being. These ecosystems can support local biodiversity and serve as critical connections for species moving between larger intact ecosystems.

Background

Terrestrial ecosystems in US states and territories span a wide range of environments, including the spectacular temperate rainforests of the Pacific Northwest, the diverse shrublands of coastal California, the fertile grasslands of the Great Plains, the vast deserts of the Southwest, the arctic and alpine tundra above tree line in Alaska and in mountainous regions, the richly diverse forests of the Pacific Islands, Hawaiʻi, and the Caribbean, and the temperate forests of the Eastern US. Terrestrial landscapes account for about 93% of the area of the contiguous US, with inland waters covering about 7% of the area. The condition of terrestrial ecosystems has broad implications for all of nature, since there is a close connection among terrestrial ecosystems, inland waters, marine ecosystems, and the atmosphere, with significant flows of nutrients, contaminants, soils, and species among land, water, and air.

Since human colonization of North America, terrestrial ecosystems have been dramatically altered. In the thousands of years before European colonization, people managed and affected landscapes across what is now the US and its territories through cultural fire practices, agriculture, water management, and other practices (see Chapter 9: Drivers). Currently, about 13% of the area of terrestrial ecosystems and inland waters in US states is under some form of protection—for example, in national, state, and local parks—for people to visit and enjoy, though the percentage of land protected varies greatly by region (1). For US territories, the percentage ranges from about 3% for the Northern Mariana Islands to 16% for Guam. Forests and grasslands have been modified by timber harvest and cultivation agriculture, and many shrublands and deserts have been used for livestock grazing. Cities and towns have been built in most terrestrial ecosystems in the US other than high mountain landscapes. The changes in land cover and land use to facilitate these activities have had significant impacts on species and ecosystems, including increased greenhouse gas emissions and altered energy balance of terrestrial ecosystems (2,3).

Despite the conversion and degradation of terrestrial ecosystems, there is a long history of conservation and restoration of these lands. Many organizations and individuals, including private landowners, nongovernmental organizations, Tribal nations, and government agencies, have practiced sustainable use of lands and have actively engaged in restoration and management to promote native species and ecosystem functioning. By drawing on diverse forms of knowledge—including Indigenous knowledge, local practices, and scientific research, as well as emerging tools from artificial intelligence and machine learning—conservation and restoration actions can prioritize areas that most effectively and efficiently promote ecosystem integrity and human well-being.

In addition to ecosystem protection garnered through conservation and restoration actions, there is also a growing recognition that working landscapes, such as rangelands, agricultural areas, and urban greenspaces, can play a critical role in conserving biodiversity and ecosystem function while sustaining human well-being. For example, urban greenspaces and green infrastructure provide habitat for many bird, plant, and pollinator species, limit stormwater runoff, reduce vulnerability to extreme heat events by providing shade and stimulating evapotranspiration, and promote human health through interactions with nature.

Key Message 8.1 Land-use, land-cover change, and other disturbances have degraded ecosystems and reduced biodiversity

Natural systems are experiencing increasing impacts from human activities, including land-use and land-cover change, introduction of invasive species, diseases, changes in disturbance regimes, pollution, and climate change (virtually certain). These environmental drivers and changes have resulted in the loss, fragmentation, and degradation of *ecosystems; contributed to species declines; and diminished the structure and functioning of ecosystems across the US (virtually certain). These impacts are expected to continue (virtually certain).*

State of Knowledge 8.1

Land-Use and Land-Cover Change

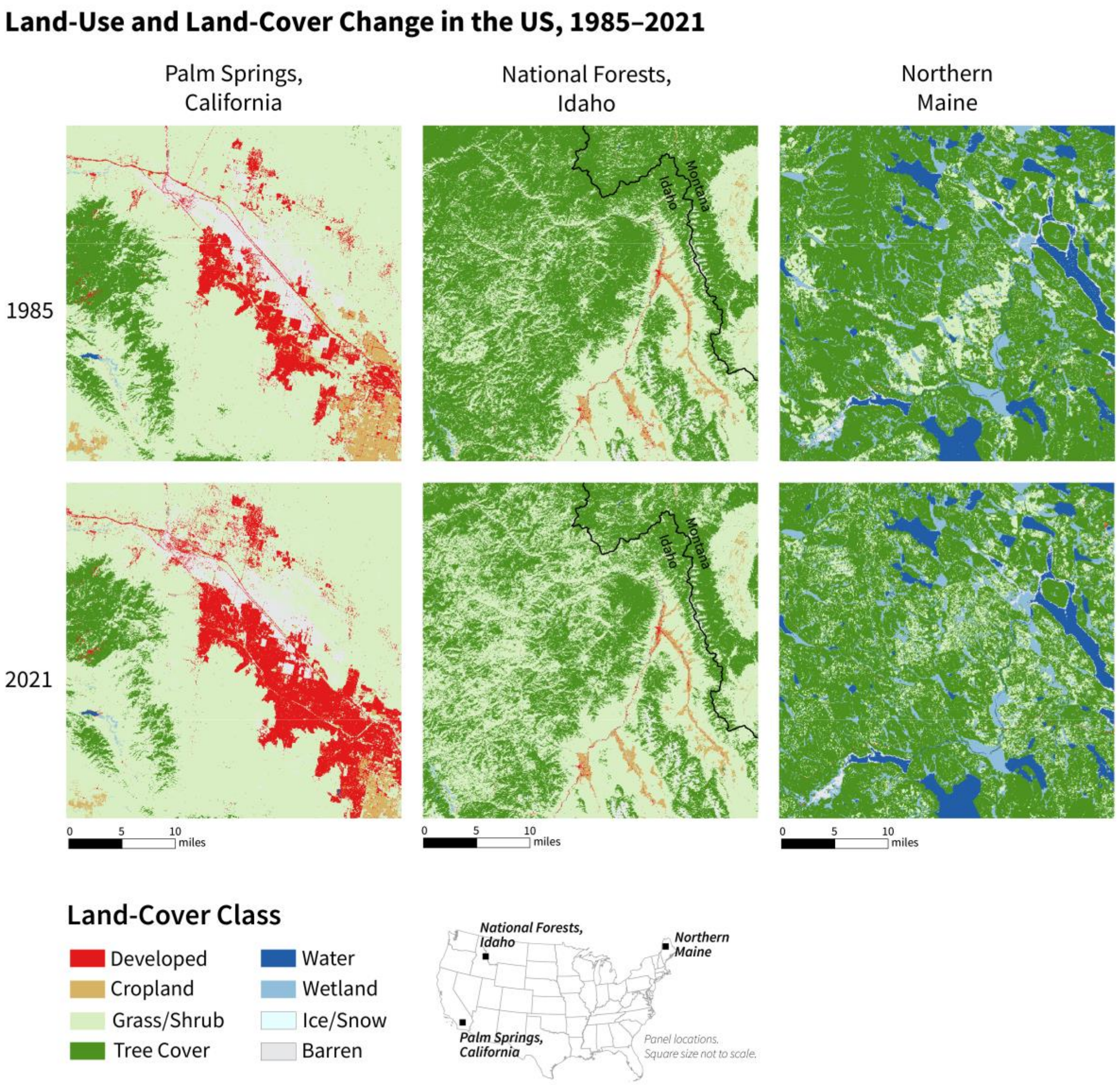
Settler colonialism of North America physically separated Indigenous Peoples from their lands—which were characterized by biocultural diversity and protected by place-based ecosystem expertise—to support new land management practices (4) (see Chapter 9: Drivers). Pressures on terrestrial ecosystems included **land-use change** (the shifting of economic and cultural activities from one practice to another), such as introducing livestock to a previously unmanaged grassland; **land-cover change** (including changes in land's primary physical characteristics), such as turning a forest into housing for people; and **intensification of land use** practices. This conversion from natural ecosystems to human activities results in the loss and fragmentation of habitats for many species. As habitat area shrinks due to land-use and land-cover (LULC) change, many species decline in abundance or disappear due to a lack of food, shelter, or breeding requirements. Species declines have been particularly severe for grassland birds, specialist insects such as monarch butterflies, and many large predators such as wolves and mountain lions that require large areas for their home ranges.

Even in the absence of LULC changes, degradation of ecosystems has significant impacts on species and ecosystems. More frequent and intense wildfires in recent decades (5–7) alter forest and grassland ecosystems and may result in shifts in landscapes from forest to shrubland (8). Introduced invasive species such as cheatgrass in the western US or the hemlock wooly adelgid, an insect pest of eastern forests, cause changes in the ecosystems' dominant species (9,10). Pollutants such as sulfur and nitrogen oxides produced by fossil fuel burning result in shifts in the chemistry of the atmosphere and inland water ecosystems from acid rain (see Chapter 7: Inland Waters) and can harm plant and soil organisms, causing tree die-offs (11). The overharvest of certain species, such as top predators, can cause massive shifts in the abundance of interacting species, such as the increase in deer populations throughout the eastern US due to reduction of predators (12). And climate change due to human activities—primarily emissions of carbon dioxide and other greenhouse gases—is associated with increased frequency and severity of extreme events such as wildfires, droughts, and heat waves. All of these drivers result in significant negative impacts on ecosystem structure and functioning.

Land-use change often replaces complex native vegetation with monocultures or paved surfaces. The resulting homogenized species composition disrupts processes including water infiltration, nutrient cycling, and carbon storage (13,14). LULC change creates human-dominated landscapes, such as buildings, roads, parking lots, mines, and agricultural land (15), and produces **fragmented** ecosystems that are often degraded in structure, functioning, and composition compared to the original ecosystems. Remnants that remain undeveloped within fragmented landscapes are often degraded through altered hydrology, increased **edge effects** (the ecological changes that happen at the border of two different habitats), and disrupted **connectivity** (16).

For example, agricultural expansion across the contiguous US significantly increased in the mid- to late 20th century, primarily through conversion of grasslands (15). From 1985 to 2021, 51,088 square miles (an area about the size of Louisiana) of natural vegetation were converted to cropland in the contiguous US, according to the USGS Land Change Monitoring, Assessment, and Projection (LCMAP) data (Figure 8.1) (17). During the same timeframe, 11,765 square miles of croplands and 15,621 square miles of natural vegetation were converted to development. Development largely takes the form of **urbanization** and suburban sprawl, resulting in the loss of valuable wildlands in many rural and **exurban** areas (18). Long-term land-cover monitoring data is less available outside of the contiguous US, but one contrasting example is Hawai‘i, where there has been an overall decline in croplands from 2000 to present and about 24 square miles of expansion in urban development (19).

Figure 8.1. Land-Use and Land-Cover Change in the US, 1985–2021



Land-use and land-cover changes caused by human and natural forces create complex mosaics and patterns of terrestrial landscapes across the US.

*This figure illustrates the dynamic and heterogeneous nature of land-use and land-cover change across the United States in 1985–2021. Inset maps highlight localized changes: (**left**) urban expansion in Palm Springs, California, (**middle**) forest loss associated with increased wildfire in Idaho, and (**right**) cyclical forest harvesting and regeneration in northern Maine. Together, these patterns demonstrate how land-cover change is driven by a combination of natural processes and human land use, producing complex mosaics that vary across regions and over time. Adapted from LCMAP Change Stories* (20).

Future projections for land-use change vary by land-cover type and by projection scenarios (21). In the continental US, it is projected that forests will continue losing area to development and forest plantations (22,23). Urban land demand is projected to continue to increase, with long-term trends dependent on which shared socioeconomic pathway (SSP) is followed (24,25). Regional projections for grass and shrubland systems show evidence of region-specific conversion to development and agriculture (26), as well as potential changes to ecosystems by encroachment of woody plants (27,28).

Additional Drivers of Impacts to Terrestrial Ecosystems

Land-use and land-cover changes are the primary drivers of ecosystem decline in the US, but several other key drivers significantly impact their status (see also Chapter 9: Drivers), including introduction of invasive species, diseases, changes in disturbance regimes, pollution, and climate change. Many of these stressors compound the effects of others, eroding ecosystems' capacity to maintain characteristic structure, perform key functions, or support native assemblages. Non-native species continue to accumulate across the US (29), including more than 12,000 documented invasions (30), with high-impact invaders fundamentally reorganizing ecosystems. For example, cheatgrass (*Bromus tectorum*) alters fire regimes and eliminates sagebrush ecosystem structure in the western US (31,32). White-nose syndrome, caused by the fungus *Pseudogymnoascus destructans*, has killed millions of bats in North America, with some species declining more than 95% (33,34). Subsequent reduction of insect pest control from bat predation means additional pesticides applied to food crops, and modeling studies show greater risk to young children from this increased pesticide use (35).

Natural disturbances, such as periodic wildfires and floods, have long shaped the structure, functioning, and species composition of ecosystems (36–38). However, human activities have significantly altered disturbance regimes. For example, decades of fire suppression created hazardous fuel accumulations that, combined with climate warming and drought, now produce larger, more severe wildfires (39–43).

Air and water pollution from chemicals generated by human activities harm ecosystems. For example, fertilizers are commonly applied in agriculture to increase crop yields, and insecticides, fungicides, and herbicides reduce pests and weeds. However, these chemicals can have unintended negative effects (44,45). Fertilizers increase nitrogen concentration of terrestrial and inland water ecosystems, which can dramatically alter species composition and human health risks (46). Pesticides degrade terrestrial ecosystems by killing non-target insect species like pollinators (e.g., bees) and some bird and amphibian species through direct toxicity and hormone disruption (45). Pesticides may have cascading trophic effects through bioaccumulation (i.e., increased concentrations of a toxin as it moves from one trophic level to a higher one) and reductions in the abundance and diversity of arthropod predators that help to control pest species (47). Burning of fossil fuels led to increasing emissions of gaseous pollutants such as sulfur dioxide (SOx) and nitrogen oxides (NOx), which in turn led to increased atmospheric deposition of sulfur and nitrogen to terrestrial and inland water ecosystems throughout the 20th century. SOX and NOx emissions have declined more than 90% and 70%, respectively, since their peaks in the 1990s (48), due to the US Clean Air Act in 1970 and its Amendments in 1990. Despite declining emissions of SOx and NOx since the 1990s, their contribution to acid deposition continues because it takes decades for terrestrial ecosystems to recover from soil acidification and aluminum toxicity. Impact to human health continues as well, as it is estimated that air pollution exposure is still associated with 100,000–200,000 deaths annually in the US (49).

Climate change has affected ecosystems through increased air temperatures, rising sea levels, reduced snowpacks, and extreme weather such as heat waves, droughts, and hurricanes (Ch. 10: Climate) (50–55). Climate change interacts with stressors like LULC change, overharvest, pollution, invasive species, and disease, to act as a **threat multiplier**, magnifying their effects on individuals, populations, and ecosystems. For example, warmer weather can allow invasive insect species to expand their range and active periods (56,57), and drought can lower the pest and disease resistance of trees (58,59) and increase the risk of wildfires (60,61). Compounding disturbances can create long-lasting changes (62,63). For example, in the Jemez Mountains in New Mexico, a combination of extreme heat and drought, insect outbreaks, and recurring wildfires converted much of the landscape from forest to non-forest (64).

Although some species may increase in abundance or expand their ranges due to climate change (65), most native species are negatively impacted (62). Many, although not all, species are moving to higher latitudes or elevations (66,67), but high-elevation species risk local extinction as the area of suitable habitat contracts (68–70). The timing of seasonal events (known as **phenology**)—such as breeding, flowering, migration, and nesting—is shifting due to climate change (71). Phenological mismatches occur when the timing of activities of interacting species no longer aligns, such as migrant species arriving later than the peak period of food availability (72). Warmer temperatures have increased the range and prevalence of disease vectors like mosquitoes and ticks, increasing prevalence of infectious disease (73).

Species Decline

Earth is experiencing its sixth mass extinction, primarily because of trends in LULC change and additional drivers of change (74,75). As of 2025, 28% of species assessed by the International Union for Conservation of Nature were threatened with extinction (76). North America's wildlife populations declined 39% between 1970 and 2020 (77). In the US, 34% of plant species and 40% of animal species are currently at risk of extinction, and 41% of ecosystems are at risk of range-wide collapse (78). Among US terrestrial animals, land snails are most at risk (74% of species), followed by amphibians (42%), bees (37%), beetles (35%), reptiles (22%), moths (20%), mammals (18%), butterflies (16%), and birds (12%) (79). Many of the most imperiled are listed under the Endangered Species Act (as of

October 2025, 742 animal and 938 plant species, subspecies, or distinct population segments).

In the continental US and Canada, the number of birds declined by nearly 3 billion (57%) between 1970 and 2017 (80). This decline occurred across all species groups, biomes, and regions, with grassland birds showing the greatest decline (80). More than a third of US bird species are now of high or moderate conservation concern, with 229 species requiring urgent conservation action (81). In Hawaiʻi, the arrival of humans, pigs, and rats around 1600 years ago drove half of the estimated 111 native bird species to extinction (82). Mosquito-borne avian malaria is an existential threat to the remaining honeycreepers in Hawaiʻi, and the few high-altitude refuges from mosquitoes are rapidly disappearing as temperatures increase (83).

Across North America, some mammals, such as bison and gray wolves, have begun to recover because of federal and state protections and reintroductions. However, many other species are declining, especially small mammals (84), bats (85) (34,86), and animals with narrow habitat needs (87). Alpine species like the American pika (*Ochotona princeps*) are seeing their habitat disappear as temperatures increase (88). Unlike birds, there is no continent-wide monitoring system for mammals, which means that many declines are likely going undetected (89,90).

Reptiles show widespread signs of stress, especially turtles, which are one of the most threatened vertebrate groups globally (91). Many turtle species have declined due to habitat loss, road mortality, collection for the pet trade, and predation by invasive species (92). Snakes and lizards also face pressures from LULC change, climate change, and disease outbreaks such as snake fungal disease (93). Although a few species have stable or increasing populations, the majority show declining trends or shrinking ranges (94). These trends indicate that reptiles face several threats that could lead to further losses without targeted conservation action.

Globally, amphibians are at greater risk than any other class of terrestrial vertebrates (95,96), with an estimated half of all species imperiled (97). In the US, habitat loss is the main reason for decline, but the fungus *Batrachochytrium dendrobatidis* also impacts amphibian populations (98). Another pathogen, *B. salamandrivorans*, has seriously affected salamander populations in Europe, and may soon arrive in the US (99). Twenty-six frog, toad, and salamander species are listed as endangered and 18 as threatened (100). At current rates of decline, amphibian species may be extirpated from half their locations in the next 20 years (98).

Insects are highly diverse and provide essential functions such as pollination and biological control (101). Many insect species have declined, with common species showing the sharpest drops (−7.72% annually) (102). The principal stressors include LULC change, climate change, pesticides, and invasive species (101). Many insects feed on specific plants and therefore disappear when their host plants are lost. In forests dominated by a single tree species such as hemlock (*Tsuga canadensis*) or ash (*Fraxinus* spp.), the loss of these trees to invasive pests (e.g., hemlock wooly adelgid, emerald ash borer) can also eliminate an entire community of arthropods (103,104).

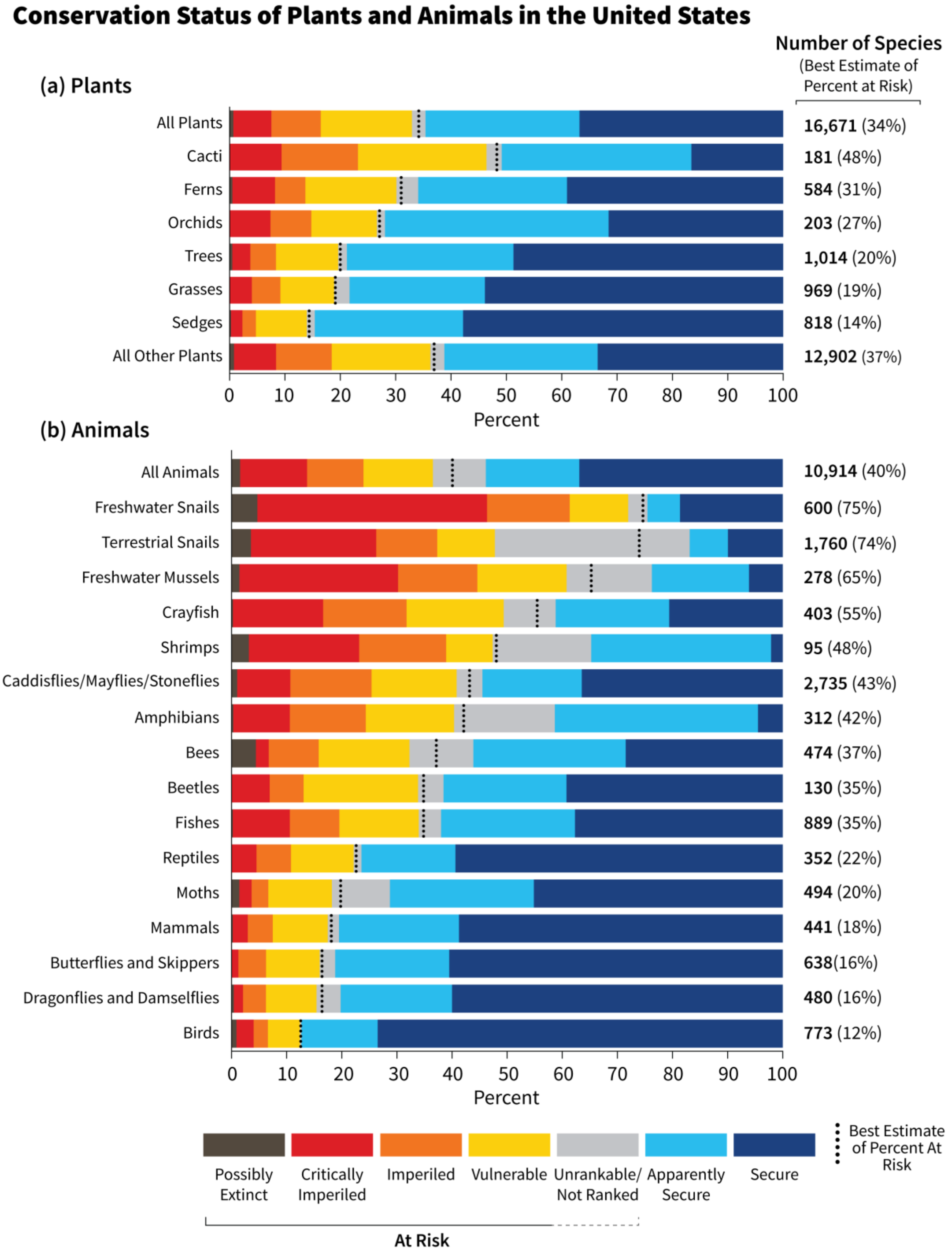
Butterfly abundance dropped 22% between 2000 and 2020, with more than 100 species declining by over 50% and 22 species by 90% or more (105). Agricultural intensification reduces the abundance of milkweed (*Asclepias* spp.), the host plant for monarch butterflies (*Danaus plexippus*) (106,107), resulting in a decline in the overwintering population size of monarch butterflies (108–111). In December 2024, the monarch was proposed to be listed as threatened under the Endangered Species Act (111).

Plants form the base of terrestrial food webs and provide ecosystem structure, refuge, and food. The flora of the US and its territories is highly diverse, with 38,000 species and subspecies of vascular (ferns, conifers, flowering plants) and non-vascular (mosses, liverworts, hornworts, and lichens) plants (112). However, 34% of America's plant species are at risk of extinction, including 48% of cactus species, 31% of ferns, 27% of orchids, 20% of trees, 19% of grasses, and 14% of sedges (79). All US tropical forests (primarily located in Puerto Rico and Hawaiʻi) are imperiled, as are many temperate and boreal ecosystems (79). Key drivers of plant diversity loss in the US include LULC change, invasive species, pollution, overharvesting, and, increasingly, climate change (113–117).

Current global estimates of microbial and fungal diversity range from up to a trillion species of bacteria and archaea (118) and from 2.2 to 3.8 million of fungi (119), with minimal understanding of extinction rates. A comprehensive checklist of North American fungi identified 44,488 species of nonlichenized fungi including mushrooms and microfungi (i.e., molds, yeasts, mildews), though this is likely a significant underestimate (120). Only 1,300 fungi (less than 1% of known taxa) have been assessed by the IUCN Red List of Threatened Species. Of the 557 species of North America fungi listed, 126 are considered critically endangered, endangered, or vulnerable. Despite threats from LULC change and pollution, microbes and fungi remain largely excluded from conservation efforts. Although the US Endangered Species Act does not explicitly protect fungi, recent efforts of the IUCN Microbial Conservation Specialist Group argue for raising awareness for their conservation alongside rare and endangered plants and animals.

Impacts of LULC change, ecosystem degradation, pollution, climate change, and invasive species continue to outpace conservation and restoration initiatives, posing ongoing threats to ecosystems throughout the US (Figure 8.2). These pressures have contributed to species declines and diminished structure and functioning of ecosystems (121), and such impacts are expected to continue. Protecting terrestrial biodiversity will require science-informed, adaptive strategies and actions that achieve the highest impact given available funding and other resources.

Figure 8.2. Conservation Status of Plants and Animals in the US



Many terrestrial plant and animal species in the US are at risk of extinction.

*The proportion of plant and animal species in the United States classified across risk categories by NatureServe, highlighting patterns of extinction risk among major taxonomic groups. Plants (**a**) exhibit substantial risk, ranging from 14% of sedges to nearly 50% of cacti considered vulnerable (yellow bars), imperiled (orange bars), critically imperiled (red bars), or possibly extinct (grey bars). Animals (**b**) show especially high risk (up to 75%) among freshwater-associated taxa, highlighting the vulnerability of freshwater ecosystems. These patterns illustrate that extinction risk is widespread across diverse taxonomic groups, with implications for ecosystem function and resilience. Adapted with permission from NatureServe 2023* (79).

Description of Evidence Base

The finding that natural systems are experiencing increasing impacts from human activities, including land-use and land-cover change, introduction of invasive species, diseases, changes in disturbance regimes, pollution, and climate change is assessed to be *virtually certain*, as it is based on hundreds of published studies across many ecosystem types, regions, and species that show consistent patterns of impacts based on observations, experiments, and modeling analyses of terrestrial ecosystems. The finding that these environmental drivers and changes have resulted in the loss, fragmentation, and degradation of ecosystems; contributed to species declines; and diminished the structure and functioning of ecosystems across the US is *virtually certain*, based on comprehensive analyses of many species and ecosystems from empirical field studies as well as remotely sensed imagery. Current observations cited in published studies based on trends in human activities and model projections indicate that it is *virtually certain* that these impacts are expected to continue.

Key Message 8.2: Effective ecosystem conservation and restoration actions promote biodiversity and strengthen resilience

Efforts to protect terrestrial biodiversity are most effective when they prioritize landscapes with the ecological and cultural characteristics most essential for sustaining life and adapting to changes (very well established). Advances in data and analytical tools, further informed by Indigenous and local knowledge, allow targeting interventions at specific locations to maximize biodiversity, increase conservation benefits, and strengthen resilience (well established). Threats to species and ecosystems can be addressed through active conservation, targeted interventions, adaptive management, restoration, real-time monitoring, information sharing, and collaboration (very well established).

State of Knowledge 8.2

Prioritizing Essential Ecological and Biocultural Characteristics

Conservation faces a fundamental challenge: There are not enough resources to protect and restore all the places that are important for ecosystem resilience, biodiversity, and cultural values. However, conservation planning can help identify the most effective use of available resources. Foundational works in systematic conservation planning and biodiversity science (122–125) provide clues to identifying these characteristics to resolve this challenge. Eight interrelated principles, identified in the conservation planning literature, can help identify landscapes of highest priority for conservation: **representation**, protecting all ecosystem types (126–128); **connectivity**, maintaining linkages for movement and adaptation(126,129–134); **intactness**, keeping the least-modified cores (135–142); **complementarity** and **irreplaceability**, maximizing unique biodiversity coverage (131,132,143–148); **climate resilience**, ensuring persistence under changing conditions (147–155); **ecosystem functions and processes**, sustaining the systems that support life; **species at risk**, preventing extinctions (156); and **biocultural significance**, honoring the inseparable relationship between people, place, and nature. Together, these principles provide a science-based foundation for identifying landscapes most vital to the persistence of biodiversity and ecosystem functioning.

Biocultural significance is increasingly recognized in conservation as a critical component of prioritization. Since time immemorial, Indigenous People have had intimate knowledge of ecosystems by living directly with their land and have evolved effective land management practices based on these intergenerational relationships. This deep and dynamic understanding of biocultural heritage built over generations is referred to as Indigenous Knowledge (IK) or Traditional Ecological Knowledges (TEK) (157). Rooted in culture and the natural environment, IK is a continually evolving system of understanding, interpretation, and meaning. It is collectively held and expressed through stories, songs, folklore, proverbs, naming and classification systems, resource use, rituals, spirituality, cultural values, community laws, local languages, and ecosystem-based practices. IK-informed Indigenous land stewardship practices are increasingly recognized as having positive outcomes for biodiversity conservation and climate adaptation (158–160).

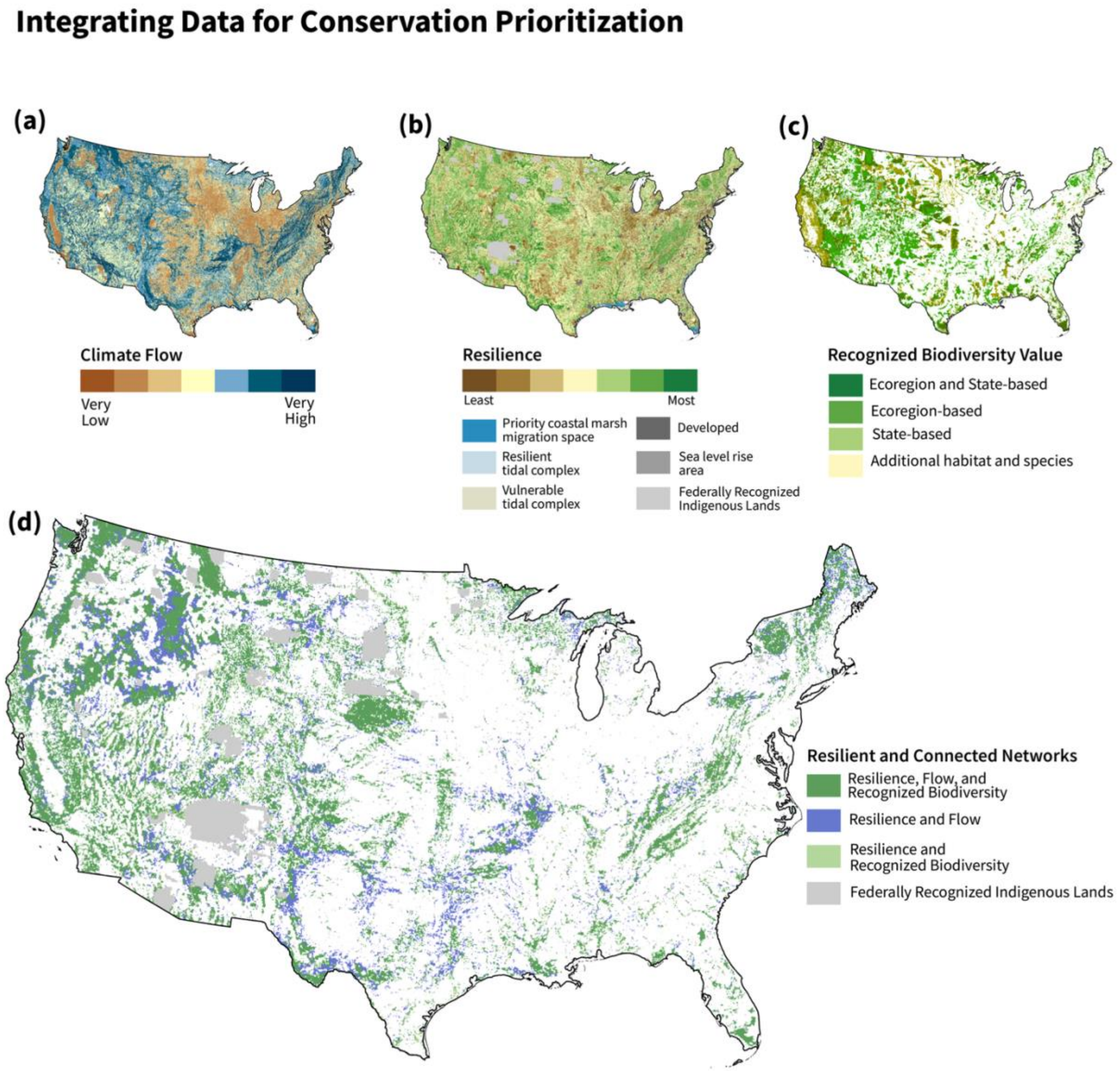
Data, Tools, and Knowledge

Artificial intelligence (AI), neural networks, and machine learning offer new strategies for spatially informed conservation, transforming it from broad, reactive protection toward a more proactive practice that directs effort to the right places at the right times. The use of AI for image and sound classification, species identification, and refining deep learning models demonstrate broad applications for biodiversity conservation (161). However, application of such technologies should consider the needs and data sovereignty considerations of local communities and Indigenous Peoples who may have data privacy concerns and assure the proper data governance protocols are in place (162).

Expanding and Integrating Data for Conservation Prioritization

Over the past decade, the amount, quality, and accessibility of environmental data have expanded dramatically, providing opportunities for more strategic conservation decisions (Figure 8.3). For example, high-resolution remote-sensing, national biodiversity inventories, and community-science initiatives now provide near-continuous information on species, habitats, and ecological processes, producing over 274 terabytes of observations on a daily basis (163).

Figure 8.3. Integrating Data for Conservation Prioritization



Ecological integrity, species distribution, connectivity, and climate resilience data can reveal overlapping conservation priorities.

*Three small maps show distribution of lands identified as providing (**a**) connectivity (climate flow, ranked from dark brown for very low to dark blue for very high), (**b**) resilience (from dark brown for least to dark green for most), and (**c**) recognized biodiversity value (for four categories). The large map (**d**) shows that combining resilience and biodiversity (light green), resilience and flow (blue), or all three (dark green) highlights where conservation and protection efforts might yield multiple benefits. When combined with datasets describing cultural or historical significance, for example, Federally Recognized Indigenous Lands, such information helps define landscapes that support both ecological and societal resilience. Adapted from The Nature Conservancy's Resilient and Connected Network Map* (164).

National programs such as the US Geological Survey's Gap Analysis Project and Protected Areas Database have enabled systematic evaluation of ecosystem **representation**, enabling systematic assessment of ecosystem coverage within conservation networks. These data reveal that roughly two-thirds of US ecosystems remain below minimum protection thresholds (165). Complementary datasets, including the Multiscale Index of Landscape Intactness, support **integrity and intactness** by mapping the relative human footprint and identifying remaining core areas with high ecological integrity. Together these resources highlight progress in conserving intact landscapes and the vast underrepresentation of grasslands, arid shrublands, and some forest types.

Advances in species-level data have expanded the use of additional prioritization principles. The Map of Biodiversity Importance uses machine learning to model habitat for more than 2,000 imperiled species, directly supporting identification of **species at risk** and highlighting **irreplaceable** locations where protection will most effectively reduce extinction risk. Dynamic datasets such as eBird's Weekly Abundance Maps provide a temporal dimension, revealing how migratory species move across regions and seasons and enabling an understanding of critical stopovers and corridors important for **connectivity**. Increasingly, these data streams are complemented by emerging technologies, such as ForWarn II for near-real-time detection, Wildlife Insights for AI-based image recognition from camera traps, environmental DNA (eDNA) for detecting rare or cryptic species, Motus for wildlife tracking with automated radio telemetry, and acoustic monitoring networks that can track biodiversity through sound. Collectively, these sources give conservation practitioners an unprecedented, multi-scale view of ecological change, further strengthening application of these principles by improving detection of population change, disturbance impacts, and movement pathways.

Data supporting **climate resilience** are now relatively well established in the US, and analyses increasingly integrate a range of climate data with **connectivity** datasets to identify landscapes likely to sustain biodiversity under climate change. Climate velocity layers quantify the rate at which species must move to track suitable climate conditions

(166), and The Nature Conservancy's Resilient and Connected Landscapes framework builds on this approach, combining geophysical diversity and microclimate heterogeneity with habitat maps to identify climate-resilient cores and corridors across the US (164).

In contrast, data supporting ecosystem functioning, cultural significance, and Indigenous co-stewardship are more distributed and context dependent. **Ecosystem functioning** is informed by measurements of carbon flux, hydrology, productivity, and disturbance regimes, but these indicators are not yet integrated into a single national prioritization layer. **Cultural significance** is supported by cultural resource inventories and place-based knowledge systems, often governed by Tribal sovereignty and ethical considerations that limit centralized aggregation (but see Indigenous Knowledge section below). Although the quantity of information is growing rapidly, the greatest value lies in integrating ecological integrity, species distribution, connectivity, and climate resilience data to reveal overlapping priorities. When combined with datasets describing cultural or historical significance, such information defines landscapes that support both ecological and societal resilience.

Integration of Decision-Support and Analytical Tools into Targeted Action

This proliferation of data has been matched by parallel advances in analytical and decision-support tools that translate information into action. Early spatial planning systems such as Marxan and NatureServe Vista established the foundation for conservation planning, optimized protected-area design, connectivity, and cost-effectiveness. These tools remain widely used by agencies and nongovernmental organizations to evaluate trade-offs among ecological representation, land cost, differing priorities, and sociopolitical feasibility. More recent platforms employ AI and optimization algorithms to handle the complexity of modern conservation problems. For example, open-source software called Prioritizr allows users to integrate multiple objectives (e.g., biodiversity, carbon, connectivity, and cost) within flexible scenarios. CAPTAIN, an AI-based system that uses adaptive learning, simulates how conservation priorities might adapt through time as threats, budgets, or climate conditions shift. These tools are moving conservation from static protected area designation toward dynamic, adaptive planning that recognizes a diversification of actions involved, each with different impacts (167). When coupled with open-access data platforms and participatory planning processes, these systems can democratize conservation decisions, increasing transparency and accountability while improving return on investment. By bringing together robust data, advanced analytical tools, and diverse knowledge systems, conservation planning has become more strategic and inclusive. This requires investment not only in technology but also in social infrastructure—such as capacity, training, collaboration, and governance—that allows data and tools to be used equitably and effectively (159). When fully realized, the combination of these advances will enable conservation that is more precise, efficient, and just, directing limited resources toward the places and practices that yield the greatest ecological and societal benefit.

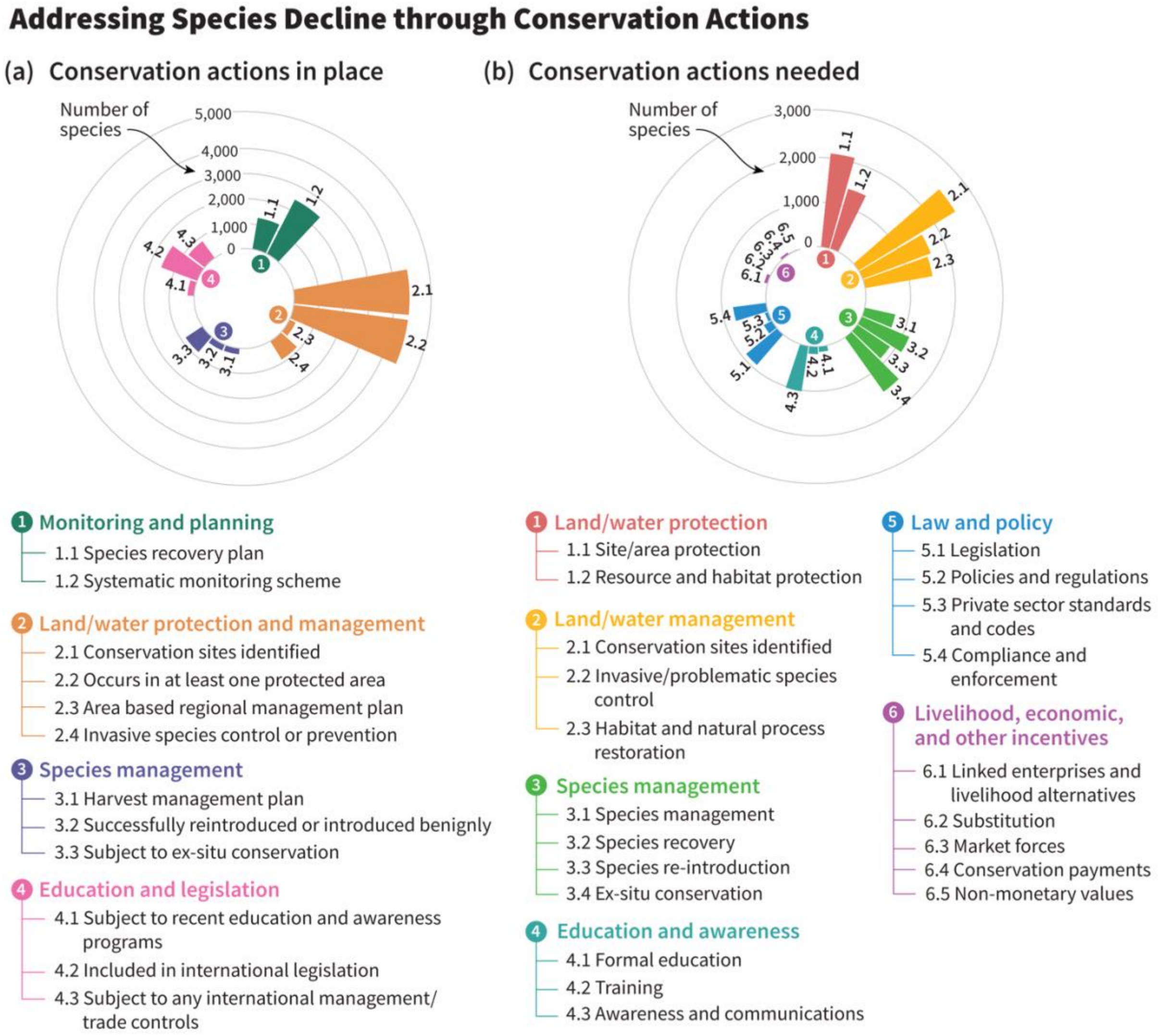
Indigenous Knowledge

Indigenous Peoples and local community knowledge systems are intergenerational, place-based expertise that have long guided land stewardship practices. When meaningfully and collaboratively included in long-term decision-making, these knowledge systems provide fine-scale understanding of ecosystem change and cultural significance that are complementary to scientific data and analytic models. Emerging frameworks for knowledge co-production (168), relational science (169), and Indigenous data sovereignty ("the inherent right of Indigenous Peoples and nations to govern the collection, ownership, and application of data that pertains to their people, lands, resources, and knowledge systems") (162,170,171) are creating clearer pathways for ethical and effective integration. Technologies and networks such as culturally informed GIS platforms that are based on Indigenous data sovereignty practices (such as Terrastories, NativeLands.Ca, and NPS Cultural Resources GIS), community-driven historical mapping of culturally significant ecosystems (such as Mapeo, Native Land Information System, and OpenHistoricalMap), and mapping of cultural regions further support the inclusion of Indigenous Peoples and local community knowledge in biodiversity and climate assessments. The data generated from these tools must also be accessible to communities at large, not just researchers (172,173), to support the rights of Indigenous Peoples and local communities, from the physical ecosystem into digital ecosystems.

Active Conservation, Monitoring, and Collaboration

The negative impacts of LULC change can be remedied through active conservation, intervention, management, and restoration (Figure 8.4). These actions are most effective when they are forward-looking and adaptive and incorporate the effects of climate change. Protected areas are crucial for biodiversity conservation because they reduce the loss and degradation of habitat and slow the rate of species extinctions, including threatened species. Over 316 million acres across the US are permanently protected with the goal of biodiversity conservation, including in locations such as national, state, and local parks and wilderness areas. The US has more than 51,000 protected areas covering just under 13% of the nation's land area and 19% of the nation's marine environments (165), which is short of global goals to protect 30% of land and sea by 2030 (174).

Figure 8.4. Addressing Species Decline Through Conservation Actions



Species imperilment can be addressed through conservation, targeted intervention, adaptive management, restoration, active collaboration, and other actions.

*This figure summarizes the range of conservation actions identified for species in the United States across taxonomic groups, illustrating both actions in place (**a**) and those determined by International Union for Conservation of Nature as needed to reduce extinction risk (**b**). The underlying data include all US species across all conservation statuses except Least Concern, highlighting opportunities for conservation actions before the species reach the highest risk levels. The results demonstrate that a diverse set of management, conservation, and restoration actions can address species imperilment and improve conservation outcomes when applied proactively and collaboratively. Figure original to The Nature Record.*

Land management tools are often employed to preserve the structure and functioning of protected, restored, and otherwise managed landscapes. Prescribed fire, grazing, and invasive species control are the most widely adopted management practices in terrestrial ecosystems of the US (175). For example, after a brief increase in fire occurrence in the period following colonial settlement, when vast areas of forest were subjected to slash-and-burn logging for agriculture (39), the amount of burned area in the US has steadily decreased since first European contact with Indigenous communities (40,176), and particularly since the 1920s when federal, state, and local governments adopted fire suppression as a cornerstone strategy to manage woody and other fire-adapted ecosystems (39,177).

Beyond conserving and managing relatively intact ecosystems, **ecological restoration** is commonly employed to repair damaged ecosystems and ensure imperiled species have the critical habitat they need to thrive. Restoration improves biodiversity and ecosystem functioning relative to degraded ecosystems, but restored systems rarely recover fully (178,179). This underscores the importance of conserving relatively intact ecosystems and preventing ecosystem damage in the first place. Conservation and restoration have both been used successfully to increase both nature and people's ability to adapt to climate change, an approach often termed **nature-based solutions** (see Chs. 2, 4, 8, 10, 12, 13, 14).

Restoration goals have undergone significant change since Western science perspectives on ecosystem restoration were first developed in the early 1900s, as well as since restoration ecology was formalized as a science in the late 1990s (180). Although it is still common to aim to restore ecosystems to the state they were at some particular time point in the past (e.g., before European colonization), there is increasing recognition that such goals are unrealistic (178,180). Because ecosystems are dynamic, using a snapshot in time may not fully capture the variation that regularly occurs in that ecosystem. Therefore, many practitioners seek to combine historical information with a projected vision of a future ecosystem to create restoration plans (181). Such goals account for ecological and social aspirations (181) and may take innovative approaches such as sourcing plants or animals targeted for restoration from climates similar to the projected state, in addition to using local genotypes or ecotypes (Ch. 10: Climate Change) (182).

Beyond publicly protected areas and those owned by nonprofit organizations, restoration and ecosystem management on privately owned lands play a critical role in shaping working lands in the US, given that they make up much more land area than protected areas. Approximately two-thirds of land in the lower 48 states is privately owned. A large share of this private land is working agricultural land (cropland, pastureland, rangeland). Rangeland alone accounts for over 400 million acres, most of which is on private land in the Midwest and West. There are numerous examples of successful programs that improve water quality, soil health, biodiversity, fire resilience, and carbon sequestration on active working lands (183–187). The most common conduit to protect private lands is conservation easements, which are voluntary legal agreements to increase conservation value. Conservation easements cover almost 38 million acres in the US (188) and, compared to public lands, are often located in higher-priority areas for conservation, hold significantly higher average species richness, and sequester more carbon per unit area (189). Successful conservation initiatives on working lands are likely to succeed when they are voluntary and driven by landowners, collaborative (involving strong partnerships and technical support), economically viable (with the financial incentives of all participants aligned), monitored (to ensure progress toward adaptive management goals), and rooted in community values and local stewardship.

Description of Evidence Base

The finding that efforts to protect terrestrial biodiversity are most effective when they prioritize landscapes with the ecological and cultural characteristics most essential for sustaining life and adapting to changes is *very well established*, based on examples from published studies and reports documenting consistent results of biodiversity protection by federal and state agencies and non-governmental conservation organizations for many ecosystems and species. The assessment that the use and effectiveness of new advances in data and analytical tools, further informed by Indigenous and local knowledge, allow targeting interventions at specific locations to maximize biodiversity, increase conservation benefits, and strengthen resilience is *well established* is based on a growing, but limited, number of successful examples to date of artificial intelligence and machine learning tools in conservation actions for several ecosystem types. The finding that threats to species and ecosystems can be addressed through active conservation, targeted interventions, adaptive management, restoration, real-time monitoring, information sharing, and collaboration is *very well established*, based on a substantial body of conservation actions documented in decades of published research by researchers and conservation practitioners.

Key Message 8.3: Human-dominated landscapes can provide benefits to nature and people

Many terrestrial ecosystems in human-dominated landscapes, such as urban greenspaces and agricultural lands, are critical for biodiversity habitat, air and water filtration, adaptation to and mitigation of climate change, and human well-being (very well established). Effective management in these landscapes has the potential to restore nature so that it can equitably provide a range of social and ecological co-benefits (well established).

State of Knowledge 8.3

Although formal protected areas remain critical for many species and communities, there is growing recognition that **working lands**—such as rangelands and agricultural areas — and urban greenspaces can play an important role in conserving biodiversity while sustaining nature's contributions to people (190,191) (see Chs. 11 and 13). These ecosystems, ranging in size from small urban parks to large swaths of timberlands, can support local biodiversity and also serve as stepping stones for species movement between larger intact ecosystems (192). These ecosystems' conservation benefits are not guaranteed, however, and they depend on context-specific management practices that promote functioning landscapes.

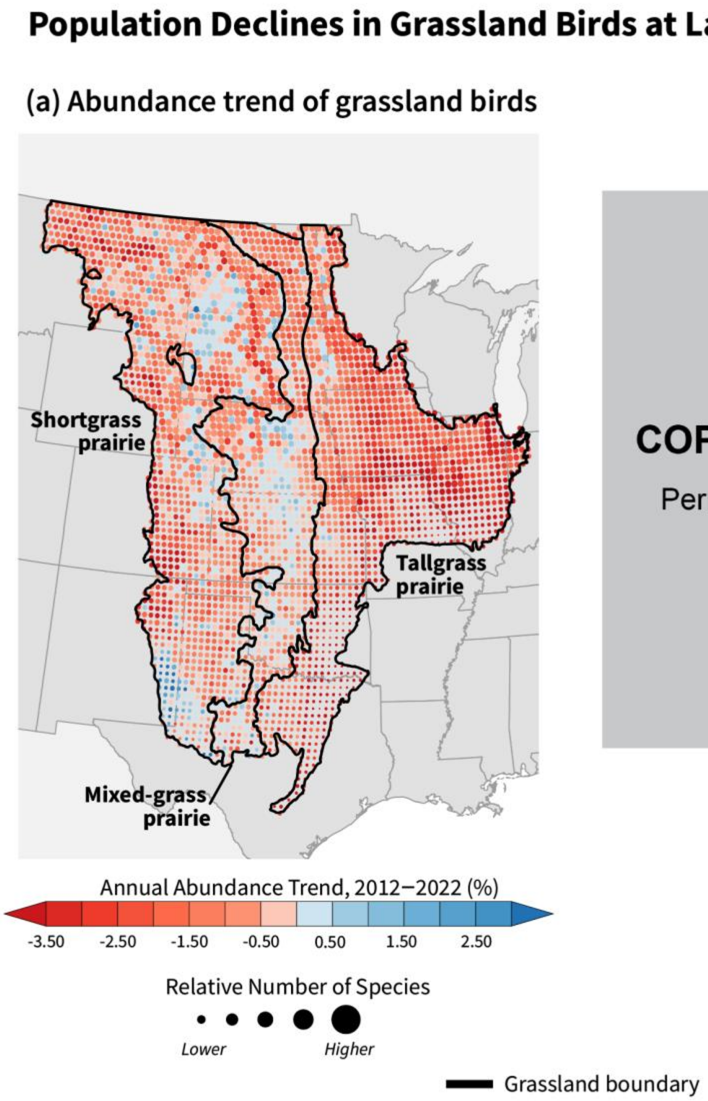
Agriculture and Rangelands

The conservation value of working lands is especially important in regions where most land is privately owned. For example, more than 100 bird species have more than 50% of their US breeding ranges on private lands, and more than 80% of the ranges of grassland birds is privately held (193). Unfortunately, ecological conditions in many working landscapes in the US continue to decline. LULC changes remain serious threats to biodiversity in many agricultural landscapes (194), with 10-year average annual conversion rates of grasslands to croplands at 2.6 million acres in the Great Plains (195) (Box 8.1). In 2022 alone, nearly 2 million acres of grassland were lost in the Great Plains, including 480,000 from the Northern Great Plains—one of the world's largest intact temperate grasslands (195). Degradation of rangelands and pasturelands since 1995 can be attributed largely to climate change, invasive species, wildfire, and woody encroachment, especially by junipers (196).

Box 8.1 Central Grasslands and Prairie

Many environmental challenges in America's heartland reflect a kind of "death by a thousand cuts" because they represent the cumulative effect of countless decisions made at the scale of individual farms or fields. Seemingly benign choices about nutrient and livestock management, pesticide application, tillage, cover crops, vegetative buffers, and wetlands aggregate in ways that profoundly affect species and ecosystems, both terrestrial and aquatic. Often choices made to improve agricultural productivity lead to only marginal gains (197). In the Corn Belt, annual crop production is estimated to be reduced by up to 6% because of topsoil loss and tillage erosion (198). Consequences are not limited to local or regional scales but result in continental impacts like **hypoxia** (areas of low oxygen levels) in the Gulf of Mexico, which is largely attributed to agricultural runoff into the Mississippi River Basin (199,200). Fortunately, relatively simple adjustments to management practices can result in meaningful ecological benefits.

Figure 8.5. Population Declines in Grassland Birds at Landscape Scales



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Agricultural intensification and conversion of grasslands to row crops contribute to population declines in grassland birds.

*Grassland bird population declines are highest where grasslands have been converted for row crop agriculture. (**a**) Annual population abundance trends in obligate grassland birds from 2012 to 2022 mapped across extant shortgrass prairie, tallgrass prairie, and mixed-grass prairie ecosystems. (**b**) A map of long-term changes in grassland extent in the same geographic regions shows that bird population losses are higher in areas with the most grassland loss to row crop agriculture, illustrating how cumulative land-use decisions in agricultural areas can result in widespread biodiversity impacts. "Plowprint" is the footprint of crop agriculture, and indicates where native grasslands have been plowed for row crops. (a) Figure original to The Nature Record, (b) permission to reproduce is pending.*

One cornerstone strategy used in sustainable agriculture is reducing runoff of water, nutrients, pesticides, or soil by using native plants to create vegetated buffers or "prairie strips" along field or riparian edges (201–203). Research shows that prairie strips need not be associated with lower yields and ultimately return disproportionate benefits to ecosystem services and biodiversity compared to croplands lacking strips (201). Indeed, a multiyear, large-scale experiment in Iowa showed that replacing only 10% of cropland with prairie strips doubled species richness of insects and birds and increased pollinator abundance by 3.5 times, while also reducing runoff such that 20 times more soil and 4.3 times more phosphorus were retained (202). Some of these benefits, like soil health, can accrue for decades (204). As many as 69 million hectares of cropland in the United States could benefit from inclusion of prairie strips (201), indicating an enormous opportunity to improve the sustainability of agricultural landscapes with relatively modest investment.

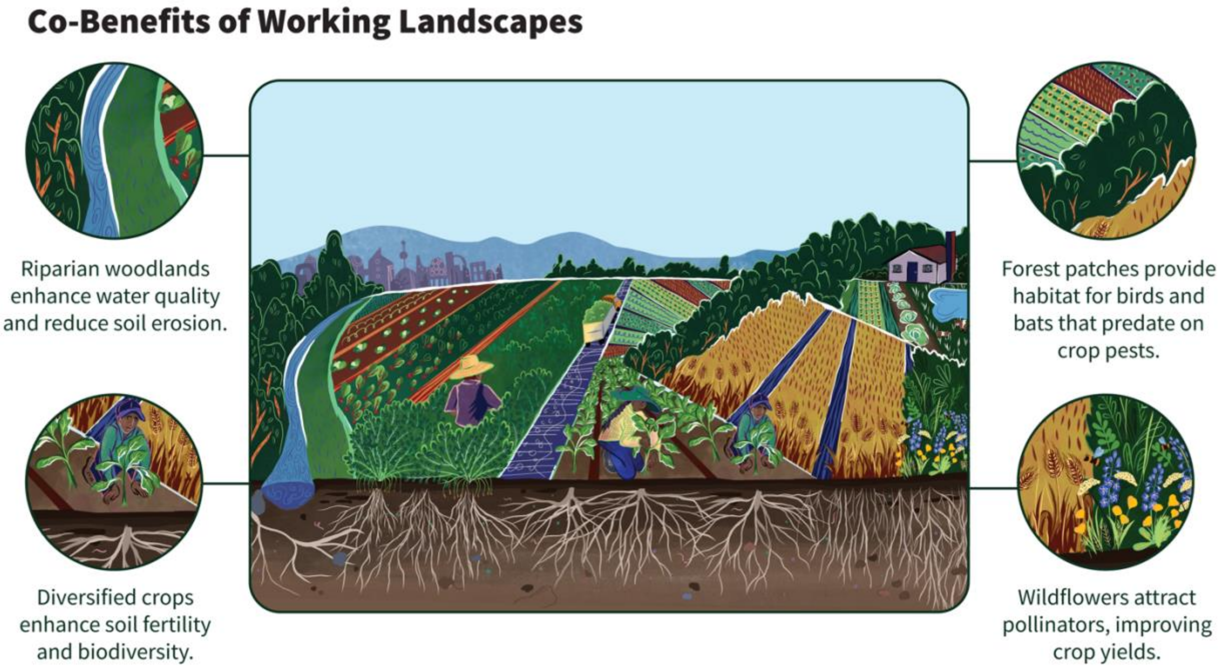
With careful design, these buffers also can provide essential resources to threatened species. For example, milkweed (*Asclepias spp.*), the host plant for the declining monarch butterfly, plummeted after the introduction of glyphosate-tolerant corn and soybean that significantly increased use of herbicides (205–207). Monarch caterpillars rely on milkweed as their only food source; without milkweed there are no monarchs (208,209). When native plants dwindle, a wide assortment of other species—pollinators, songbirds, game birds, and waterfowl—also struggle to find sufficient food and cover resources. To the extent that milkweed and other native plants can be incorporated into prairie strips and buffers, growers can both reduce runoff and help to reverse shocking declines in native wildlife. Moreover, managing agricultural systems to include natural elements that are floristically diverse—especially among grasses, legumes, and forbs (herbaceous plants)—can improve forage yield and quality, soil nitrogen levels, abundance of pollinators and birds, and populations of natural predators of agricultural pests (203,210). Ultimately, relatively straightforward adjustments to agricultural practices return benefits that extend far beyond farm and landscape-scale benefits, including much-needed reductions to nutrient flows that contribute to hypoxia in the gulf (200,211).

[BOX 8.1 ENDS HERE]

These changes can profoundly affect wildlife populations across western states, where 67% of species—including more than 125 species of conservation concern—use rangelands (212). Grassland birds in particular have sharply declined in abundance since 1970 (213), with recent declines steepest in locations where species formerly were most abundant (214). Insects, including iconic monarch butterflies and once-common pollinators, have also experienced widespread declines (215). As biodiversity is lost from these working landscapes, so too are many of the benefits provided by species, such as pollination, pest control, and seed dispersal—all of which improve the health and productivity of agroecosystems (216–218).

Fortunately, many opportunities exist to manage working lands for benefits to both people and ecosystems (Figure 8.6; see Chapter 11). Maintaining at least 20% native or seminatural habitat—such as hedgerows, field borders, and road edges—can support some biodiversity and ecosystem services, as well as food security, with optimal outcomes accruing when more than 50% is maintained (190,219,220). Notably, even working lands managed to maximize biodiversity cannot support the same species as intact ecosystems (190). For example, working lands cannot support species that specialize in unmodified habitats such as mature, intact native forests (e.g., ʻakiapōlāʻau, or *Hemignathus wilsoni*) or species with large home ranges (e.g., wolverines, or *Gulo gulo luscus*). Crop diversification and seminatural habitats benefit biodiversity within agricultural landscapes (221,222), which is associated with improved agricultural yields, ecosystem resilience, and human well-being (221). Even on-farm practices matter: crop diversification was as effective as non-crop-diversification measures (e.g., natural areas, landscape heterogeneity) in managing pests (223). In contrast, landscapes with less than 5% native habitat that are dominated by intensive practices like tillage and pesticide use suffer significant losses in biodiversity (190,224). Nature-positive interventions are increasingly important with climate change, which may exacerbate environmental impacts of agricultural production (225).

Figure 8.6. Co-Benefits of Working Landscapes



Integrating ecological components into working agricultural landscapes can generate multiple benefits for both nature and people.

A working agricultural landscape is designed to integrate ecological components, providing resilience to climate change, biodiversity loss, and food insecurity. Native wildflowers support pollinators that enhance crop yields, riparian woodlands enhance water quality and reduce soil erosion, forest patched provide habitat for birds and bats that predate crop *pests, and diversified crops enhance soil fertility and biodiversity. Diversified agricultural systems can sustain productivity while supporting resilient ecosystems. Adapted from Peterson-Rockney et al., 2021* (226).

Because most working lands are privately owned, conservation incentive programs are crucial for engaging landowners. The widespread presence of farms and ranches that are not owner-operated poses a challenge for the broad adoption of nature-friendly practices, as absentee landownership complicates incentive structures (227). Furthermore, funding for the Conservation Reserve Program—the largest federal source of funding for conservation—has declined by over one-third in the past 15 years after reaching a peak of supporting nearly 37 million acres. This decline is largely due to fewer resources being offered for the program rather than to declining interest from farmers. Support for conservation by Tribal Nations is equally important; 80% of Tribal lands in the Great Plains remain intact grasslands, compared to 55% of total land in the region (195).

The National Audubon Society's Conservation Ranching Program is a land-based, market-connected initiative that conserves grasslands while supporting economic outcomes for rural communities. Ranchers voluntarily implement habitat management plans that promote regenerative grazing, control invasive species, and restore native vegetation. In return, they market beef and bison products under the Audubon Certified Bird-Friendly Land designation, signaling to consumers the use of sustainable practices through the Bird-Friendliness Index (BFI) (228). Since 2016, BFI scores across more than 100 ranches in the Great Plains, Upper Midwest, and West have increased by 8.4% annually and 76% overall.

Forests

Working forest landscapes include privately owned forests and public lands managed for multiple uses. These forests provide timber and other wood products, biomass fuel, non-timber forest products (e.g., medicinal plants such as ginseng in the Appalachians and noni in Hawai'i and American Sāmoa, as well as edible mushrooms and fruits), wildlife habitat, and opportunities for hunting, fishing, birdwatching, hiking, and other outdoor recreation (229–234). Of these benefits, timber production has the largest ecological impact, as logging and silviculture can change the structure and composition of forests, reduce habitat for old-growth forest specialist species, increase habitat fragmentation, and alter local hydrology (235–238). Working forests include both natural and planted forests (plantations) (239), although in the US only 11% of forests managed for timber production are planted (240), and more than 70% of those (i.e., 45 million acres) are located in the southeastern US (241). While private forests account for more than three-quarters of timber harvest in the US, public lands (e.g., National Forests, Bureau of Land Management forests) also produce timber (242).

LULC change and timber harvesting cleared an estimated 256 million acres of forest in US states from 1630 to the present, with the steepest declines in forest cover in the late 19th century (242). There was a net increase in forest cover from 754 million acres in 1910 to more than 765 million acres in 2022 (242,243), with reforestation outpacing an increase in timber harvest from the 1950s to 2000 (244). Over the last century, the geographic distribution of forests has changed across the US through processes including logging, urban growth, rural development, and reforestation (245,246). Notably, while forested area increased in the Northeast, Puerto Rico, and the US Virgin Islands through reforestation over the 20th century, forest area declined in the West, Texas, and Florida (247–249).

Working forests can be managed through practices that seek to optimize a range of objectives, including timber production, biodiversity, and carbon storage (245). Ecosystem-based management—a holistic approach to management that considers the entire forest ecosystem and its ecological and socioeconomic values (250,251)—and improved forest management—encompassing activities that seek to increase forest carbon stocks (252)—promote a mix of stand ages across the landscape to provide habitat for specialist species, retain dead and downed trees, maintain tree diversity, and increase carbon storage (253–255). Forest certification programs such as the Sustainable Forestry Initiative, the Forest Stewardship Council, and the American Tree Farm System provide forest managers and owners with recognition for meeting standards for sustainable management (245,256–260). However, in situations where the goal of improved forest management is to increase carbon storage, biodiversity co-benefits are not guaranteed: forest management practices that optimize for carbon storage by maximizing stand density may decrease abundance of some species (261), such as the federally endangered red-cockaded woodpecker (*Picoides borealis*) in the southeastern Coastal Plain (262), as well as overall bird biodiversity in riparian forests in California and northern hardwood–conifer forests in the Northeast (263,264).

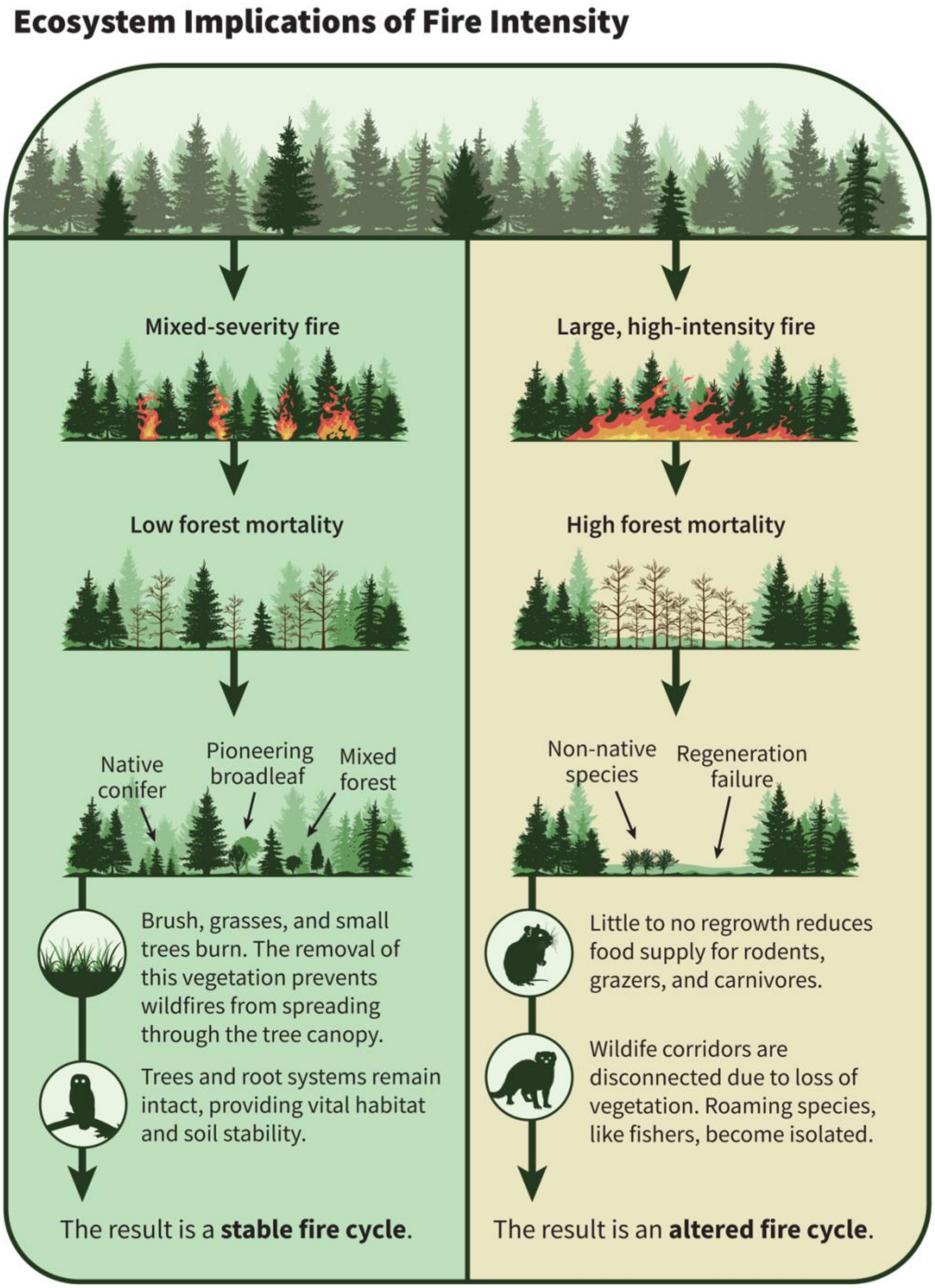
Despite efforts to promote sustainable management of working forests, forests across the US are changing in response to wildfire, insect and disease outbreaks, climate change, and harvesting (265,266). For example, insects and disease affected more than 7 million hectares of US forest each year from 1997 to 2013, with larger areas impacted in years with outbreak events (267). Native bark beetles (e.g., fir engraver [*Scolytus ventralis*], western pine beetle [*Dendroctonus brevicomis*], and spruce beetle [*Dendroctonus rufipennis*]) have caused large areas of tree mortality in forests of the western US and Alaska, while introduced species, including the hemlock woolly adelgid (*Adelges tsugae*), emerald ash borer (*Agrilus planipennis*), and spongy moth (*Lymantria dispar*) have affected forests in the East (267,268). The spread of fungi and pathogens has also caused tree mortality, including rapid ʻōhiʻa death in Hawaiʻi and Dutch elm disease in urban forests (268,269). As new forest pests are introduced each year and established species increase their ranges, the impacts of biotic disturbances are expected to increase (270).

On average, the area of forest in the western US experiencing wildfire each year has increased since the mid-1980s, as have high-severity fires (271–274). These trends appear to be accelerating: All regions of the contiguous US experienced more fire events post-2000 than during the period 1984–1999; fires in the western US were larger; and extreme fire activity increased in the West (275). Crucially, the proportion of forest area burned at high severity in the western US increased by a factor of 15 from 1985 to 2022 (276). Despite these increases in fire activity, all forest types in the contiguous US are still burning less frequently than they did prior to the late 1800s, when forest management shifted towards a policy of aggressive fire suppression (277). Changes to fire regimes have reshaped forest composition, structure, and functioning across the western US (Box 8.2) (278). Climate change, human development, and invasion by non-native grass species has also increased wildfire impacts on Hawaiʻi's forests (279), while wildfires driven by human ignitions and flammable grasses threaten forests in Guam and the Northern Mariana Islands (280,281). Changes in the frequency, severity, and duration of drought have also affected forests in the western US. While forests in the eastern US experienced wetter-than-average conditions over 2000–2021, western forests experienced record drought over the same period (282–284). Drought can directly cause tree mortality (285), and it can make surviving trees more susceptible to insect and pathogens (286–288) while increasing fuel aridity for wildfires (289).

Box 8.2 Western Forests

US wildfire management has focused on aggressive fire suppression for more than a century (290), dramatically reshaping forest structure, composition, and functioning across the western US (278). These shifts make forests more vulnerable to stressors such as drought, insect infestations, pathogens, and wildfire (291–293). By facilitating fuel accumulation, fire suppression paradoxically leads to higher-severity wildfires (294). As the frequency and extent of high-severity fires increases with climate change, some conifer forests are transitioning toward dominance by fire-adapted hardwoods, while in other locations forests are failing to regenerate, leading to ecological transformations to shrublands, meadows, and grasslands (295–297).

Figure 8.7. Ecosystem Implications of Fire Intensity



Brush, grasses, and small trees burn. The removal of this vegetation prevents wildfires from spreading through the tree canopy.

Trees and root systems remain intact, providing vital habitat and soil stability.

The result is a **stable fire cycle**.

Little to no regrowth reduces food supply for rodents, grazers, and carnivores.

Wildife corridors are disconnected due to loss of vegetation. Roaming species, like fishers, become isolated.

The result is an **altered fire cycle**.

Mixed- versus high-severity fires reshape forests in very different ways, with implications for tree regeneration, wildlife, ecosystems, and carbon emissions.

Climate change is leading to more, and more frequent, fires of high severity. High-severity fires alter the otherwise stable fire cycle, causing additional, less predictable damage to wildlife and the ecosystem, including high tree mortality, establishment by non-native species, and regeneration failure. Mixed-severity fire cycles are stable, resulting in low tree mortality, native tree persistence and regeneration, and support for wildlife. At a large scale, high-severity fires can be very damaging to wildlife and the ecosystem. Adapted from Zhao et al. 2024 (298) *(CC-BY-4.0) and USFWS 2022* (299).

Changes to fire regimes in western forests have diverse ecological impacts. Whereas mixed-severity fires may promote biodiversity (300), high-severity fires can negatively impact wildlife habitat and plant species such as the iconic, declining giant sequoia (*Sequoiadendron giganteum*) (301,302). Habitat degradation from fire suppression and changing fire regimes impacts local hydrology and water resources (303,304) and has contributed to the decline of over half of western forest bird species (305–307). Increases in the frequency and extent of high-severity fire also threaten carbon storage by releasing carbon stored in aboveground biomass (308,309).

Changing fire regimes also have stark social and health consequences, including loss of human lives and property and increased exposure to hazardous air and water quality (310–312), as well as potential economic losses for the timber industry and investors in forest carbon markets (233,313). Annual costs can reach over a hundred billion dollars annually (314).

Despite the challenges posed for fire management in the western US, there are bright spots. Management practices such as prescribed fire and mechanical thinning can reduce the risk of high-severity wildfire (315), and advances in remote sensing and machine learning tools enable more-targeted interventions (316,317). Critically, Indigenous groups are working to bring cultural burning practices back to western forests (318,319), conserving biocultural diversity and supporting Indigenous sovereignty (320,321) while increasing resilience to drought and wildfire.

[BOX 8.2 ENDS HERE]

Renewable Energy and Other Land Uses

Renewable energy in the US continues to show rapid growth, with solar and wind leading the expansion and accounting for most newly installed capacity in recent years (48). The large spatial footprint of renewable energy may involve trade-offs among the competing priorities of decarbonization, protecting natural habitats, preserving productive croplands and rangelands, and benefitting communities.

Land-saving approaches and technology implementation strategies that include input from all relevant government agencies, landholders, and local communities can mitigate some of the challenges related to large-scale implementation of renewable energy. For example, the co-location of wind and solar projects minimizes habitat disturbance. In the Bureau of

Land Management's updated Western Solar Plan, more than 31 million acres of public land were identified as suitable for solar development through an approach that prioritizes areas near transmission lines or on previously disturbed lands while excluding sensitive areas like critical wildlife habitats and cultural resources (322).

Agrivoltaic systems co-locate agriculture and solar technologies on the same land to preserve croplands and rangelands while producing energy, thereby improving efficiencies in land and water use and energy generation (323). Agrivoltaic systems reduce the need to convert additional land solely for solar energy production and therefore reduce the competition between energy generation and food production. There is growing evidence that agrivoltaic systems provide additional benefits, including the establishment of native plants, soil carbon sequestration, and erosion control (324).

Urban Greenspace and Green Infrastructure

Urban green spaces and associated **green infrastructure** are essential components of landscapes in human-dominated areas, providing habitat, climate regulation, and air and water filtration, in addition to enhancing human well-being (Ch. 13: Health and Well-Being). In the US, current trends reveal both increasing recognition of these contributions and persistent structural gaps in implementation and equity.

National assessments indicate that urban green space in the US follows divergent trajectories—expanding in some metropolitan areas through targeted greening initiatives while declining overall in the extent of tree canopy. Analyses of high-resolution imagery revealed a net annual loss of approximately 175,000 acres of urban tree cover, equivalent to roughly 36 million trees per year (325). This decline has continued in several regions, particularly in fast-growing metropolitan areas of the South and Great Plains where development pressures are highest, and where drought, heat, pests, and storm damage have contributed to sustained canopy loss (326). Local trends vary substantially across cities: some metropolitan areas report pockets of stability or modest gains associated with sustained greening programs, while others continue to experience net declines when redevelopment and disturbance outpace new plantings.

Persistent distributional inequities compound these trends. Urban neighborhoods with a majority of people of color have, on average, 11% less tree canopy and 14% more impervious surface than predominantly white neighborhoods (327). Low-income blocks also experience higher surface temperatures and lower vegetation density (328) than higher-income neighborhoods. These patterns highlight overall decline as well as uneven urban green space trajectories: progress in some cities and neighborhoods is offset by losses in others.

Urban green space and green infrastructure in the US are increasingly assessed not only by their extent but by their capacity to deliver multiple ecosystem functions under changing climate conditions. Empirical studies demonstrate that vegetation structure and composition strongly influence local microclimate regulation, water retention, and biodiversity. For example, urban canopy cover can substantially reduce land-surface temperatures during extreme heat events (329), while infrastructure such as bioswales and green roofs substantially decrease stormwater runoff and pollution loads (330). Moreover, the selection of tree species for urban canopy plantings is critical, given that some species emit high levels of volatile organic compounds or produce high pollen volumes, further exacerbating human health conditions such as asthma or respiratory distress (331).

Recent assessments of the functional performance of urban green space and green infrastructure emphasize their multifunctionality, meaning their ability to simultaneously deliver hydrological, ecological, and social co-benefits (332). Integrated assessments of urban green infrastructure reveal that multifunctional performance peaks when green infrastructure networks are spatially connected and embedded within broader ecological corridors (333). However, most municipal monitoring programs still rely on single indicators, such as canopy cover or green acreage, without evaluating co-benefits or resilience under climate stress. Establishing standardized indicators of ecological function, maintenance intensity, and adaptive capacity will be critical for linking green infrastructure investments with measurable outcomes.

Description of Evidence Base

The finding that many terrestrial ecosystems in human-dominated landscapes, such as urban greenspaces and agricultural lands, are critical for biodiversity habitat, air and water filtration, adaptation to and mitigation of climate change, and human well-being is *very well established*, based on hundreds of published studies of field observations and experiments across a wide range of working landscape types and locations that show consistent patterns. The assessment that effective management in these landscapes has the potential to restore nature so that it can equitably provide a range of social and ecological co-benefits is *well established*, based on a growing but limited number of published studies of direct measurements of ecological and social benefits of these landscapes.

Environmental Justice and Equity Highlights

This review of status and trends in terrestrial ecosystems reveals patterns of environmental disparities in land-use and land-cover change, and in responsive conservation and restoration actions, including instances of inequitable exposure among demographic groups. For example, trends in tree canopy cover in urban landscapes show that some cities with strong green protection ordinances or large-scale planting campaigns (e.g., Atlanta, New York, Baltimore) show localized canopy gains, while other cities continue to experience net losses in tree canopy cover.

Landscape conservation and restoration trends also show disparities in distribution. Despite the emphasis of international restoration goals on equitable restoration, traditional ecological knowledge, and BIPOC (Black, Indigenous, and People of Color)-led restoration

(334), social responses to restoration, BIPOC knowledge, and the socioecological dynamics of restoration are rarely incorporated (335–338). This lack of focus likely reduces restoration efficacy and means those communities most vulnerable to the impacts of ailing ecosystems are not reaping the benefits of ecosystem repair.

Emerging Issues

Several emerging issues would benefit from additional attention in research, practice, or policy. First, the recognition of nature as a valuable asset to business operations has led to the development of frameworks to support market-driven, nature-based solutions, which are expected to influence future patterns of LULC change. For example, the Task Force on Nature-Based Financial Disclosures will provide guidance and metrics for reporting on how organizational activities affect the status of nature (339). Second, the proliferation of artificial intelligence and machine learning tools for quantifying and monitoring ecosystem status will provide greater real-time access to information from global to local scales. Ongoing efforts ensure that the data is both FAIR (findable, accessible, interoperable, and reusable) (340) and CARE (collective benefit, authority to control, responsibility, and ethics) (170), by involving Indigenous communities in decision-making about how data is collected, used, and shared; recognizing their sovereignty over data; and ensuring benefits from data use flow back to the communities environmental stewardship (162). Third, there is increasing recognition of the critical importance of the deep knowledge held by local communities and Indigenous Peoples related to ecosystem status and change. Projects that privilege such understanding produce more enduring conservation and restoration outcomes for both nature and people. Fourth, the implementation of renewable energy production has increased dramatically over the past decade. Further attention to research, planning, and policy would help decision-makers understand and quantify the co-benefits of renewable energy production related to enhancing biodiversity conservation, reducing water use, and improving soil health. Fifth, climate change is accelerating, increasing the need for adaptive solutions. Translocations to suitable future habitats require consideration of potential impacts to both the relocated species and the receiving ecosystem, as well as long-term monitoring and possible changes in management tactics. Sixth, nature-based solutions (NBS) are increasingly deployed across terrestrial systems, yet their long-term effectiveness cannot be assumed. Ensuring that expanding NBS investments translate into sustained ecological function and climate risk reduction requires explicit evaluation of their long-term ecological dynamics under ongoing environmental change.

References

1. United States Geological Survey. Protected Areas Database of the United States (PAD-US) 4 [Internet]. U.S. Geological Survey; 2024 [2025 Nov 17]. https://doi.org/10.5066/P96WBCHS

2. Dale VH. The Relationship Between Land-Use Change and Climate Change. Ecol Appl. 1997 Aug;7(3):753–69. https://doi.org/10.1890/1051-0761(1997)007%255B0753:TRBLUC%255D2.0.CO;2

3. Li L, Awada T, Zhang Y, Paustian K. Global Land Use Change and Its Impact on Greenhouse Gas Emissions. Glob Change Biol. 2024 Dec;30(12):e17604. https://doi.org/10.1111/gcb.17604

4. Whyte K. Settler Colonialism, Ecology, and Environmental Injustice. Environ Soc. 2018;9:125–44.

5. Singleton MP, Thode AE, Sánchez Meador AJ, Iniguez JM. Increasing trends in high-severity fire in the southwestern USA from 1984 to 2015. For Ecol Manag. 2019 Feb;433:709–19. https://doi.org/10.1016/j.foreco.2018.11.039

6. Tyukavina A, Potapov P, Hansen MC, Pickens AH, Stehman SV, Turubanova S, et al. Global Trends of Forest Loss Due to Fire From 2001 to 2019. Front Remote Sens. 2022 Mar 15;3:825190. https://doi.org/10.3389/frsen.2022.825190

7. Cunningham CX, Williamson GJ, Bowman DMJS. Increasing frequency and intensity of the most extreme wildfires on Earth. Nat Ecol Evol. 2024 Jun 24;8(8):1420–5. https://doi.org/10.1038/s41559-024-02452-2

8. Davis KT, Higuera PE, Dobrowski SZ, Parks SA, Abatzoglou JT, Rother MT, et al. Fire-catalyzed vegetation shifts in ponderosa pine and Douglas-fir forests of the western United States. Environ Res Lett. 2020 Oct 1;15(10):1040b8. https://doi.org/10.1088/1748-9326/abb9df

9. Ellison AM, Orwig DA, Fitzpatrick MC, Preisser EL. The Past, Present, and Future of the Hemlock Woolly Adelgid (Adelges tsugae) and Its Ecological Interactions with Eastern Hemlock (Tsuga canadensis) Forests. Insects. 2018 Dec;9(4):172. https://doi.org/10.3390/insects9040172

10. Smith JT, Allred BW, Boyd CS, Davies KW, Kleinhesselink AR, Morford SL, et al. Fire needs annual grasses more than annual grasses need fire. Biol Conserv. 2023 Oct;286:110299. https://doi.org/10.1016/j.biocon.2023.110299

11. Dietze MC, Moorcroft PR. Tree mortality in the eastern and central United States: patterns and drivers. Glob Change Biol. 2011 Nov;17(11):3312–26. https://doi.org/10.1111/j.1365-2486.2011.02477.x

12. Shelton AL, Henning JA, Schultz P, Clay K. Effects of abundant white-tailed deer on vegetation, animals, mycorrhizal fungi, and soils. For Ecol Manag. 2014 May;320:39–49. https://doi.org/10.1016/j.foreco.2014.02.026

13. Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, et al. Global Consequences of Land Use. Science. 2005 Jul 22;309(5734):570–4. https://doi.org/10.1126/science.1111772

14. McKinney ML. Urbanization as a major cause of biotic homogenization. Biol Conserv. 2006 Jan 1;127(3):247–60. https://doi.org/10.1016/j.biocon.2005.09.005

15. Li X, Tian H, Lu C, Pan S. Four-century history of land transformation by humans in the United States (1630–2020): annual and 1 km grid data for the HIStory of LAND changes (HISLAND-US). Earth Syst Sci Data. 2023 Mar 3;15(2):1005–35. https://doi.org/10.5194/essd-15-1005-2023

16. Haddad NM, Brudvig LA, Clobert J, Davies KF, Gonzalez A, Holt RD, et al. Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci Adv. 2015 Mar 20;1(2):e1500052. https://doi.org/10.1126/sciadv.1500052

17. U.S. Geological Survey. LCMAP Land Cover and Land Change Conterminous U.S. Collection 1.3 [Internet]. U.S. Geological Survey; 2024 [2025 Dec 12]. https://doi.org/10.5066/P9C46NG0

18. Hansen AJ, Mullan K, Theobald DM, Powell S, Robinson N, East A. Natural vegetation cover on private lands: locations and risk of loss in the northwestern United States. Ecosphere. 2021;12(10):e03756. https://doi.org/10.1002/ecs2.3756

19. Pengra B, Stehman V S, Horton A J, Auch RF, Kambly S, Taylor J. LCMAP Hawaii Reference Data Product land cover, land use and change process attributes [Internet]. U.S. Geological Survey; 2021 [2025 Dec 12]. https://doi.org/10.5066/P9X42T97

20. LCMAP Change Stories | U.S. Geological Survey [Internet]. [2026 Jan 29]. https://www.usgs.gov/special-topics/lcmap/lcmap-change-stories

21. Stehfest E, van Zeist WJ, Valin H, Havlik P, Popp A, Kyle P, et al. Key determinants of global land-use projections. Nat Commun. 2019 May 15;10(1):2166. https://doi.org/10.1038/s41467-019-09945-w

22. Alig R. Urbanization in the US: land use trends, impacts on forest area, projections, and policy considerations. J Resour Energy Dev 72 35-60. 2010;7:35–60.

23. Alig RJ, Plantinga AJ, Ahn S, Kline JD. Land use changes involving forestry in the United States: 1952 to 1997, with projections to 2050. Gen Tech Rep PNW-GTR-587 Portland US Dep Agric For Serv Pac Northwest Res Stn 92 P [Internet]. 2003 [2025 Oct 2];587. https://doi.org/10.2737/PNW-GTR-587

24. Li X, Zhou Y, Eom J, Yu S, Asrar GR. Projecting Global Urban Area Growth Through 2100 Based on Historical Time Series Data and Future Shared Socioeconomic Pathways. Earths Future. 2019;7(4):351–62. https://doi.org/10.1029/2019EF001152

25. Chen G, Li X, Liu X, Chen Y, Liang X, Leng J, et al. Global projections of future urban land expansion under shared socioeconomic pathways. Nat Commun. 2020 Jan 27;11(1):537. https://doi.org/10.1038/s41467-020-14386-x

26. Barnes KW, Niemuth ND, Iovanna R. Landscape-scale predictions of future grassland conversion to cropland or development. Conserv Biol. 2025;39(1):e14346. https://doi.org/10.1111/cobi.14346

27. Schreiner-McGraw AP, Vivoni ER, Ajami H, Sala OE, Throop HL, Peters DPC. Woody Plant Encroachment has a Larger Impact than Climate Change on Dryland Water Budgets. Sci Rep. 2020 May 15;10(1):8112. https://doi.org/10.1038/s41598-020-65094-x

28. Shriver RK, Pletcher E, Biondi F, Urza AK, Weisberg PJ. Long-term tree population growth can predict woody encroachment patterns. Proc Natl Acad Sci. 2025 May 6;122(18):e2424096122. https://doi.org/10.1073/pnas.2424096122

29. Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, et al. No saturation in the accumulation of alien species worldwide. Nat Commun. 2017 Feb 15;8(1):14435. https://doi.org/10.1038/ncomms14435

30. Simpson A, Eyler MC, Guala F, Cannister MJ, Kozlowsky N, Libby R, et al. A comprehensive list of non-native species established in three major regions of the United States: Version 3.0 | U.S. Geological Survey [Internet]. 2019 [2025 Sep 25]. https://www.usgs.gov/data/a-comprehensive-list-non-native-species-established-three-major-regions-united-states-version

31. Mahood AL, Balch JK. Repeated fires reduce plant diversity in low-elevation Wyoming big sagebrush ecosystems (1984–2014). Ecosphere. 2019;10(2):e02591. https://doi.org/10.1002/ecs2.2591

32. Pilliod DS, Welty JL, Arkle RS. Refining the cheatgrass–fire cycle in the Great Basin: Precipitation timing and fine fuel composition predict wildfire trends. Ecol Evol. 2017;7(19):8126–51. https://doi.org/10.1002/ece3.3414

33. Cheng TL, Reichard JD, Coleman JTH, Weller TJ, Thogmartin WE, Reichert BE, et al. The scope and severity of white-nose syndrome on hibernating bats in North America. Conserv Biol. 2021 Oct;35(5):1586–97. https://doi.org/10.1111/cobi.13739

34. Hoyt JR, Kilpatrick AM, Langwig KE. Ecology and impacts of white-nose syndrome on bats. Nat Rev Microbiol. 2021 Mar;19(3):196–210. https://doi.org/10.1038/s41579-020-00493-5

35. Frank EG. The economic impacts of ecosystem disruptions: Costs from substituting biological pest control. Science. 2024 Sep 6;385(6713):eadg0344. https://doi.org/10.1126/science.adg0344

36. Hansen AJ, Noble BP, Veneros J, East A, Goetz SJ, Supples C, et al. Toward monitoring forest ecosystem integrity within the post-2020 Global Biodiversity Framework. Conserv Lett. 2021 Jul;14(4):e12822. https://doi.org/10.1111/conl.12822

37. Parrish JD, Braun DP, Unnasch RS. Are We Conserving What We Say We Are? Measuring Ecological Integrity within Protected Areas. BioScience. 2003 Sep 1;53(9):851–60. https://doi.org/10.1641/0006-3568(2003)053%255B0851:AWCWWS%255D2.0.CO;2

38. Wurtzebach Z, Schultz C. Measuring Ecological Integrity: History, Practical Applications, and Research Opportunities. BioScience. 2016 Jun 1;66(6):446–57. https://doi.org/10.1093/biosci/biw037

39. Nowacki GJ, Abrams MD. The Demise of Fire and “Mesophication” of Forests in the Eastern United States. BioScience. 2008 Feb 1;58(2):123–38. https://doi.org/10.1641/B580207

40. Power MJ, Codding BF, Taylor AH, Swetnam TW, Magargal KE, Bird DW, et al. Human fire legacies on ecological landscapes. Front Earth Sci. 2018;6:151.

41. Ryan KC, Knapp EE, Varner JM. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Front Ecol Environ. 2013;11(s1):e15–24. https://doi.org/10.1890/120329

42. Lamica A, Parajuli R, Brandeis C. Evaluating hurricane impacts on timber Markets in the Southeastern United States: A case of hurricane Michael. For Policy Econ. 2025 Sep;178:103590. https://doi.org/10.1016/j.forpol.2025.103590

43. Intergovernmental Panel On Climate Change (Ipcc). Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Internet]. 1st ed. Cambridge University Press; 2023 [2025 Oct 29]. https://doi.org/10.1017/9781009157896

44. Sharma A, Kumar V, Shahzad B, Tanveer M, Sidhu GPS, Handa N, et al. Worldwide pesticide usage and its impacts on ecosystem. SN Appl Sci. 2019 Nov;1(11):1446. https://doi.org/10.1007/s42452-019-1485-1

45. Bamal D, Duhan A, Pal A, Beniwal RK, Kumawat P, Dhanda S, et al. Herbicide risks to non-target species and the environment: A review. Environ Chem Lett. 2024 Dec;22(6):2977–3032. https://doi.org/10.1007/s10311-024-01773-9

46. Townsend AR, Howarth RW, Bazzaz FA, Booth MS, Cleveland CC, Collinge SK, et al. Human health effects of a changing global nitrogen cycle. Front Ecol Environ. 2003 Jun;1(5):240–6. https://doi.org/10.1890/1540-9295(2003)001%255B0240:HHEOAC%255D2.0.CO;2

47. Tison L, Beaumelle L, Monceau K, Thiéry D. Transfer and bioaccumulation of pesticides in terrestrial arthropods and food webs: State of knowledge and perspectives for research. Chemosphere. 2024 Jun;357:142036. https://doi.org/10.1016/j.chemosphere.2024.142036

48. Energy Information Administration (EIA). Annual Energy Outlook 2023 [Internet]. Energy Information Administration (EIA); 2023 [2025 Oct 27]. https://www.eia.gov/outlooks/aeo/

49. Thakrar SK, Balasubramanian S, Adams PJ, Azevedo IML, Muller NZ, Pandis SN, et al. Reducing Mortality from Air Pollution in the United States by Targeting Specific Emission Sources. Environ Sci Technol Lett. 2020 Sep 8;7(9):639–45. https://doi.org/10.1021/acs.estlett.0c00424

50. AghaKouchak A, Huning LS, Sadegh M, Qin Y, Markonis Y, Vahedifard F, et al. Toward impact-based monitoring of drought and its cascading hazards. Nat Rev Earth Environ. 2023 Aug;4(8):582–95. https://doi.org/10.1038/s43017-023-00457-2

51. Higuera PE, Abatzoglou JT. Record-setting climate enabled the extraordinary 2020 fire season in the western United States. Glob Change Biol. 2021;27(1):1–2. https://doi.org/10.1111/gcb.15388

52. Marvel K, Su W, Delgado R, Aarons S, Chatterjee A, Garcia ME, et al. Chapter 2 : Climate Trends. Fifth National Climate Assessment [Internet]. U.S. Global Change Research Program; 2023 [2025 Oct 30]. https://doi.org/10.7930/NCA5.2023.CH2

53. Ostoja SM, Crimmins AR, Byron RG, East AE, Méndez M, O’Neill SM, et al. Focus on ii : Focus on Western Wildfires. Fifth National Climate Assessment [Internet]. U.S. Global Change Research Program; 2023 [2025 Oct 30]. https://doi.org/10.7930/NCA5.2023.F2

54. Williams AP, Seager R, Macalady AK, Berkelhammer M, Crimmins MA, Swetnam TW, et al. Correlations between components of the water balance and burned area reveal

new insights for predicting forest fire area in the southwest United States. Int J Wildland Fire. 2014 Nov 13;24(1):14–26. https://doi.org/10.1071/WF14023

55. Crimmins AR (editor), Avery CW (editor), Easterling DR, Kunkel KE (editor), Stewart BC (editor), Maycock TK (editor). Fifth National Climate Assessment [Internet]. U.S. Global Change Research Program.; 2023 [2025 Oct 30]. https://doi.org/10.7930/NCA5.2023

56. Bentz BJ, Régnière J, Fettig CJ, Hansen EM, Hayes JL, Hicke JA, et al. Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. BioScience. 2010 Sep 1;60(8):602–13. https://doi.org/10.1525/bio.2010.60.8.6

57. Lehmann J, Bossio DA, Kögel-Knabner I, Rillig MC. The concept and future prospects of soil health. Nat Rev Earth Environ [Internet]. 2020 Aug 25; https://doi.org/10.1038/s43017-020-0080-8

58. Gely C, Laurance SGW, Stork NE. How do herbivorous insects respond to drought stress in trees? Biol Rev. 2020 Apr;95(2):434–48. https://doi.org/10.1111/brv.12571

59. Kolb TE, Fettig CJ, Ayres MP, Bentz BJ, Hicke JA, Mathiasen R, et al. Observed and anticipated impacts of drought on forest insects and diseases in the United States. For Ecol Manag. 2016 Nov;380:321–34. https://doi.org/10.1016/j.foreco.2016.04.051

60. Parks SA, Abatzoglou JT. Warmer and Drier Fire Seasons Contribute to Increases in Area Burned at High Severity in Western US Forests From 1985 to 2017. Geophys Res Lett. 2020 Nov 28;47(22):e2020GL089858. https://doi.org/10.1029/2020GL089858

61. Littell JS, Peterson DL, Riley KL, Liu Y, Luce CH. A review of the relationships between drought and forest fire in the United States. Glob Change Biol. 2016 Jul;22(7):2353–69. https://doi.org/10.1111/gcb.13275

62. McElwee PD, Carter SL, Hyde KJW, West JM, Akamani K, Babson AL, et al. Chapter 8 : Ecosystems, Ecosystem Services, and Biodiversity. Fifth National Climate Assessment [Internet]. U.S. Global Change Research Program; 2023 [2024 Oct 22]. https://doi.org/10.7930/NCA5.2023.CH8

63. Singh D, Crimmins AR, Pflug JM, Barnard PL, Helgeson JF, Hoell A, et al. Focus on i : Focus on Compound Events. Fifth National Climate Assessment [Internet]. U.S. Global Change Research Program; 2023 [2025 Oct 30]. https://doi.org/10.7930/NCA5.2023.F1

64. Krawchuk MA, Meigs GW, Cartwright JM, Coop JD, Davis R, Holz A, et al. Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks. Front Ecol Environ. 2020 Jun;18(5):235–44. https://doi.org/10.1002/fee.2190

65. Bradley D, Caughman AM, Fogg SA, Cabral RB, Mayorga J, Goodell W, et al. Marine Fish Movement: home range sizes for commercially relevant species. Sci Data. 2024 Aug 10;11:865. https://doi.org/10.1038/s41597-024-03728-9

66. Mamantov MA, Gibson-Reinemer DK, Linck EB, Sheldon KS. Climate-driven range shifts of montane species vary with elevation. Lenoir J, editor. Glob Ecol Biogeogr. 2021 Apr;30(4):784–94. https://doi.org/10.1111/geb.13246

67. Rubenstein MA, Weiskopf SR, Bertrand R, Carter SL, Comte L, Eaton MJ, et al. Climate change and the global redistribution of biodiversity: substantial variation in empirical support for expected range shifts. Environ Evid. 2023 Apr 11;12(1):7. https://doi.org/10.1186/s13750-023-00296-0

68. Pörtner HO, Scholes RJ, Agard J, Archer E, Arneth A, Bai X, et al. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change [Internet]. Zenodo; 2021 Jun [2024 Dec 18]. https://doi.org/10.5281/zenodo.5101125

69. Wason JW, Bevilacqua E, Dovciak M. Climates on the move: Implications of climate warming for species distributions in mountains of the northeastern United States. Agric For Meteorol. 2017 Nov;246:272–80. https://doi.org/10.1016/j.agrformet.2017.05.019

70. May CL, Osler MS, Stockdon HF, Barnard PL, Callahan JA, Collini RC, et al. Chapter 9 : Coastal Effects. Fifth National Climate Assessment [Internet]. U.S. Global Change Research Program; 2023 [2025 Nov 17]. https://doi.org/10.7930/NCA5.2023.CH9

71. US EPA O. Climate Change Indicators: Great Lakes Water Levels and Temperatures [Internet]. 2016 [2025 Oct 30]. https://www.epa.gov/climate-indicators/great-lakes

72. Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK, et al. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Internet]. 2017 [2025 Oct 30]. https://doi.org/10.7930/NCA4.2018

73. Jiguet F, Julliard R, Thomas CD, Dehorter O, Newson SE, Couvet D. Thermal range predicts bird population resilience to extreme high temperatures. Ecol Lett. 2006 Dec;9(12):1321–30. https://doi.org/10.1111/j.1461-0248.2006.00986.x

74. Ceballos G, Ehrlich PR. Mutilation of the tree of life via mass extinction of animal genera. Proc Natl Acad Sci. 2023 Sep 26;120(39):e2306987120. https://doi.org/10.1073/pnas.2306987120

75. Cowie RH, Bouchet P, Fontaine B. The Sixth Mass Extinction: fact, fiction or speculation? Biol Rev. 2022 Apr;97(2):640–63. https://doi.org/10.1111/brv.12816

76. IUCN Red List of Threatened Species [Internet]. 2025 [2025 Oct 27]. The IUCN Red List of Threatened Species. https://www.iucnredlist.org/en

77. ZSL (Zoological Society of London) Institute of Zoology. WWF Living Planet Report 2024 A system in peril. 1. unveränderte engl.-sprachige Gesamtausgabe 2024. Berlin WWF Deutschland 2024; 2024.

78. NatureServe. Biodiversity in Focus: United States Edition. Arlington, VA; 2023.

79. NatureServe. Biodiversity in Focus: United Stated Edition. Arlington, VA: NatureServe; 2023.

80. Rosenberg KV, Dokter AM, Blancher PJ, Sauer JR, Smith AC, Smith PA, et al. Decline of the North American avifauna. Science. 2019;366(6461):120–4.

81. The State of the Birds in the U.S.A. [Internet]. State of the Birds 2025. 2025 [2025 Oct 30]. https://www.stateofthebirds.org/2025/state-of-the-birds-usa/

82. Boyer AG. Extinction patterns in the avifauna of the Hawaiian islands. Divers Distrib. 2008 May;14(3):509–17. https://doi.org/10.1111/j.1472-4642.2007.00459.x

83. Hunt NJ, Crampton LH, Winter TA, Alexander JD, Gilb R, Camp RJ. Disease-driven collapse of the native Kauaʻi avifauna and the rise of introduced bird species. Biodivers Conserv. 2025 Aug;34(10):3511–33. https://doi.org/10.1007/s10531-025-03111-z

84. Medd A, Martin AE, Smith AC, Fahrig L. Continental declines in North American small mammal populations. Biol Conserv. 2025 Jun;306:111109. https://doi.org/10.1016/j.biocon.2025.111109

85. Adams AM, Trujillo LA, Campbell CJ, Akre KL, Arroyo-Cabrales J, Burns L, et al. The state of the bats in North America. Ann N Y Acad Sci. 2024 Nov;1541(1):115–28. https://doi.org/10.1111/nyas.15225

86. Frick WF, Puechmaille SJ, Hoyt JR, Nickel BA, Langwig KE, Foster JT, et al. Disease alters macroecological patterns of N orth A merican bats. Glob Ecol Biogeogr. 2015 Jul;24(7):741–9. https://doi.org/10.1111/geb.12290

87. Hornseth ML, Walpole AA, Walton LR, Bowman J, Ray JC, Fortin MJ, et al. Habitat Loss, Not Fragmentation, Drives Occurrence Patterns of Canada Lynx at the Southern Range Periphery. Fenton B, editor. PLoS ONE. 2014 Nov 17;9(11):e113511. https://doi.org/10.1371/journal.pone.0113511

88. Smith AT, Millar CI, White ER. Fifty-year population trajectory in a marginal American Pika (*Ochotona princeps*) population. Frey J, editor. J Mammal. 2024 Nov 23;105(6):1418–29. https://doi.org/10.1093/jmammal/gyae083

89. Schipper J, Chanson JS, Chiozza F, Cox NA, Hoffmann M, Katariya V, et al. The Status of the World's Land and Marine Mammals: Diversity, Threat, and Knowledge. Science. 2008 Oct 10;322(5899):225–30. https://doi.org/10.1126/science.1165115

90. Ceballos G, Ehrlich PR, Dirzo R. Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. Proc Natl Acad Sci [Internet]. 2017 Jul 25 [2025 Dec 22];114(30). https://doi.org/10.1073/pnas.1704949114

91. Stanford CB, Iverson JB, Rhodin AGJ, Paul Van Dijk P, Mittermeier RA, Kuchling G, et al. Turtles and Tortoises Are in Trouble. Curr Biol. 2020 Jun;30(12):R721–35. https://doi.org/10.1016/j.cub.2020.04.088

92. Lovich JE, Ennen JR, Agha M, Gibbons JW. Where Have All the Turtles Gone, and Why Does It Matter? BioScience. 2018 Oct 1;68(10):771–81. https://doi.org/10.1093/biosci/biy095

93. Allender MC, Raudabaugh DB, Gleason FH, Miller AN. The natural history, ecology, and epidemiology of Ophidiomyces ophiodiicola and its potential impact on free-ranging snake populations. Fungal Ecol. 2015 Oct;17:187–96. https://doi.org/10.1016/j.funeco.2015.05.003

94. Gibbon JW, Scott DE, Ryan TJ, Buhlmann KA, Tuberville TD, Metts BS, et al. The Global Decline of Reptiles, Déjà Vu Amphibians. BioScience. 2000;50(8):653. https://doi.org/10.1641/0006-3568(2000)050%255B0653:TGDORD%255D2.0.CO;2

95. Hoffmann M, Hilton-Taylor C, Angulo A, Böhm M, Brooks TM, Butchart SHM, et al. The Impact of Conservation on the Status of the World's Vertebrates. Science. 2010 Dec 10;330(6010):1503–9. https://doi.org/10.1126/science.1194442

96. Iucn Ssc ASG. Draft for Open Consultation. The Amphibian Conservation Action Plan (ACAP): A status review and roadmap for global amphibian conservation. [Internet]. 2022 [2025 Dec 15]. https://doi.org/10.32942/OSF.IO/BRFAS

97. González-del-Pliego P, Freckleton RP, Edwards DP, Koo MS, Scheffers BR, Pyron RA, et al. Phylogenetic and Trait-Based Prediction of Extinction Risk for Data-Deficient Amphibians. Curr Biol. 2019 May;29(9):1557-1563.e3. https://doi.org/10.1016/j.cub.2019.04.005

98. USGS ARMI Ecosystems Mission Area, Species Management Research Program. USGS ARMI. [2025 Dec 22]. The State of Amphibians in the United States. https://armi.usgs.gov/sota/

99. Waddle JH, Grear DA, Mosher BA, Grant EHC, Adams MJ, Backlin AR, et al. Batrachochytrium salamandrivorans (Bsal) not detected in an intensive survey of wild

North American amphibians. Sci Rep. 2020 Aug 3;10(1):13012. https://doi.org/10.1038/s41598-020-69486-x

100. FWS-Listed U.S. Species by Taxonomic Group - Amphibians [Internet]. [2026 Jan 29]. https://ecos.fws.gov/ecp/report/species-listings-by-tax-group?statusCategory=Listed&groupName=Amphibians&total=44

101. Wagner DL, Grames EM, Forister ML, Berenbaum MR, Stopak D. Insect decline in the Anthropocene: Death by a thousand cuts. Proc Natl Acad Sci. 2021;118(2):e2023989118. https://doi.org/10.1073/pnas.2023989118

102. Van Klink R, Bowler DE, Gongalsky KB, Shen M, Swengel SR, Chase JM. Disproportionate declines of formerly abundant species underlie insect loss. Nature. 2024 Apr 11;628(8007):359–64. https://doi.org/10.1038/s41586-023-06861-4

103. Rohr JR, Mahan CG, Kim KC. Response of arthropod biodiversity to foundation species declines: The case of the eastern hemlock. For Ecol Manag. 2009 Sep;258(7):1503–10. https://doi.org/10.1016/j.foreco.2009.07.002

104. Gandhi KJK, Herms DA. North American arthropods at risk due to widespread Fraxinus mortality caused by the Alien Emerald ash borer. Biol Invasions. 2010 Jun 1;12(6):1839–46. https://doi.org/10.1007/s10530-009-9594-1

105. Edwards CB, Zipkin EF, Henry EH, Haddad NM, Forister ML, Burls KJ, et al. Rapid butterfly declines across the United States during the 21st century. Science. 2025 Mar 7;387(6738):1090–4. https://doi.org/10.1126/science.adp4671

106. Pleasants JM, Oberhauser KS. Milkweed loss in agricultural fields because of herbicide use: effect on the monarch butterfly population. Insect Conserv Divers. 2013;6(2):135–44. https://doi.org/10.1111/j.1752-4598.2012.00196.x

107. Pleasants J. Milkweed restoration in the Midwest for monarch butterfly recovery: estimates of milkweeds lost, milkweeds remaining and milkweeds that must be added to increase the monarch population. Insect Conserv Divers. 2017;10(1):42–53. https://doi.org/10.1111/icad.12198

108. Semmens BX, Semmens DJ, Thogmartin WE, Wiederholt R, López-Hoffman L, Diffendorfer JE, et al. Quasi-extinction risk and population targets for the eastern, migratory population of monarch butterflies (Danaus plexippus). Sci Rep. 2016 Mar 21;6:23265. https://doi.org/10.1038/srep23265

109. Thogmartin WE, López-Hoffman L, Rohweder J, Diffendorfer J, Drum R, Semmens D, et al. Restoring monarch butterfly habitat in the Midwestern US: ‘all hands on deck.’ Environ Res Lett. 2017 Jul 1;12(7):074005. https://doi.org/10.1088/1748-9326/aa7637

110. USFWS. Monarch (Danaus plexippus) species status assessment report, version 2.1 [Internet]. 2020. https://ecos.fws.gov/ServCat/DownloadFile/191345

111. USFWS. Endangered and Threatened Wildlife and Plants; Threatened Species Status With Section 4(d) Rule for Monarch Butterfly and Designation of Critical Habitat [Internet]. 2024. https://www.fws.gov/sites/default/files/documents/2024-12/threatened-species-status-with-section-4-d-rule-for-monarch-butterfly-and-designation-of-critical-habitat_0.pdf

112. Natural Resources Conservation Service. PLANTS Database. United States Department of Agriculture;

113. Ellis EC, Antill EC, Kreft H. All Is Not Loss: Plant Biodiversity in the Anthropocene. Moen J, editor. PLoS ONE. 2012 Jan 17;7(1):e30535. https://doi.org/10.1371/journal.pone.0030535

114. IPBES. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [Internet]. Brondizio ES, Settele J, Díaz S, Ngo HT, editors. Bonn, Germany: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; 2019 [2024 May 18]. https://doi.org/10.5281/zenodo.6417333

115. Niederman TE, Aronson JN, Gainsbury AM, Nunes LA, Dreiss LM. US Imperiled species and the five drivers of biodiversity loss. BioScience. 2025 Aug 13;75(7):524–33. https://doi.org/10.1093/biosci/biaf019

116. Brondízio ES, Settele J, Díaz S, Ngo HT, editors. The global assessment report of the intergovernmental science-policy platform on biodiversity and ecosystem services. Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES); 2019. 1082 p.

117. Wrobleski A, Ernst S, Weber T, Delach A. The impact of climate change on endangered plants and lichen. Wilkening JL, editor. PLOS Clim. 2023 Jul 26;2(7):e0000225. https://doi.org/10.1371/journal.pclm.0000225

118. Locey KJ, Lennon JT. Scaling laws predict global microbial diversity. Proc Natl Acad Sci. 2016 May 24;113(21):5970–5. https://doi.org/10.1073/pnas.1521291113

119. Hawksworth DL, Lücking R. Fungal Diversity Revisited: 2.2 to 3.8 Million Species. Heitman J, James TY, editors. Microbiol Spectr. 2017 Aug 25;5(4):5.4.10. https://doi.org/10.1128/microbiolspec.FUNK-0052-2016

120. Bates ST, Miller AN, The Macrofungi Collections And Microfungi Collections Consor. The protochecklist of North American nonlichenized Fungi. Mycologia. 2018 Nov 2;110(6):1222–348. https://doi.org/10.1080/00275514.2018.1515410

121. Mackelprang R, Grube AM, Lamendella R, Jesus EDC, Copeland A, Liang C, et al. Microbial Community Structure and Functional Potential in Cultivated and Native Tallgrass Prairie Soils of the Midwestern United States. Front Microbiol. 2018 Aug 15;9:1775. https://doi.org/10.3389/fmicb.2018.01775

122. Margules CR, Pressey RL. Systematic conservation planning. Nature. 2000 May;405(6783):243–53. https://doi.org/10.1038/35012251

123. Groves CR, Jensen DB, Valutis LL, Redford KH, Shaffer ML, Scott JM, et al. Planning for Biodiversity Conservation: Putting Conservation Science into Practice. BioScience. 2002;52(6):499. https://doi.org/10.1641/0006-3568(2002)052%255B0499:PFBCPC%255D2.0.CO;2

124. Brooks TM, Mittermeier RA, Da Fonseca GAB, Gerlach J, Hoffmann M, Lamoreux JF, et al. Global Biodiversity Conservation Priorities. Science. 2006 Jul 7;313(5783):58–61. https://doi.org/10.1126/science.1127609

125. Jenkins CN, Pimm SL, Joppa LN. Global patterns of terrestrial vertebrate diversity and conservation. Proc Natl Acad Sci [Internet]. 2013 Jul 9 [2025 Nov 17];110(28). https://doi.org/10.1073/pnas.1302251110

126. Weber T, Norman J. Functional connectivity modeling and optimal siting of conservation networks in the Midwest USA. Ecol Inform. 2015 Nov;30:277–83. https://doi.org/10.1016/j.ecoinf.2015.07.002

127. Hanson JO, Rhodes JR, Butchart SHM, Buchanan GM, Rondinini C, Ficetola GF, et al. Global conservation of species' niches. Nature. 2020 Apr;580(7802):232–4. https://doi.org/10.1038/s41586-020-2138-7

128. Beazley KF, Baldwin ED, Reining C. Integrating Expert Judgment into Systematic Ecoregional Conservation Planning. In: Trombulak SC, Baldwin RF, editors. Landscape-scale Conservation Planning [Internet]. Dordrecht: Springer Netherlands; 2010 [2025 Nov 14]. p. 235–55. https://doi.org/10.1007/978-90-481-9575-6_11

129. Howell PE, Muths E, Hossack BR, Sigafus BH, Chandler RB. Increasing connectivity between metapopulation ecology and landscape ecology. Ecology. 2018 May;99(5):1119–28. https://doi.org/10.1002/ecy.2189

130. Castillo JA, Epps CW, Jeffress MR, Ray C, Rodhouse TJ, Schwalm D. Replicated landscape genetic and network analyses reveal wide variation in functional connectivity for American pikas. Ecol Appl. 2016 Sep;26(6):1660–76. https://doi.org/10.1890/15-1452.1

131. Hilty JA. Corridor ecology: linking landscapes for biodiversity conservation and climate adaptation. Second edition. Washington: Island Press; 2019. 1 p.

132. Beckmann JP. Safe Passages: Highways, Wildlife, and Habitat Connectivity. Washington DC: Island Press; 2014. 1 p.

133. Hilty JA, Chester CC, Wright PA, Zenkewich K. Uniting hearts and lands: advancing conservation and restoration across the Yellowstone to Yukon region. Front Conserv Sci. 2024 Jan 5;4:1264460. https://doi.org/10.3389/fcosc.2023.1264460

134. Hoctor TS, Bohnett E, O'Brien M, Thompson E, Noss R, Lockhart S, et al. Refining the Florida ecological greenways network for improved landscape planning and conservation prioritization. Landsc Ecol. 2025 Jan 31;40(2):36. https://doi.org/10.1007/s10980-025-02049-5

135. Oliver TH, Brereton T, Roy DB. Population resilience to an extreme drought is influenced by habitat area and fragmentation in the local landscape. Ecography. 2013 May;36(5):579–86. https://doi.org/10.1111/j.1600-0587.2012.07665.x

136. Weber TC, Blank PJ, Sloan A. Field Validation of a Conservation Network on the Eastern Shore of Maryland, USA, Using Breeding Birds as Bio-Indicators. Environ Manage. 2008 Apr;41(4):538–50. https://doi.org/10.1007/s00267-008-9076-8

137. Thornton DH, Branch LC, Sunquist ME. The influence of landscape, patch, and within-patch factors on species presence and abundance: a review of focal patch studies. Landsc Ecol. 2011 Jan 1;26(1):7–18. https://doi.org/10.1007/s10980-010-9549-z

138. Robinson JG, LaBruna D, O'Brien T, Clyne PJ, Dudley N, Andelman SJ, et al. Scaling up area-based conservation to implement the Global Biodiversity Framework's 30x30 target: The role of Nature's Strongholds. PLOS Biol. 2024 May 21;22(5):e3002613. https://doi.org/10.1371/journal.pbio.3002613

139. Theobald DM, Kennedy C, Chen B, Oakleaf J, Baruch-Mordo S, Kiesecker J. Earth transformed: detailed mapping of global human modification from 1990 to 2017. Earth Syst Sci Data. 2020 Sep 2;12(3):1953–72. https://doi.org/10.5194/essd-12-1953-2020

140. Theobald DM. A general model to quantify ecological integrity for landscape assessments and US application. Landsc Ecol. 2013 Dec;28(10):1859–74. https://doi.org/10.1007/s10980-013-9941-6

141. Chapin Iii FS, Sommerkorn M, Robards MD, Hillmer-Pegram K. Ecosystem stewardship: A resilience framework for arctic conservation. Glob Environ Change. 2015 Sep;34:207–17. https://doi.org/10.1016/j.gloenvcha.2015.07.003

142. Macander MJ, Nelson PR, Nawrocki TW, Frost GV, Orndahl KM, Palm EC, et al. Time-series maps reveal widespread change in plant functional type cover across Arctic and boreal Alaska and Yukon. Environ Res Lett. 2022 May 1;17(5):054042. https://doi.org/10.1088/1748-9326/ac6965

143. Evans DM, Che-Castaldo JP, Crouse D, Davis FW, Epanchin-Niell R, Flather CH, et al. Species recovery in the United States: Increasing the effectiveness of the Endangered Species Act. Issues Ecol Rep Number 20 Ecol Soc Am 27 P [Internet]. 2016 [2025 Mar 3];20. https://research.fs.usda.gov/treesearch/50145

144. Trombulak SC. Assessing Irreplaceability for Systematic Conservation Planning. In: Trombulak SC, Baldwin RF, editors. Landscape-scale Conservation Planning [Internet]. Dordrecht: Springer Netherlands; 2010 [2025 Nov 14]. p. 303–24. https://doi.org/10.1007/978-90-481-9575-6_14

145. Rosauer D, Laffan SW, Crisp MD, Donnellan SC, Cook LG. Phylogenetic endemism: a new approach for identifying geographical concentrations of evolutionary history. Mol Ecol. 2009 Oct;18(19):4061–72. https://doi.org/10.1111/j.1365-294X.2009.04311.x

146. Fattorini S. Endemism in historical biogeography and conservation biology: concepts and implications. Biogeogr – J Integr Biogeogr. 2017 Nov 14;32(1):47–75. https://doi.org/10.21426/B632136433

147. Muller JJ, Nagel LM, Palik BJ. Forest adaptation strategies aimed at climate change: Assessing the performance of future climate-adapted tree species in a northern Minnesota pine ecosystem. For Ecol Manag. 2019 Nov 1;451:117539. https://doi.org/10.1016/j.foreco.2019.117539

148. Anderson MG, Clark M, Olivero AP, Barnett AR, Hall KR, Cornett MW, et al. A resilient and connected network of sites to sustain biodiversity under a changing climate. Proc Natl Acad Sci. 2023;120(7):e2204434119.

149. Ashcroft MB. Identifying refugia from climate change. J Biogeogr. 2010 Aug;37(8):1407–13. https://doi.org/10.1111/j.1365-2699.2010.02300.x

150. Stralberg D, Arseneault D, Baltzer JL, Barber QE, Bayne EM, Boulanger Y, et al. Climate-change refugia in boreal North America: what, where, and for how long? Front Ecol Environ. 2020 Jun;18(5):261–70. https://doi.org/10.1002/fee.2188

151. Morelli TL, Barrows CW, Ramirez AR, Cartwright JM, Ackerly DD, Eaves TD, et al. Climate-change refugia: biodiversity in the slow lane. Front Ecol Environ. 2020 Jun;18(5):228–34. https://doi.org/10.1002/fee.2189

152. Michalak JL, Stralberg D, Cartwright JM, Lawler JJ. Combining physical and species-based approaches improves refugia identification. Front Ecol Environ. 2020 Jun;18(5):254–60. https://doi.org/10.1002/fee.2207

153. Keppel G, Wardell-Johnson GW. Refugia: keys to climate change management. Glob Change Biol. 2012 Aug;18(8):2389–91. https://doi.org/10.1111/j.1365-2486.2012.02729.x

154. Hylander K, Greiser C, Christiansen DM, Koelemeijer IA. Climate adaptation of biodiversity conservation in managed forest landscapes. Conserv Biol. 2022 Jun;36(3):e13847. https://doi.org/10.1111/cobi.13847

155. Cho FHT, Aglonucci P, Bateman IJ, Lee CF, Lovett A, Mancini MC, et al. Resilient tree-planting strategies for carbon dioxide removal under compounding climate and economic uncertainties. Proc Natl Acad Sci. 2025 Mar 11;122(10):e2320961122. https://doi.org/10.1073/pnas.2320961122

156. Tierney GL, Faber-Langendoen D, Mitchell BR, Shriver WG, Gibbs JP. Monitoring and evaluating the ecological integrity of forest ecosystems. Front Ecol Environ. 2009 Aug;7(6):308–16. https://doi.org/10.1890/070176

157. McGregor D. Coming Full Circle: Indigenous Knowledge, Environment, and Our Future. Am Indian Q. 2004;28(3/4):385–410.

158. Giacomini G. Participatory Rights, Conservation and Indigenous Customary Law. In: Indigenous Peoples and Climate Justice [Internet]. Cham: Springer International Publishing; 2022 [2025 Dec 22]. p. 227–314. (Energy, Climate and the Environment). https://doi.org/10.1007/978-3-031-09508-5_5

159. Jennings L, Jones K, Taitingfong R, Martinez A, David-Chavez D, Alegado R ʻAnolani, et al. Governance of Indigenous data in open earth systems science. Nat Commun. 2025 Jan 10;16(1):572. https://doi.org/10.1038/s41467-024-53480-2

160. Jessen TD, Ban NC, Claxton NX, Darimont CT. Contributions of Indigenous Knowledge to ecological and evolutionary understanding. Front Ecol Environ. 2022;20(2):93–101. https://doi.org/10.1002/fee.2435

161. Kahl S, Wood CM, Eibl M, Klinck H. BirdNET: A deep learning solution for avian diversity monitoring. Ecol Inform. 2021 Mar 1;61:101236. https://doi.org/10.1016/j.ecoinf.2021.101236

162. Jennings L, Anderson T, Martinez A, Sterling R, Chavez DD, Garba I, et al. Applying the “CARE Principles for Indigenous Data Governance” to ecology and biodiversity research. Nat Ecol Evol. 2023 Oct;7(10):1547–51. https://doi.org/10.1038/s41559-023-02161-2

163. Wilkinson R, Mleczko MM, Brewin RJW, Gaston KJ, Mueller M, Shutler JD, et al. Environmental impacts of earth observation data in the constellation and cloud computing era. Sci Total Environ. 2024 Jan 20;909:168584. https://doi.org/10.1016/j.scitotenv.2023.168584

164. Anderson MG, Clark M, Olivero AP, Barnett AR, Hall KR, Cornett MW, et al. A resilient and connected network of sites to sustain biodiversity under a changing climate. Proc

Natl Acad Sci. 2023 Feb 14;120(7):e2204434119. https://doi.org/10.1073/pnas.2204434119

165. Protected Areas Database of the United States (PAD-US) 3.0 - World Database on Protected Areas (WDPA) Submission [Internet]. U.S. Geological Survey; 2023 [2025 Dec 23]. https://catalog.data.gov/dataset/protected-areas-database-of-the-united-states-pad-us-3-0-world-database-on-protected-areas

166. Loarie SR, Duffy PB, Hamilton H, Asner GP, Field CB, Ackerly DD. The velocity of climate change. Nature. 2009 Dec;462(7276):1052–5. https://doi.org/10.1038/nature08649

167. Tallis H, Fargione J, Game E, McDonald R, Baumgarten L, Bhagabati N, et al. Prioritizing actions: spatial action maps for conservation. Ann N Y Acad Sci. 2021 Dec;1505(1):118–41. https://doi.org/10.1111/nyas.14651

168. Grimm J, Jarvis-Cross M, Bailey M, Ban NC, Bartlett M, Cadman R, et al. Co-producing knowledge with Indigenous Peoples: challenges and solutions for academic institutions. Trends Ecol Evol [Internet]. 2025 Nov 20 [2025 Dec 23]; https://doi.org/10.1016/j.tree.2025.10.012

169. David-Chavez DM, Gavin MC, Ortiz N, Valdez S, Carroll SR. A values-centered relational science model: supporting Indigenous rights and reconciliation in research. Ecol Soc [Internet]. 2024 May 31 [2025 Oct 30];29(2). https://doi.org/10.5751/ES-14768-290211

170. Carroll SR, Garba I, Figueroa-Rodríguez OL, Holbrook J, Lovett R, Materechera S, et al. The CARE Principles for Indigenous Data Governance. Data Sci J. 2020 Nov 4;19(1):43. https://doi.org/10.5334/dsj-2020-043

171. Indigenous Knowledge Guidance for Federal Agencies | Indian Affairs [Internet]. [2025 Dec 23]. https://www.bia.gov/events/indigenous-knowledge-guidance-federal-agencies

172. Local Contexts Hub [Internet]. [2025 Dec 23]. Penobscot Nation. https://localcontextshub.org/communities/view/6/

173. Open data for people and purpose: GBIF establishes task group on Indigenous data governance [Internet]. [2025 Dec 23]. https://www.gbif.org/news/1Ke3Gk2USgdIW5OgDlBIKY/open-data-for-people-and-purpose-gbif-establishes-task-group-on-indigenous-data-governance

174. Belote RT, Barnett K, Dietz MS, Burkle L, Jenkins CN, Dreiss L, et al. Options for prioritizing sites for biodiversity conservation with implications for “30 by 30.” Biol Conserv. 2021 Dec 1;264:109378. https://doi.org/10.1016/j.biocon.2021.109378

175. Fuhlendorf SD, Limb RF, Engle DM, Miller RF. Assessment of prescribed fire as a conservation practice. Conserv Benefits Rangel Pract Assess Recomm Knowl Gaps. 2011;75–104.

176. Spetich MA, Perry RW, Harper CA, Clark SL. Fire in Eastern Hardwood Forests Through 14,000 Years. In: Greenberg C, Collins B, Thompson Iii F, editors. Sustaining Young Forest Communities [Internet]. Dordrecht: Springer Netherlands; 2011 [2025 Oct 24]. p. 41–58. (Managing Forest Ecosystems; vol. 21). https://doi.org/10.1007/978-94-007-1620-9_4

177. Ryan KC, Knapp EE, Varner JM. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Front Ecol Environ. 2013;11(s1):e15–24. https://doi.org/10.1890/120329

178. Jones HP, Jones PC, Barbier EB, Blackburn RC, Rey Benayas JM, Holl KD, et al. Restoration and repair of Earth’s damaged ecosystems. Proc R Soc B Biol Sci. 2018;285(1873):20172577–20172577. https://doi.org/10.1098/rspb.2017.2577

179. Atkinson J, Brudvig LA, Mallen-Cooper M, Nakagawa S, Moles AT, Bonser SP. Terrestrial ecosystem restoration increases biodiversity and reduces its variability, but not to reference levels: A global meta-analysis. Crowther T, editor. Ecol Lett. 2022 Jul;25(7):1725–37. https://doi.org/10.1111/ele.14025

180. Higgs E, Falk DA, Guerrini A, Hall M, Harris J, Hobbs RJ, et al. The changing role of history in restoration ecology. Front Ecol Environ. 2014 Nov;12(9):499–506. https://doi.org/10.1890/110267

181. Suding K, Higgs E, Palmer M, Callicott JB, Anderson CB, Baker M, et al. Committing to ecological restoration. Science. 2015 May 8;348(6235):638–40. https://doi.org/10.1126/science.aaa4216

182. McKone MJ, Hernández DL. Community-level assisted migration for climate-appropriate prairie restoration. Restor Ecol. 2021 Sep;29(7):e13416. https://doi.org/10.1111/rec.13416

183. Herkert JR. Conservation Reserve Program Benefits on Henslow’s Sparrows Within the United States. J Wildl Manag. 2007 Nov;71(8):2749–51. https://doi.org/10.2193/2007-002

184. Johnson KA, Dalzell BJ, Donahue M, Gourevitch J, Johnson DL, Karlovits GS, et al. Conservation Reserve Program (CRP) lands provide ecosystem service benefits that exceed land rental payment costs. Ecosyst Serv. 2016;18:175–85.

185. Lizotte RE, Yasarer LMW, Locke MA, Bingner RL, Knight SS. Lake Nutrient Responses to Integrated Conservation Practices in an Agricultural Watershed. J Environ Qual. 2017 Mar;46(2):330–8. https://doi.org/10.2134/jeq2016.08.0324

186. USDA-FSA. Conservation Reserve Program (CRP) 35 Year History | Farm Service Agency [Internet]. 2020 [2025 Dec 12]. https://www.fsa.usda.gov/resources/programs/conservation-reserve-program/statistics/35-year-history

187. Nessel MP, Maguire K, Iovanna R, Duchardt CJ, Loss SR. Scoping review of the literature on outcomes of the conservation reserve program. PLOS ONE. 2025 Aug 12;20(8):e0329962. https://doi.org/10.1371/journal.pone.0329962

188. National Conservation Easement Database [Internet]. 2017. https://www.conservationeasement.us/downloads/

189. Chapman M, Boettiger C, Brashares JS. Leveraging private lands to meet 2030 biodiversity targets in the United States. Conserv Sci Pract. 2023 Apr;5(4):e12897. https://doi.org/10.1111/csp2.12897

190. Garibaldi LA, Oddi FJ, Miguez FE, Bartomeus I, Orr MC, Jobbágy EG, et al. Working landscapes need at least 20% native habitat. Conserv Lett. 2021;14(2):e12773.

191. Kremen C, Merenlender AM. Landscapes that work for biodiversity and people. Science. 2018 Oct 19;362(6412). https://doi.org/10.1126/science.aau6020

192. Belote RT, Dietz MS, McRae BH, Theobald DM, McClure ML, Irwin GH, et al. Identifying Corridors among Large Protected Areas in the United States. Baldwin RF, editor. PLOS ONE. 2016 Apr 22;11(4):e0154223. https://doi.org/10.1371/journal.pone.0154223

193. State of the Birds 2025 [Internet]. [2025 Oct 27]. The State of the Birds in the U.S.A. https://www.stateofthebirds.org/2025/state-of-the-birds-usa/

194. Olimb SK, Lendrum PE. Tracking Cumulative Cropland Expansion across the Great Plains. Gt Plains Res. 2021;31(1):111–4.

195. World Wildlife Fund. 2024 Plowprint Report [Internet]. World Wildlife Fund; 2024. https://www.worldwildlife.org/publications/2024-plowprint-report/

196. Bundy LR, Gensini VA, Ashley WS. United States pasture and rangeland conditions: 1995–2022. Agron J. 2025;117(1):e21736.

197. Lark TJ, Spawn SA, Bougie M, Gibbs HK. Cropland expansion in the United States produces marginal yields at high costs to wildlife. Nat Commun [Internet]. 2020 Sep 9 [2025 Oct 23];11(1):4295. https://doi.org/10.1038/s41467-020-18045-z

198. Thaler EA, Larsen IJ, Yu Q. The extent of soil loss across the US Corn Belt. Proc Natl Acad Sci. 2021 Feb 23;118(8):e1922375118. https://doi.org/10.1073/pnas.1922375118

199. Bailey A, Meyer L, Pettingell N, Macie M, Korstad J. Agricultural Practices Contributing to Aquatic Dead Zones. In: Bauddh K, Kumar S, Singh RP, Korstad J, editors. Ecological and Practical Applications for Sustainable Agriculture [Internet]. Singapore: Springer; 2020 [2025 Oct 31]. p. 373–93. https://doi.org/10.1007/978-981-15-3372-3_17

200. Porter PA, Mitchell RB, Moore KJ. Reducing hypoxia in the Gulf of Mexico: Reimagining a more resilient agricultural landscape in the Mississippi River Watershed. J Soil Water Conserv [Internet]. 2015 May 1 [2025 Oct 31];70(3):63A-68A. https://doi.org/10.2489/jswc.70.3.63A

201. Liebman M, Helmers MJ, Schulte LA, Chase CA. Using biodiversity to link agricultural productivity with environmental quality: Results from three field experiments in Iowa. Renew Agric Food Syst [Internet]. 2013 Jun [2025 Oct 31];28(2):115–28. https://doi.org/10.1017/S1742170512000300

202. Schulte LA, Niemi J, Helmers MJ, Liebman M, Arbuckle JG, James DE, et al. Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn–soybean croplands. Proc Natl Acad Sci. 2017 Oct 17;114(42):11247–52. https://doi.org/10.1073/pnas.1620229114

203. Savage J, Woodcock BA, Bullock JM, Nowakowski M, Tallowin JRB, Pywell RF. Management to Support Multiple Ecosystem Services from Productive Grasslands. Sustainability [Internet]. 2021 Jan [2025 Oct 23];13(11):6263. https://doi.org/10.3390/su13116263

204. Dutter CR, Rieke EL, Pottebaum S, McDaniel MD. Prairie strips improve many measures of soil health in nearly a decade. J Soil Water Conserv [Internet]. [2025 Oct 31];0(0):1–17. https://doi.org/10.1080/00224561.2024.2435683

205. Semmens BX, Semmens DJ, Thogmartin WE, Wiederholt R, López-Hoffman L, Diffendorfer JE, et al. Quasi-extinction risk and population targets for the Eastern, migratory population of monarch butterflies (Danaus plexippus). Sci Rep [Internet]. 2016 Mar 21 [2025 Oct 31];6(1):23265. https://doi.org/10.1038/srep23265

206. Pleasants JM, Oberhauser KS. Milkweed loss in agricultural fields because of herbicide use: effect on the monarch butterfly population. Insect Conserv Divers [Internet]. 2013 [2025 Oct 31];6(2):135–44. https://doi.org/10.1111/j.1752-4598.2012.00196.x

207. Pleasants J. Milkweed restoration in the Midwest for monarch butterfly recovery: estimates of milkweeds lost, milkweeds remaining and milkweeds that must be added to increase the monarch population. Insect Conserv Divers [Internet]. 2017 [2025 Oct 31];10(1):42–53. https://doi.org/10.1111/icad.12198

208. Thogmartin WE, López-Hoffman L, Rohweder J, Diffendorfer J, Drum R, Semmens D, et al. Restoring monarch butterfly habitat in the Midwestern US: 'all hands on deck.' Environ Res Lett [Internet]. 2017 Jun [2025 Oct 31];12(7):074005. https://doi.org/10.1088/1748-9326/aa7637

209. U.S. Fish and Wildlife Service. Endangered and Threatened Wildlife and Plants; Threatened Species Status With Section 4(d) Rule for Monarch Butterfly and Designation of Critical Habitat [Internet]. 50 CFR Part 17. Sect. Vol. 89, No. 239 Dec 12, 2024 p. 100662–716. https://www.fws.gov/sites/default/files/documents/2024-12/threatened-species-status-with-section-4-d-rule-for-monarch-butterfly-and-designation-of-critical-habitat_0.pdf

210. Díaz-Siefer P, Olmos-Moya N, Fontúrbel FE, Lavandero B, Pozo RA, Celis-Diez JL. Bird-mediated effects of pest control services on crop productivity: a global synthesis. J Pest Sci [Internet]. 2022 Mar 1 [2025 Oct 23];95(2):567–76. https://doi.org/10.1007/s10340-021-01438-4

211. Rabalais NN, Turner RE. Gulf of Mexico Hypoxia: Past, Present, and Future. Limnol Oceanogr Bull [Internet]. 2019 [2025 Oct 31];28(4):117–24. https://doi.org/10.1002/lob.10351

212. Leipold EA, Stier HS, Haynam RT, Robison L, Sullivan AR, Kaltenbach TL, et al. An inventory of rangeland wildlife in the Western United States. Rangel Ecol Manag. 2025;98:170–6.

213. Rosenberg KV, Dokter AM, Blancher PJ, Sauer JR, Smith AC, Smith PA, et al. Decline of the North American avifauna. Science. 2019 Oct 4;366(6461):120–4. https://doi.org/10.1126/science.aaw1313

214. Johnston A, Rodewald AD, Strimas-Mackey M, Auer T, Hochachka WM, Stillman AN, et al. North American bird declines are greatest where species are most abundant. Science. 2025;388(6746):532–7.

215. van Klink R, Bowler DE, Gongalsky KB, Shen M, Swengel SR, Chase JM. Disproportionate declines of formerly abundant species underlie insect loss. Nature. 2024;628(8007):359–64.

216. Calderone NW. Insect Pollinated Crops, Insect Pollinators and US Agriculture: Trend Analysis of Aggregate Data for the Period 1992–2009. Smagghe G, editor. PLoS ONE. 2012 May 22;7(5):e37235. https://doi.org/10.1371/journal.pone.0037235

217. Green AJ, Elmberg J. Ecosystem services provided by waterbirds. Biol Rev. 2014;89(1):105–22. https://doi.org/10.1111/brv.12045

218. Whelan CJ, Şekercioğlu ÇH, Wenny DG. Why birds matter: from economic ornithology to ecosystem services. J Ornithol. 2015 Dec 1;156(1):227–38. https://doi.org/10.1007/s10336-015-1229-y

219. Perrot T, Rusch A, Coux C, Gaba S, Bretagnolle V. Proportion of Grassland at Landscape Scale Drives Natural Pest Control Services in Agricultural Landscapes. Front Ecol Evol. 2021 Apr 14;9:607023. https://doi.org/10.3389/fevo.2021.607023

220. Savage J, Woodcock BA, Bullock JM, Nowakowski M, Tallowin JRB, Pywell RF. Management to Support Multiple Ecosystem Services from Productive Grasslands. Sustainability. 2021 Jan;13(11):6263. https://doi.org/10.3390/su13116263

221. Estrada-Carmona N, Sánchez AC, Remans R, Jones SK. Complex agricultural landscapes host more biodiversity than simple ones: A global meta-analysis. Proc Natl Acad Sci. 2022;119(38):e2203385119.

222. Priyadarshana TS, Martin EA, Sirami C, Woodcock BA, Goodale E, Martínez-Núñez C, et al. Crop and landscape heterogeneity increase biodiversity in agricultural landscapes: A global review and meta-analysis. Ecol Lett. 2024;27(3):e14412.

223. Jaworski CC, Thomine E, Rusch A, Lavoir AV, Wang S, Desneux N. Crop diversification to promote arthropod pest management: A review. Agric Commun. 2023;1(1):100004.

224. Outhwaite CL, McCann P, Newbold T. Agriculture and climate change are reshaping insect biodiversity worldwide. Nature. 2022;605(7908):97–102.

225. Yang Y, Tilman D, Jin Z, Smith P, Barrett CB, Zhu YG, et al. Climate change exacerbates the environmental impacts of agriculture. Science. 2024;385(6713):eadn3747.

226. Petersen-Rockney M, Baur P, Guzman A, Bender SF, Calo A, Castillo F, et al. Narrow and Brittle or Broad and Nimble? Comparing Adaptive Capacity in Simplifying and Diversifying Farming Systems. Front Sustain Food Syst [Internet]. 2021 Mar 15 [2026 Jan 29];5. https://doi.org/10.3389/fsufs.2021.564900

227. Petrzelka P. Absentee Landlords and Agriculture. In: Encyclopedia of Food and Agricultural Ethics. Dordrecht: Springer Science+Business Media; 2014.

228. Michel NL, Burkhalter C, Wilsey CB, Holloran M, Holloran A, Langham GM. Metrics for conservation success: Using the “Bird-Friendliness Index” to evaluate grassland and aridland bird community resilience across the Northern Great Plains ecosystem. Divers Distrib. 2020;26(12):1687–702. https://doi.org/10.1111/ddi.13163

229. Rosenberger RS, White EM, Kline JD, Cvitanovich C. Recreation economic values for estimating outdoor recreation economic benefits from the National Forest System. Portland, O.R.: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 2017 p. 33. Report No.: Gen. Tech. Rep. PNW-GTR-957.

230. Chamberlain JL, Emery MR, Patel-Weynand T. Assessment of nontimber forest products in the United States under changing conditions [Internet]. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station; 2018 p. 260. Report No.: Gen. Tech. Rep. SRS-232. https://doi.org/10.2737/SRS-GTR-232

231. Chamberlain J, Honor RD, Malcolm K, Mahoney SP, Bellmore JR, Reeves MC, et al. Provisioning food and medicine from public forests in the United States. Trees For People. 2025 Mar 1;19:100738. https://doi.org/10.1016/j.tfp.2024.100738

232. Liu N, Dobbs RG, Caldwell PV, Miniat CF, Sun G, Duan K, et al. Inter-Basin Transfers Extend the Benefits of Water From Forests to Population Centers Across the Conterminous U.S. Water Resour Res. 2022;58(5):e2021WR031537.

233. Kaarakka L, Rothey J, Dee LE. Managing forests for carbon–Status of the forest carbon offset markets in the United States. Ashraf MI, editor. PLOS Clim. 2023 Jul 6;2(7):e0000158. https://doi.org/10.1371/journal.pclm.0000158

234. Kamelamela KL, Chamberlain J, Lehman AD, Sprecher I, Friday JB, Ticktin T. Hawaiʻi nontimber forest products: cultural and economic foundations [Internet]. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 2023 Oct [2025 Dec 16] p. PNW-GTR-1011. Report No.: PNW-GTR-1011. https://doi.org/10.2737/PNW-GTR-1011

235. Homyack JA, Haas CA. Long-term effects of experimental forest harvesting on abundance and reproductive demography of terrestrial salamanders. Biol Conserv. 2009;142(1):110–21.

236. Lavoie M, Renard A, Larivière S. Timber harvest jeopardize marten persistence in the heart of its range. For Ecol Manag. 2019 Jun;442:46–52. https://doi.org/10.1016/j.foreco.2019.03.060

237. Segura C, Bladon KD, Hatten JA, Jones JA, Hale VC, Ice GG. Long-term effects of forest harvesting on summer low flow deficits in the Coast Range of Oregon. J Hydrol. 2020 Jun;585:124749. https://doi.org/10.1016/j.jhydrol.2020.124749

238. Williams CA, Gu H, MacLean R, Masek JG, Collatz GJ. Disturbance and the carbon balance of US forests: A quantitative review of impacts from harvests, fires, insects, and droughts. Glob Planet Change. 2016 Aug;143:66–80. https://doi.org/10.1016/j.gloplacha.2016.06.002

239. Lesiv M, Schepaschenko D, Buchhorn M, See L, Dürauer M, Georgieva I, et al. Global forest management data for 2015 at a 100 m resolution. Sci Data. 2022 May 10;9(1):199. https://doi.org/10.1038/s41597-022-01332-3

240. Stanturf JA, Zhang D. Plantations forests in the United States of America: Past, present and future. In Athens, GA: U.S. Department of Agriculture Forest Service; 2003.

241. Oswalt SN, Smith WB, Miles PD, Pugh SA. Forest Resources of the United States, 2017: a technical document supporting the Forest Service 2020 RPA Assessment [Internet]. U.S. Department of Agriculture, Forest Service; 2019. https://doi.org/10.2737/wo-gtr-97

242. Oswalt SN, Smith WB. U.S. Forest Resource Facts and Historical Trends. U.S. Forest Service; 2014 p. 63. Report No.: FS-1035.

243. Perry CH, Finco MV, Wilson BT. Forest Atlas of the United States [Internet]. Washington, D.C.: U.S. Department of Agriculture, Forest Service; 2022 p. 94. Report No.: FS-1172. https://doi.org/10.2737/FS-1172

244. Haynes RW. An analysis of the timber situation in the United States: 1952 to 2050. [Internet]. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 2003 [2025 Oct 30] p. PNW-GTR-560. Report No.: PNW-GTR-560. https://doi.org/10.2737/PNW-GTR-560

245. D’Amato AW, Jokela EJ, O’Hara KL, Long JN. Silviculture in the United States: An Amazing Period of Change over the Past 30 Years. J For [Internet]. 2017 [2025 Oct 31]; https://doi.org/10.5849/JOF-2016-035

246. Drummond MA, Loveland TR. Land-use Pressure and a Transition to Forest-cover Loss in the Eastern United States. BioScience. 2010 Apr;60(4):286–98. https://doi.org/10.1525/bio.2010.60.4.7

247. Rudel TK, Perez-Lugo M, Zichal H. When Fields Revert to Forest: Development and Spontaneous Reforestation in Post-War Puerto Rico. Prof Geogr. 2000 Aug 1;52(3):386–97. https://doi.org/10.1111/0033-0124.00233

248. Brandeis TJ, Helmer EH, Marcano-Vega H, Lugo AE. Climate shapes the novel plant communities that form after deforestation in Puerto Rico and the U.S. Virgin Islands. For Ecol Manag. 2009 Sep;258(7):1704–18. https://doi.org/10.1016/j.foreco.2009.07.030

249. Ramankutty N, Heller E, Rhemtulla J. Prevailing Myths About Agricultural Abandonment and Forest Regrowth in the United States. Ann Assoc Am Geogr. 2010 Jun 25;100(3):502–12. https://doi.org/10.1080/00045601003788876

250. Jõgiste K, Keith Moser W, Mandre M. Disturbance dynamics and ecosystem-based forest management. Scand J For Res. 2005;20(sup6):2–4. https://doi.org/10.1080/14004080510043370

251. NOAA. Integrated Ecosystem Assessment. 2025 [2025 Dec 18]. Ecosystem-Based Management. https://www.integratedecosystemassessment.noaa.gov/about-iea/ecosystem-based-management

252. UN-REDD Program. Improved Forest Management (IFM) [Internet]. 2025 [2025 Dec 18]. https://www.un-redd.org/glossary/improved-forest-management-ifm

253. Chandler CC, King DI, Chandler RB. Do mature forest birds prefer early-successional habitat during the post-fledging period? For Ecol Manag. 2012 Jan;264:1–9. https://doi.org/10.1016/j.foreco.2011.09.018

254. Isbell F, Adler PR, Eisenhauer N, Fornara D, Kimmel K, Kremen C, et al. Benefits of increasing plant diversity in sustainable agroecosystems. Bardgett R, editor. J Ecol. 2017 Jul;105(4):871–9. https://doi.org/10.1111/1365-2745.12789

255. Kaarakka L, Cornett M, Domke G, Ontl T, Dee LE. Improved forest management as a natural climate solution: A review. Ecol Solut Evid. 2021 Jul;2(3):e12090. https://doi.org/10.1002/2688-8319.12090

256. George AK, Kizha AR, Daigneault A. Is forest certification working on the ground? Forest managers perspectives from the northeast U.S. Trees For People. 2022 Mar;7:100197. https://doi.org/10.1016/j.tfp.2022.100197

257. Cubbage F, Moore S, Cox J, Jervis L, Edeburn J, Richter D, et al. Forest Certification of State and University Lands in North Carolina: A Comparison. J For. 2003 Dec 1;101(8):26–31. https://doi.org/10.1093/jof/101.8.26

258. Van Der Ven H, Cashore B. Forest certification: the challenge of measuring impacts. Curr Opin Environ Sustain. 2018 Jun;32:104–11. https://doi.org/10.1016/j.cosust.2018.06.001

259. Kilgore MA, Leahy JE, Hibbard CM, Donnay JS. Assessing Family Forestland Certification Opportunities: A Minnesota Case Study. J For. 2007 Jan 1;105(1):27–33. https://doi.org/10.1093/jof/105.1.27

260. Tian N, Pelkki M. Nonindustrial private forest landowner perspectives on forest certification: A look at awareness and barriers. For Policy Econ. 2021 Oct;131:102552. https://doi.org/10.1016/j.forpol.2021.102552

261. Littlefield CE, D'Amato AW. Identifying trade-offs and opportunities for forest carbon and wildlife using a climate change adaptation lens. Conserv Sci Pract. 2022 Apr;4(4):e12631. https://doi.org/10.1111/csp2.12631

262. Martin KL, Hurteau MD, Hungate BA, Koch GW, North MP. Carbon Tradeoffs of Restoration and Provision of Endangered Species Habitat in a Fire-Maintained Forest. Ecosystems. 2015 Jan;18(1):76–88. https://doi.org/10.1007/s10021-014-9813-1

263. Schwenk WS, Donovan TM, Keeton WS, Nunery JS. Carbon storage, timber production, and biodiversity: comparing ecosystem services with multi-criteria decision analysis. Ecol Appl. 2012 Jul;22(5):1612–27. https://doi.org/10.1890/11-0864.1

264. Dybala KE, Steger K, Walsh RG, Smart DR, Gardali T, Seavy NE. Optimizing carbon storage and biodiversity co-benefits in reforested riparian zones. Macinnis-Ng C, editor. J Appl Ecol. 2019 Feb;56(2):343–53. https://doi.org/10.1111/1365-2664.13272

265. Costanza JK, Koch FH, Reeves M, Potter KM, Schleeweis K, Riitters K, et al. Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment [Internet]. Washington, DC: U.S. Department of Agriculture, Forest Service; 2023 [2025 Oct 30] p. WO-GTR-102. Report No.: WO-GTR-102. https://doi.org/10.2737/WO-GTR-102

266. U.S. Department of Agriculture Forest Service, U.S. Department of the Interior Bureau of Land Management. Mature and old-growth forests: Analysis of threats on lands managed by the Forest Service and Bureau of Land Management [Internet]. United States Department of Agriculture, Forest Service; 2024. Report No.: FS-1215c. https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/MOG-threat-analysis.pdf

267. Kautz M, Meddens AJH, Hall RJ, Arneth A. Biotic disturbances in Northern Hemisphere forests – a synthesis of recent data, uncertainties and implications for forest monitoring and modelling. Glob Ecol Biogeogr. 2017 May;26(5):533–52. https://doi.org/10.1111/geb.12558

268. Pandit K, Conkling BL. Forest Health Monitoring: National Status, Trends, and Analysis 2023 [Internet]. Washington, D.C.: Department of Agriculture, Forest Service; 2024 p. 159. Report No.: General Technical Report WO-105. https://doi.org/10.2737/WO-GTR-105

269. Fei S, Morin RS, Oswalt CM, Liebhold AM. Biomass losses resulting from insect and disease invasions in US forests. Proc Natl Acad Sci. 2019 Aug 27;116(35):17371–6. https://doi.org/10.1073/pnas.1820601116

270. Lovett GM, Weiss M, Liebhold AM, Holmes TP, Leung B, Lambert KF, et al. Nonnative forest insects and pathogens in the United States: Impacts and policy options. Pan Y, editor. Ecol Appl. 2016 Jul;26(5):1437–55. https://doi.org/10.1890/15-1176

271. Abatzoglou JT, Williams AP. Impact of anthropogenic climate change on wildfire across western US forests. Proc Natl Acad Sci. 2016 Oct 18;113(42):11770–5. https://doi.org/10.1073/pnas.1607171113

272. Dennison PE, Brewer SC, Arnold JD, Moritz MA. Large wildfire trends in the western United States, 1984–2011. Geophys Res Lett. 2014 Apr 28;41(8):2928–33. https://doi.org/10.1002/2014GL059576

273. Parks SA, Abatzoglou JT. Warmer and Drier Fire Seasons Contribute to Increases in Area Burned at High Severity in Western US Forests From 1985 to 2017. Geophys Res Lett. 2020 Nov 28;47(22):e2020GL089858. https://doi.org/10.1029/2020GL089858

274. Westerling AL. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philos Trans R Soc B Biol Sci. 2016 Jun 5;371(1696):20150178. https://doi.org/10.1098/rstb.2015.0178

275. Iglesias V, Balch JK, Travis WR. U.S. fires became larger, more frequent, and more widespread in the 2000s. Sci Adv. 2022 Mar 18;8(11):eabc0020. https://doi.org/10.1126/sciadv.abc0020

276. Parks SA, Coop JD, Davis KT. Intensifying Fire Season Aridity Portends Ongoing Expansion of Severe Wildfire in Western US Forests. Glob Change Biol. 2025 Aug;31(8):e70429. https://doi.org/10.1111/gcb.70429

277. Parks SA, Guiterman CH, Margolis EQ, Lonergan M, Whitman E, Abatzoglou JT, et al. A fire deficit persists across diverse North American forests despite recent increases in area burned. Nat Commun. 2025 Feb 10;16(1):1493. https://doi.org/10.1038/s41467-025-56333-8

278. Hagmann RK, Hessburg PF, Prichard SJ, Povak NA, Brown PM, Fulé PZ, et al. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. Ecol Appl. 2021 Dec;31(8):e02431. https://doi.org/10.1002/eap.2431

279. Trauernicht C, Pickett E, Giardina CP, Litton CM, Cordell S, Beavers A. The Contemporary Scale and Context of Wildfire in Hawaiʻi. Pac Sci. 2015 Oct;69(4):427–44. https://doi.org/10.2984/69.4.1

280. Bubb IE, Williams ZB. Spatial and Temporal Patterns of Fire on Saipan, CNMI. Pac Sci [Internet]. 2022 Mar 2 [2025 Dec 18];76(1). https://doi.org/10.2984/76.1.1

281. Pacific Drought Knowledge Exchange. Wildland Fire on Guam. Pacific Drought Knowledge Exchange; 2023.

282. Costanza JK, Koch FH, Reeves MC. Recent forest exposure to multiyear drought across the coterminous United States. In: Forest Health Monitoring: national status, trends, and analysis 2023 [Internet]. Washngton, D.C.: Department of Agriculture, Forest Service; 2024. p. 113–29. (Gen. Tech. Rep. WO-105). https://doi.org/10.2737/WO-GTR-105-Chap6

283. Krakauer NY, Lakhankar T, Hudson D. Trends in Drought over the Northeast United States. Water. 2019 Sep 4;11(9):1834. https://doi.org/10.3390/w11091834

284. Williams AP, Cook BI, Smerdon JE. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. Nat Clim Change. 2022 Mar;12(3):232–4. https://doi.org/10.1038/s41558-022-01290-z

285. Goulden ML, Bales RC. California forest die-off linked to multi-year deep soil drying in 2012–2015 drought. Nat Geosci. 2019 Aug;12(8):632–7. https://doi.org/10.1038/s41561-019-0388-5

286. Gaylord ML, Kolb TE, Pockman WT, Plaut JA, Yepez EA, Macalady AK, et al. Drought predisposes piñon–juniper woodlands to insect attacks and mortality. New Phytol. 2013 Apr;198(2):567–78. https://doi.org/10.1111/nph.12174

287. Kolb T, Keefover-Ring K, Burr SJ, Hofstetter R, Gaylord M, Raffa KF. Drought-Mediated Changes in Tree Physiological Processes Weaken Tree Defenses to Bark Beetle Attack. J Chem Ecol. 2019 Oct;45(10):888–900. https://doi.org/10.1007/s10886-019-01105-0

288. Robbins ZJ, Xu C, Aukema BH, Buotte PC, Chitra-Tarak R, Fettig CJ, et al. Warming increased bark beetle-induced tree mortality by 30% during an extreme drought in California. Glob Change Biol. 2022 Jan;28(2):509–23. https://doi.org/10.1111/gcb.15927

289. Goodwin MJ, Zald HSJ, North MP, Hurteau MD. Climate-Driven Tree Mortality and Fuel Aridity Increase Wildfire's Potential Heat Flux. Geophys Res Lett. 2021 Dec 28;48(24):e2021GL094954. https://doi.org/10.1029/2021GL094954

290. Stephens SL, Ruth LW. Federal Forest-Fire Policy in the United States. Ecol Appl. 2005 Apr;15(2):532–42. https://doi.org/10.1890/04-0545

291. Stephens SL, Collins BM, Biber E, Fulé PZ. U.S. federal fire and forest policy: emphasizing resilience in dry forests. Ecosphere. 2016;7(11):e01584. https://doi.org/10.1002/ecs2.1584

292. Stephens SL, Westerling AL, Hurteau MD, Peery MZ, Schultz CA, Thompson S. Fire and climate change: conserving seasonally dry forests is still possible. Front Ecol Environ. 2020 Aug;18(6):354–60. https://doi.org/10.1002/fee.2218

293. Van Mantgem PJ, Caprio AC, Stephenson NL, Das AJ. Does Prescribed Fire Promote Resistance to Drought in Low Elevation Forests of the Sierra Nevada, California, USA? Fire Ecol. 2016 Apr;12(1):13–25. https://doi.org/10.4996/fireecology.1201013

294. Kreider MR, Higuera PE, Parks SA, Rice WL, White N, Larson AJ. Fire suppression makes wildfires more severe and accentuates impacts of climate change and fuel accumulation. Nat Commun. 2024 Mar 25;15(1):2412. https://doi.org/10.1038/s41467-024-46702-0

295. Kodero JM, Felzer BS, Shi Y. Future transition from forests to shrublands and grasslands in the western United States is expected to reduce carbon storage. Commun Earth Environ. 2024 Feb 12;5(1):78. https://doi.org/10.1038/s43247-024-01253-6

296. Coop JD, Parks SA, Stevens-Rumann CS, Crausbay SD, Higuera PE, Hurteau MD, et al. Wildfire-Driven Forest Conversion in Western North American Landscapes. BioScience. 2020 Aug 1;70(8):659–73. https://doi.org/10.1093/biosci/biaa061

297. Davis KT, Dobrowski SZ, Higuera PE, Holden ZA, Veblen TT, Rother MT, et al. Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. Proc Natl Acad Sci. 2019 Mar 26;116(13):6193–8. https://doi.org/10.1073/pnas.1815107116

298. Zhao J, Yue C, Wang J, Hantson S, Wang X, He B, et al. Forest fire size amplifies postfire land surface warming. Nature. 2024 Sep;633(8031):828–34. https://doi.org/10.1038/s41586-024-07918-8

299. How Does Wildfire Impact Wildlife and Forests? | U.S. Fish & Wildlife Service [Internet]. 2022 [2026 Jan 29]. https://www.fws.gov/story/2022-10/how-does-wildfire-impact-wildlife-and-forests

300. Jones GM, Tingley MW. Pyrodiversity and biodiversity: A history, synthesis, and outlook. Divers Distrib. 2022 Mar;28(3):386–403. https://doi.org/10.1111/ddi.13280

301. Shive KL, Wuenschel A, Hardlund LJ, Morris S, Meyer MD, Hood SM. Ancient trees and modern wildfires: Declining resilience to wildfire in the highly fire-adapted giant sequoia. For Ecol Manag. 2022 May;511:120110. https://doi.org/10.1016/j.foreco.2022.120110

302. Ayars J, Kramer HA, Jones GM. The 2020 to 2021 California megafires and their impacts on wildlife habitat. Proc Natl Acad Sci. 2023 Nov 28;120(48):e2312909120. https://doi.org/10.1073/pnas.2312909120

303. Boisramé GFS, Thompson SE, Tague C (Naomi), Stephens SL. Restoring a Natural Fire Regime Alters the Water Balance of a Sierra Nevada Catchment. Water Resour Res. 2019 Jul;55(7):5751–69. https://doi.org/10.1029/2018WR024098

304. Williams AP, Livneh B, McKinnon KA, Hansen WD, Mankin JS, Cook BI, et al. Growing impact of wildfire on western US water supply. Proc Natl Acad Sci. 2022 Mar 8;119(10):e2114069119. https://doi.org/10.1073/pnas.2114069119

305. Phalan BT, Northrup JM, Yang Z, Deal RL, Rousseau JS, Spies TA, et al. Impacts of the Northwest Forest Plan on forest composition and bird populations. Proc Natl Acad Sci. 2019 Feb 19;116(8):3322–7. https://doi.org/10.1073/pnas.1813072116

306. Steel ZL, Fogg AM, Burnett R, Roberts LJ, Safford HD. When bigger isn't better—Implications of large high-severity wildfire patches for avian diversity and community composition. Archibald S, editor. Divers Distrib. 2022 Mar;28(3):439–53. https://doi.org/10.1111/ddi.13281

307. North American Bird Conservation Initiative. State of the Birds Report: United States of America [Internet]. North American Bird Conservation Initiative; 2025. https://www.stateofthebirds.org/2025/download-pdf-report/

308. Zheng B, Ciais P, Chevallier F, Chuvieco E, Chen Y, Yang H. Increasing forest fire emissions despite the decline in global burned area. Sci Adv. 2021 Sep 24;7(39):eabh2646. https://doi.org/10.1126/sciadv.abh2646

309. Hall J, Sandor ME, Harvey BJ, Parks SA, Trugman AT, Williams AP, et al. Forest Carbon Storage in the Western United States: Distribution, Drivers, and Trends. Earths Future. 2024 Jul;12(7):e2023EF004399. https://doi.org/10.1029/2023EF004399

310. Higuera PE, Cook MC, Balch JK, Stavros EN, Mahood AL, St. Denis LA. Shifting social-ecological fire regimes explain increasing structure loss from Western wildfires. Liu J, editor. PNAS Nexus. 2023 Mar 3;2(3):pgad005. https://doi.org/10.1093/pnasnexus/pgad005

311. Burke M, Driscoll A, Heft-Neal S, Xue J, Burney J, Wara M. The changing risk and burden of wildfire in the United States. Proc Natl Acad Sci. 2021 Jan 12;118(2):e2011048118. https://doi.org/10.1073/pnas.2011048118

312. Brucker CP, Livneh B, Rosario-Ortiz FL, Yao F, Williams AP, Becker WC, et al. Wildfires drive multi-year water quality degradation over the western United States. Commun Earth Environ. 2025 Jun 23;6(1):489. https://doi.org/10.1038/s43247-025-02427-6

313. Badgley G, Freeman J, Hamman JJ, Haya B, Trugman AT, Anderegg WRL, et al. Systematic over-crediting in California's forest carbon offsets program. Glob Change Biol. 2022 Feb;28(4):1433–45. https://doi.org/10.1111/gcb.15943

314. Wang D, Guan D, Zhu S, Kinnon MM, Geng G, Zhang Q, et al. Economic footprint of California wildfires in 2018. Nat Sustain. 2021 Mar;4(3):252–60. https://doi.org/10.1038/s41893-020-00646-7

315. Davis KT, Peeler J, Fargione J, Haugo RD, Metlen KL, Robles MD, et al. Tamm review: A meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the Western US. For Ecol Manag. 2024 Jun;561:121885. https://doi.org/10.1016/j.foreco.2024.121885

316. LoPresti A, Hayden MT, Siegel K, Poulter B, Stavros EN, Dee LE. Remote sensing applications for prescribed burn research. Int J Wildland Fire. 2024 May 24;33(6):WF23130. https://doi.org/10.1071/WF23130

317. He K, Shen X, Anagnostou E. Global burn severity in forest ecoregions: trends, climate drivers, and predictive insights. Npj Nat Hazards. 2025 Jul 9;2(1):61. https://doi.org/10.1038/s44304-025-00113-3

318. Lake FK, Wright V, Morgan P, McFadzen M, McWethy D, Stevens-Rumann C. Returning Fire to the Land: Celebrating Traditional Knowledge and Fire. J For. 2017 Sep 20;115(5):343–53. https://doi.org/10.5849/jof.2016-043R2

319. Carter VA, Brunelle A, Power MJ, DeRose RJ, Bekker MF, Hart I, et al. Legacies of Indigenous land use shaped past wildfire regimes in the Basin-Plateau Region, USA. Commun Earth Environ. 2021 Apr 14;2(1):72. https://doi.org/10.1038/s43247-021-00137-3

320. Long JW, Lake FK, Goode RW. The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. For Ecol Manag. 2021 Nov;500:119597. https://doi.org/10.1016/j.foreco.2021.119597

321. Knight CA, Anderson L, Bunting MJ, Champagne M, Clayburn RM, Crawford JN, et al. Land management explains major trends in forest structure and composition over the last millennium in California's Klamath Mountains. Proc Natl Acad Sci. 2022 Mar 22;119(12):e2116264119. https://doi.org/10.1073/pnas.2116264119

322. Department of the Interior, Bureau of Land Management. Notice of Availability of the Approved Resource Management Plan Amendments and Record of Decision for Utility-Scale Solar Energy Development [Internet]. (Federal Register). Report No.: Vol. 89, No. 248. https://www.federalregister.gov/d/2024-30953

323. Barron-Gafford GA, Pavao-Zuckerman MA, Minor RL, Sutter LF, Barnett-Moreno I, Blackett DT, et al. Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nat Sustain. 2019 Sep 2;2(9):848–55. https://doi.org/10.1038/s41893-019-0364-5

324. Walston LJ, Barley T, Bhandari I, Campbell B, McCall J, Hartmann HM, et al. Opportunities for agrivoltaic systems to achieve synergistic food-energy-environmental needs and address sustainability goals. Front Sustain Food Syst. 2022 Sep 16;6:932018. https://doi.org/10.3389/fsufs.2022.932018

325. Nowak DJ, Greenfield EJ. Declining urban and community tree cover in the United States. Urban For Urban Green. 2018 May;32:32–55. https://doi.org/10.1016/j.ufug.2018.03.006

326. Nowak DJ, Greenfield EJ, Ellis A. Assessing Urban Forest Threats across the Conterminous United States. J For. 2022 Nov 2;120(6):676–92. https://doi.org/10.1093/jofore/fvac019

327. McDonald RI, Biswas T, Chakraborty TC, Kroeger T, Cook-Patton SC, Fargione JE. Current inequality and future potential of US urban tree cover for reducing heat-related health impacts. Npj Urban Sustain. 2024 Apr 8;4(1):18. https://doi.org/10.1038/s42949-024-00150-3

328. McDonald RI, Biswas T, Sachar C, Housman I, Boucher TM, Balk D, et al. The tree cover and temperature disparity in US urbanized areas: Quantifying the association with income across 5,723 communities. Singh KK, editor. PLOS ONE. 2021 Apr 28;16(4):e0249715. https://doi.org/10.1371/journal.pone.0249715

329. Wang C, Wang ZH, Wang C, Myint SW. Environmental cooling provided by urban trees under extreme heat and cold waves in U.S. cities. Remote Sens Environ. 2019 Jun;227:28–43. https://doi.org/10.1016/j.rse.2019.03.024

330. Monteiro CM, Mendes AM, Santos C. Green Roofs as an Urban NbS Strategy for Rainwater Retention: Influencing Factors—A Review. Water. 2023 Aug 1;15(15):2787. https://doi.org/10.3390/w15152787

331. Xu L, Guo H, Boyd CM, Klein M, Bougiatioti A, Cerully KM, et al. Effects of anthropogenic emissions on aerosol formation from isoprene and monoterpenes in the southeastern United States. Proc Natl Acad Sci. 2015 Jan 6;112(1):37–42. https://doi.org/10.1073/pnas.1417609112

332. Zhang W, Burgis CR, Hayes GM, Henderson DA, Smith JA. Evaluation of maintenance efficiency for multiple green infrastructure designs based on water quality performance and economic costs. Ecol Eng. 2024 Sep;206:107326. https://doi.org/10.1016/j.ecoleng.2024.107326

333. Li L, Carter J. Exploring the relationship between urban green infrastructure connectivity, size and multifunctionality: a systematic review. Landsc Ecol. 2025 Mar 10;40(3):61. https://doi.org/10.1007/s10980-025-02069-1

334. Nelson CR, Hallett JG, Romero Montoya AE, Andrade A, Besacier C, Boerger V, et al. Standards of practice to guide ecosystem restoration: a contribution to the United Nations decade on ecosystem restoration 2021–2030 [Internet]. Food & Agriculture Org.; 2024 [2025 Oct 31]. https://books.google.com/books?hl=en&lr=&id=SMMHEQAAQBAJ&oi=fnd&pg=PR5&dq=%22Indigenous+Peoples+Biocentric+Restoration%22&ots=ILn9nQx9mF&sig=pbhyT8rFOQeceSSq5IEey3kf5l4

335. Hallett LM, Diver S, Eitzel MV, Olson JJ, Ramage BS, Sardinas H, et al. Do We Practice What We Preach? Goal Setting for Ecological Restoration. Restor Ecol. 2013 May;21(3):312–9. https://doi.org/10.1111/rec.12007

336. Wortley L, Hero J, Howes M. Evaluating Ecological Restoration Success: A Review of the Literature. Restor Ecol. 2013 Sep;21(5):537–43. https://doi.org/10.1111/rec.12028

337. Rosa S, Hollis S, Francia RM, Renner A, Johnson N, Barak RS, et al. Shifting dynamics in restoration ecology: Concrete steps towards centering Black, Indigenous, and People of Color's communities and perspectives. Ecol Solut Evid. 2024 Apr;5(2):e12345. https://doi.org/10.1002/2688-8319.12345

338. Dickson-Hoyle S, Ignace RE, Ignace MB, Hagerman SM, Daniels LD, Copes-Gerbitz K. Walking on two legs: a pathway of Indigenous restoration and reconciliation in fire-adapted landscapes. Restor Ecol. 2022 May;30(4):e13566. https://doi.org/10.1111/rec.13566

339. TNFD. The Taskforce on Nature-related Financial Disclosures [Internet]. 2025 [2025 Oct 20]. https://tnfd.global/

340. Wilkinson MD, Dumontier M, Aalbersberg IjJ, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data. 2016 Mar 15;3(1):160018. https://doi.org/10.1038/sdata.2016.18