REVIEW SUMMARY

GREENHOUSE GASES

Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases

Philip B. Duffy*†, Christopher B. Field*, Noah S. Diffenbaugh*, Scott C. Doney, Zoe Dutton, Sherri Goodman, Lisa Heinzerling, Solomon Hsiang, David B. Lobell, Loretta J. Mickley, Samuel Myers, Susan M. Natali, Camille Parmesan, Susan Tierney, A. Park Williams

BACKGROUND: The Clean Air Act requires the Environmental Protection Agency (EPA) to regulate air pollutants when the EPA Administrator finds that they "cause, or contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare." In *Massachusetts* v. *EPA*, the U.S. Supreme Court held that the EPA has the authority to regulate greenhouse gases (GHGs) under the Clean Air Act and that the EPA may not refuse to regulate once it has made a finding of endangerment.

In December 2009, the EPA released its "Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act," known informally as the Endangerment Finding (EF). The EF found that six long-lived GHGs, in combination, should be defined as "air pollution" under the Clean Air Act and may reasonably be anticipated to endanger the health and welfare of current and future generations.

The EF is an essential element of the legal basis for regulating GHG emissions under the Clean Air Act. It provides foundational support for important aspects of U.S. climate policy, including vehicle mileage standards for cars and light trucks and the emissions standards for electricity generation known as the "Clean Power Plan."

The EF was rooted in careful evaluation of observed and projected effects of GHGs, with assessments from the U.S. Global Change Research Program, the Intergovernmental Panel on Climate Change, and the U.S. National Research Council providing primary evidence. The EF was clear that, although many aspects of climate change were still uncertain, the evidence available in 2009 was strong. Since the original EF, scientific information about the causes, historical impacts, and future risks of climate change has continued to accumulate. This Review assesses that new information in the context of the EF.

ADVANCES: The EF was structured around knowledge related to public health and public welfare, with a primary focus on impacts in the United States. The information on public welfare was grouped into sections on air quality; food production and agriculture; forestry; water resources; sea level rise and coastal areas; energy, infrastructure, and settlements; and ecosystems and wildlife.

In this Review, we assess new evidence in the impact areas addressed in the EF, as well as emergent areas that were not addressed in the EF but in which there have been important advances in understanding the risks of climate change. For each area, we characterize changes since the EF in terms of the strength of evidence for a link with anthropogenic climate change, the severity of observed and projected impacts, and the risk of additional categories of impact beyond those considered in the EF.

For each of the areas addressed in the EF, the amount, diversity, and sophistication of the evidence has increased markedly, clearly strengthening the case for endangerment (see Fig. 1 in the full article). New evidence about the extent, severity, and interconnectedness of impacts detected to date and projected for the future reinforces the case that climate change endangers the health and welfare of current and future generations. For the sectors analyzed in the 2009 EF, new evidence expands the range of case studies, deepens the understanding of mechanisms, and analyzes the contribution of climate change to particular types of extreme events. In many cases, new evidence points to the risk of impacts that are more severe or widespread than those anticipated in 2009. Further, several categories of climate change impacts, including effects on ocean acidification, violence, national security, and economic well-being, are now supported by such broad evidence that they warrant inclusion in the framing of endangerment.

OUTLOOK: The EPA Administrator found in 2009 that the EF for six long-lived GHGs was "compellingly" supported by "strong and clear" scientific evidence. Our review of evidence published since the EF shows that the case for endangerment, which was already overwhelming in 2009, is even more strongly justified in 2018. ■

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PHOTO (FROM LEFT TO RIGHT): NASA; W. MCNAMEE; L. DEGUIA.

New evidence relevant to the EF. New evidence strengthens the link with anthropogenic climate change (category 1); suggests more severe observed and/or projected impacts (category 2); or identifies new types of risks beyond those considered in the EF (category 3). Examples discussed in this Review include, for category 1, wildfire (left); for category 2, coastal flooding (center); and for category 3, ocean acidification (right).

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Philip B. Duffy[1]*†, Christopher B. Field[2,3]*, Noah S. Diffenbaugh[2,3]*, Scott C. Doney[4], Zoe Dutton[5], Sherri Goodman[5], Lisa Heinzerling[6], Solomon Hsiang[7,8], David B. Lobell[2,3], Loretta J. Mickley[9], Samuel Myers[10,11], Susan M. Natali[1], Camille Parmesan[12,13,14], Susan Tierney[15], A. Park Williams[16]

We assess scientific evidence that has emerged since the U.S. Environmental Protection Agency's 2009 Endangerment Finding for six well-mixed greenhouse gases and find that this new evidence lends increased support to the conclusion that these gases pose a danger to public health and welfare. Newly available evidence about a wide range of observed and projected impacts strengthens the association between the risk of some of these impacts and anthropogenic climate change, indicates that some impacts or combinations of impacts have the potential to be more severe than previously understood, and identifies substantial risk of additional impacts through processes and pathways not considered in the Endangerment Finding.

The Clean Air Act (CAA) requires the U.S. Environmental Protection Agency (EPA) to regulate air pollutants when the EPA Administrator finds that they "cause, or contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare" (*1*). In *Massachusetts* v. *EPA*, the U.S. Supreme Court held that the EPA has the authority to regulate greenhouse gases (GHGs) under the CAA and that the EPA may not refuse to regulate these pollutants once it has made a finding of endangerment (*2*). In this decision, the Supreme Court characterized an endangerment finding on GHGs as a "scientific judgment" about "whether greenhouse gas emissions contribute to climate change."

The courts have long held that the CAA embraces a precautionary approach to findings of endangerment. For example, the federal court of appeals in Washington, DC, has held that "evidence of potential harm as well as actual harm" meets the endangerment threshold and that the EPA's degree of certitude may be lower where the hazards are most grave (*3*). Moreover, public health and welfare are broad concepts under the act, encompassing not only human morbidity and mortality but also effects on soils, water, crops, vegetation, animals, wildlife, weather, and climate (*4*).

In December 2009, the EPA released its "Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act," known informally as the Endangerment Finding (EF). The EF found that six long-lived GHGs, in combination, should be defined as "air pollution" under the CAA and may reasonably be anticipated to endanger the health and welfare of current and future generations. In addition, the EPA explained that "it is fully reasonable and rational to expect that events occurring outside our borders can affect the U.S. population" (*5*).

The EF is an essential element of the legal basis for regulating GHG emissions under the CAA. It provides foundational support for important aspects of U.S. climate policy, including vehicle mileage standards for cars and light trucks and the emissions standards for fossil fuel–fired electric utility generating units (the "Clean Power Plan").

As the DC Circuit held in affirming the EF, the EPA may not decline to find endangerment on the basis of the perceived effectiveness or ineffectiveness of the regulations that may follow in the wake of an endangerment finding or on the basis of predictions about the potential for societal adaptation to climate change (*6*). The DC Circuit held that arguments to the contrary were "foreclosed by the language of the [Clean Air Act] and the Supreme Court's decision in *Massachusetts* v. *EPA*." The court also rejected the argument that the EPA must find that the air pollutants it regulates are the dominant source of the harms it identifies, as the act provides that the pollutants being regulated need only contribute to (or, under some provisions of the statute, "significantly" contribute to) (*7*) harmful air pollution.

The EF was rooted in careful evaluation of the observed and projected effects of GHGs, with assessments from the U.S. Global Change Research Program, the Intergovernmental Panel on Climate Change (IPCC), and the U.S. National Research Council providing primary scientific evidence. The EF was clear that, although many aspects of climate change were still uncertain, the evidence available in 2009 strongly supported the finding. Since the original EF, scientific information about the causes, historical impacts, and future risks of climate change has continued to accumulate. This Review assesses that new information in the context of the EF. We find that the case for endangerment, which was already overwhelming in 2009, is even stronger now.

The EF was structured around knowledge related to public health and public welfare, with a primary focus on effects in the United States. The information on public welfare was grouped into sections on air quality; food production and agriculture; forestry; water resources; sea level rise (SLR) and coastal areas; energy, infrastructure, and settlements; and ecosystems and wildlife. We follow that organization here. In addition, some of the most important advances in understanding the risks of climate change involve sectors or impact types not highlighted in the EF. We summarize the evidence for four of these that are broadly important: ocean acidification, violence and social instability, national security, and economic well-being. We characterize changes since the EF in terms of the strength of the evidence for a link with anthropogenic climate change, the potential severity of observed and projected impacts, and the risks of additional kinds of impacts beyond those considered in the EF (Fig. 1).

Our focus is on the evidence for endangerment rather than the potential for adaptation. Although evidence that a risk might be reduced by some future action is certainly relevant for developing an effective portfolio of responses, the DC Circuit has affirmed that such evidence does not change the core question of whether long-lived GHGs endanger public health and welfare (*6*). In addition, adaptation options are often limited or impose economic costs that reduce adoption (*8*). Even ambitious adaptation rarely eliminates risk. For 32 specific risks evaluated by the IPCC in its recent special report,

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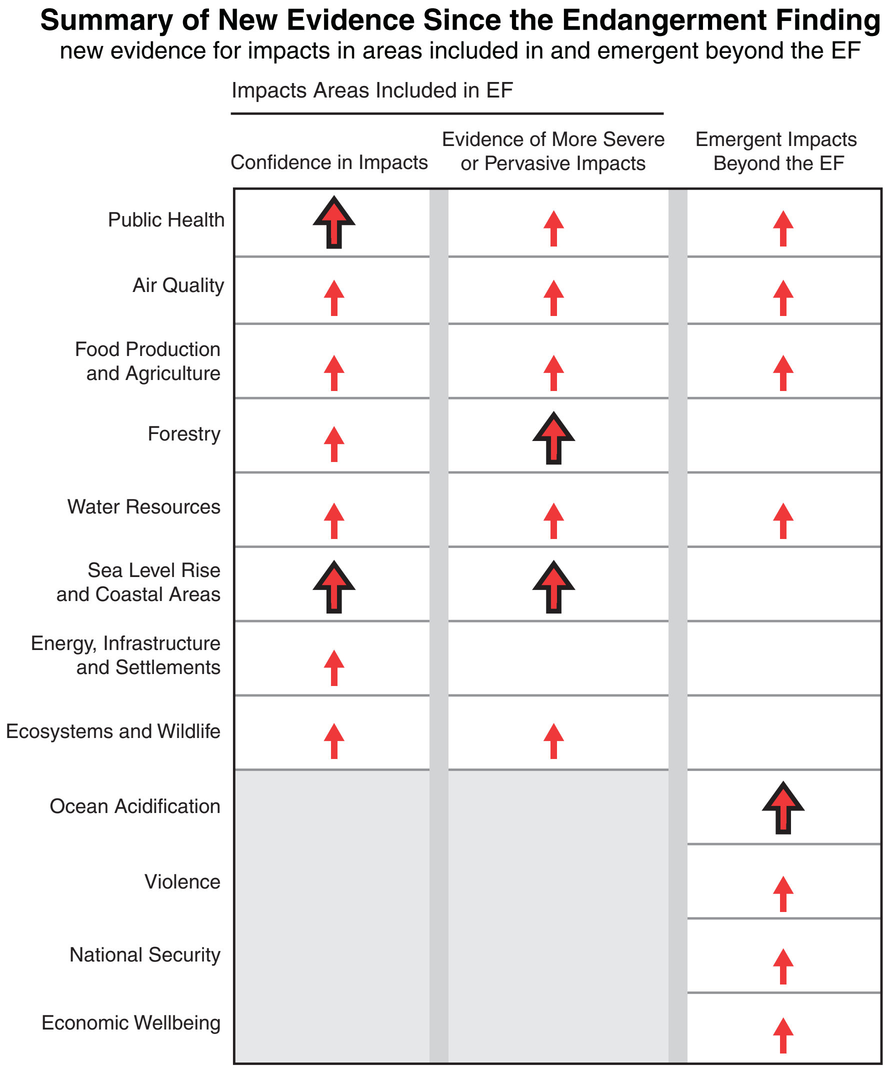

Fig. 1. New evidence since the EF. The columns summarize changes in the amount and implications of new evidence since the EF for each of the impact areas discussed in the EF and four additional impact areas where evidence of climate sensitivity has matured since the EF. An upward-pointing arrow indicates increasing evidence of endangerment. A downward-pointing arrow would indicate decreasing evidence of endangerment. A plain red arrow indicates that the new evidence is abundant and robust. An outlined arrow indicates that the new evidence, in addition, comes from multiple approaches, is derived from independent lines of information, or builds on a new level of mechanistic understanding. The left column refers to confidence in the impacts discussed in the EF. The middle column refers to impact areas that are discussed in the EF but where new evidence points to specific impacts that are fundamentally more severe or pervasive than those discussed in the EF. The right column refers to types of impacts not discussed in the EF.

the potential for adaptation was assessed as low or very low for 25% of risks at a warming of 1.5°C and 53% of risks at 2°C (*9*).

One area of scientific progress since the EF is the attribution of extreme weather events (and some of their consequences) to human-caused climate change. This includes observed effects on human health and security, agriculture, and ecosystems (see below), as well as the probability and/or intensity of specific extreme weather events (*10*, *11*). For extreme event attribution in North America, this includes more than 70% of recent record-setting hot, warm, and wet events and ~50% of record-setting dry spells (*12*), along with the recent California drought (*13*, *14*), the storm-surge flooding during Superstorm Sandy (*15*) and Hurricane Katrina (*16*), and heavy precipitation during Hurricane Harvey (*17*–*19*). Although the realization of risk is not required for a finding of endangerment, cases where extreme events can be confidently attributed to historical emissions reinforce the understanding that we are already seeing impacts and the risks they bring.

Public health

Since the EF, numerous scientific reports, reviews, and assessments have strengthened our understanding of the global health threats posed by climate change [e.g., (*20*, *21*)] (Fig. 1, left column). New evidence validates and deepens the understanding of threats, including increased exposure to extreme heat, reduced air quality, more frequent and/or intense natural hazards, and increased exposure to infectious diseases and aeroallergens. New evidence also highlights additional health-related threats not discussed in the EF, including reduced nutritional security, effects on mental health, and increased risk of population displacement and conflict (Fig. 1, right column).

Extreme heat is the most direct health impact (Fig. 2). With future warming, >200 U.S. cities face increased risk of aggregated premature mortality (*22*). In addition, extreme heat is linked to rising incidence of sleep loss (*23*), kidney stones (*24*), low birth weight (*25*), violence (*26*), and suicide (*27*) (Fig. 1, middle column).

New studies also strengthen evidence for health impacts via increased exposure to ozone and other air pollutants (*28*), including smoke from forest fires (*29*). Likewise, evidence for links among climate change, extreme weather, and climate-related disasters is growing rapidly (*30*). These events often lead to physical trauma, reduced air quality, infectious disease outbreaks, interruption of health service delivery, undernutrition, and both acute and chronic mental health effects (*31*).

Changes in temperature, precipitation, and soil moisture are also altering habitats, life cycles, and feeding behaviors of vectors for most vector-borne diseases (*32*), with recent research documenting changes in exposure to malaria (*33*), dengue (*34*), West Nile virus (*35*), and Lyme disease (*36*), among others. Recent work also reinforces the evidence that increased outbreaks of waterborne (*37*) and foodborne (*38*) illnesses are likely to follow increasing temperatures and extreme precipitation. Likewise, recent research reinforces the conclusion that rising temperatures and carbon dioxide (CO_2) levels will increase pollen production and lengthen the pollen season for many allergenic plants (*39*, *40*), leading to increased allergic respiratory disease (*41*).

One area of new understanding not covered in the EF is threats to global nutrition. Staple crops grown at 550 parts of CO_2 per million have lower amounts of zinc, iron, and protein than the same cultivars grown at ambient CO_2 (*42*). These nutrient losses could push hundreds of millions of people into deficiencies of zinc (*43*), protein (*44*), and iron (*45*), in addition to aggravating existing deficiencies in more than one billion people. These effects on nutritional quality exacerbate the impacts of climate change on agricultural yield, discussed below. Together, these effects underscore a substantial headwind in assuring access to nutritious diets for the global population (*46*).

Mental health impacts represent another area of new understanding (*47*). In particular, increased exposure to climate and weather disasters is associated with posttraumatic stress, anxiety, depression, and suicide (*27*, *48*).

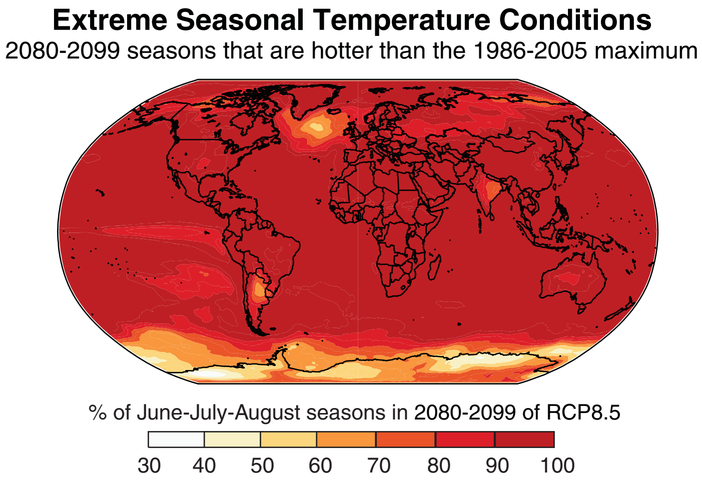

Fig. 2. The frequency of years from 2080 to 2099 of the RCP8.5 scenario in which the June-July-August (JJA) seasonal temperature equals or exceeds the warmest JJA value in the period from 1986 to 2005. [Adapted from (282)]

Lastly, climate change is increasingly understood to function as a threat magnifier, raising the risk of population displacement and armed conflict (discussed below), which can also amplify risks to human health.

Public welfare

Air quality

Evidence for the climate penalty on air quality stressed in the EF has strengthened (Fig. 1, left column). Mechanisms include extreme heat, leading to amplified production of surface ozone (49, 50); strong temperature inversions, leading to increased concentrations of particulate matter (PM) (51, 52); and stagnant atmospheric conditions (53). The most persistent and extreme episodes of elevated temperature, ozone, and PM in the United States have a high incidence of co-occurrence (54). Further global warming is likely to cause air stagnation events to increase over many midlatitude regions, including the western United States (53).

Recent studies confirm the increased risk of higher surface ozone concentrations as climate changes [e.g., (55–57)]. By the 2050s, the United States could experience more ozone episodes (days with 8-hour maximum daily averaged ozone concentrations greater than 75 parts per billion), including three to nine more episodes per year in the Northeast and California (58). By the 2090s, increases could reach 10 episodes per year across the Northeast (59). The U.S. ozone season, typically confined to summer, could also lengthen into spring and/or fall as climate warms (60) (Fig. 1, middle column).

Modeling studies of changes in PM present a mixed picture, arising from the complex responses of PM emissions and chemistry to meteorology [e.g., (61, 62)]. However, as the measurement record has lengthened, more robust estimates have come from observationally based statistical models. By using this approach and assuming no change in emissions of anthropogenic PM sources, one study projected that the annual mean $PM_{2.5}$ (the concentration of particles ≤2.5 μm in diameter) could increase by 0.4 to 1.4 μg m^{-3} in the eastern United States by the 2050s, with small decreases in the West (58). However, summertime mean $PM_{2.5}$ was projected to increase as much as 2 to 3 μg m^{-3} in the East because of faster oxidation and greater biogenic emissions.

Warmer and drier conditions in the West and Southwest [e.g., (63)] have implications for wildfire smoke and dust storms, as discussed below. By the 2050s, increased wildfire activity could elevate the concentrations of organic particles across the West by 46 to 70%, depending on the ecoregion (64), and the frequency of smoke episodes could double in California (65) (Fig. 1, right column). Future projections of the frequency of dust storms are mixed [e.g., (66)]. However, seasonal means of fine dust particles are projected to increase 26 to 46% by the 2050s in the Southwest under a scenario of very high GHG emissions (67).

Taken together, these studies imply that the health impacts of changing air quality due to changing climate will vary across the United States, with greater effects from anthropogenic $PM_{2.5}$ in the East and greater effects from dust and wildfire smoke in the West. The effect of changing ozone on health is projected to be greatest in the Northeast and California. Even seasonal exacerbation in pollutants, though relatively short term, would likely have negative consequences for health (68). The projected degradation of air quality could be mitigated to some extent by more stringent restrictions on the anthropogenic emissions of pollution precursors [e.g., (57)].

Food production and agriculture

Research since the EF has confirmed the EF's conclusion that "the body of evidence points towards increasing risk of net adverse impacts on U.S. food production and agriculture over time, with the potential for significant disruptions and crop failure in the future" (Fig. 1, left column). There is still an expectation that certain aspects of increasing CO_2 and temperature will be beneficial in the next few decades for some crops and locations within the United States but that these positive effects are likely to be outweighed by negative impacts, especially in the long term.

There is substantial new evidence quantifying and explaining the mechanisms behind crop yield losses that result from short periods of exposure to high growing-season temperatures (e.g., greater than 30°C, or 86°F) (69, 70) (Fig. 1, middle column). Likewise, warmer winter nights will also negatively affect perennial crops, such as apples and cherries, that require a certain amount of winter chill for high yields (71), an impact not included in the 2009 EF (Fig. 1, right column).

New understanding of weed and pest responses to climate and CO_2 highlights the risks from these biotic stresses [e.g., (72, 73)]. For example, weeds typically respond more quickly than crops to higher CO_2, which "will contribute to increased risk of crop loss due to weed pressure" (70).

Understanding of agricultural vulnerability has also extended beyond the main commodity crops (Fig. 1, right column). For example, national aggregate agricultural total factor productivity (TFP) exhibits strong sensitivity to weather in regions having high-value crops or livestock production or specializing in commodity crops (74). Sensitivity was highest in recent time periods, and projected warming could reduce TFP at a rate faster than that of technological improvement.

Measurements since the EF enable more thorough characterization of ongoing impacts and adaptation responses. Climate changes since 1980 have had net negative impacts on yields of maize and wheat in most major producing regions globally, with less substantial impacts for rice and soybeans (69). Warming trends in the United States have been more muted than those in other regions, resulting in smaller impacts to date. Studies have also assessed the ability of farmers to adapt to ongoing changes, for example, by comparing regions with different rates of warming or by evaluating sensitivity to spatial gradients in temperature at different points in time. These studies generally indicate a limited ability of farmers to simultaneously raise yields and reduce yield sensitivity to warming (75, 76), which is consistent with the increased aggregate sensitivity of TFP. Other adaptations such as switching crops or adding irrigation have been less rigorously tested. Overall, the conclusion of the 2014 National Climate Assessment was that "although agriculture has a long history of successful adaptation to climate variability, the accelerating pace of climate change and the intensity of projected climate change represent new and unprecedented challenges to the sustainability of U.S. agriculture" (Fig. 1, middle column) (70).

Forestry

Evidence available at the time of the EF indicated that anthropogenic climate change would likely bring more harm than benefits for U.S. forests during the 21st century. Research since the EF broadly confirms that forest ecosystems are not in equilibrium with ongoing and projected trends in extreme heat and drought, making large ecological shifts in U.S. forests likely (77–81) (Fig. 1, left column).

Anthropogenic warming has reduced snowpack across the majority of the montane western United States (82, 83), and Earth system models project reduced summer soil moisture across most of the United States (63, 84). Warming also elevates plant respiration rates and atmospheric evaporative demand, aggravating drought stress and the risk of tree mortality. Further, projected increases in precipitation variability (85) are likely to promote increasingly severe droughts even in regions of increased mean precipitation (13, 86).

Whereas CO_2 fertilization, warming-induced lengthening of the growing season, and nitrogen deposition pose potential benefits to trees, models substantially overestimate CO_2-driven increases in global vegetation productivity over recent decades (87).

A large body of new evidence points to increasing risks of tree mortality or forest loss in the western United States from wildfire, insect outbreaks, and physiological failure due to drought stress (88) (Fig. 1, middle column). Although such disturbances occur naturally, increases in disturbance size, frequency, and severity can have long-term impacts on forest ecosystems (78, 89). Annual western U.S. forest-fire area increased by ~1000% from 1984 to 2017 (90, 91) (Fig. 3). Studies consistently attribute a substantial fraction of this trend to warming-induced fuel drying (92–94) and suggest continued increases in western U.S. forest-fire activity (95, 96) and resultant tree mortality (97) until fuels become limiting (98).

Land management has amplified the effects of warming on western U.S. forest-fire activity (Fig. 1, left column). A century of fire suppression caused fuels to accumulate, creating fire deficits in many forested areas (99). Accumulated fuels and warming combine to aggravate the risk of large, high-intensity wildfires (100–102). This risk may be further exacerbated where CO_2 fertilization or precipitation trends enhance biomass (103) or where humans add to natural ignitions (104).

Recent bark beetle outbreaks in western North America appear to be more massive than those in previous centuries (105), with new research since the EF documenting millions of hectares of tree mortality (106, 107) (Fig. 1, middle column). Warming may intensify bark beetle outbreaks by decreasing cold-season beetle mortality, accelerating the beetle life cycle, and weakening tree defenses (108). However, the full range of effects of climate change on bark beetle outbreaks remains unconstrained (109, 110).

Heat- and drought-driven tree mortality in western forests may be increasing even in the absence of wildfire or insects, as more intense droughts can damage the water transporting xylem and reduce carbon reserves (111, 112). Quaking aspens in the Rocky Mountains have experienced particularly severe drought-driven mortality since 2002, with the risk of repeated events projected to rise throughout the century (113). Some of the impacts of drought intensification may be moderated by adaptation or enhanced capacity for postdrought injury repair (114, 115), but understanding of that potential is limited.

Climate change impacts on eastern forests have been more ambiguous because of the legacy effects of land management, complex competition dynamics, and in some locations, muted warming and/or increased precipitation. Nonetheless, eastern U.S. forests are vulnerable to extreme heat and drought (116, 117). Warming is implicated in the northward expansion of eastern forest pests, including the southern pine beetle (108) and nonnative hemlock woolly adelgid (118). Recent drought-driven fires in the Southeast may portend warming-exacerbated fire activity in that region (119).

The current distributions and assemblages of vegetation species are not in equilibrium with future climate and CO_2 levels. Research over the past decade suggests that the velocity of climate change could exceed the rate of migration of some forest species (120, 121), enhancing the evidence in the EF that rapid 21st-century climate change will profoundly disrupt U.S. forest ecosystems (78) (Fig. 1, middle column).

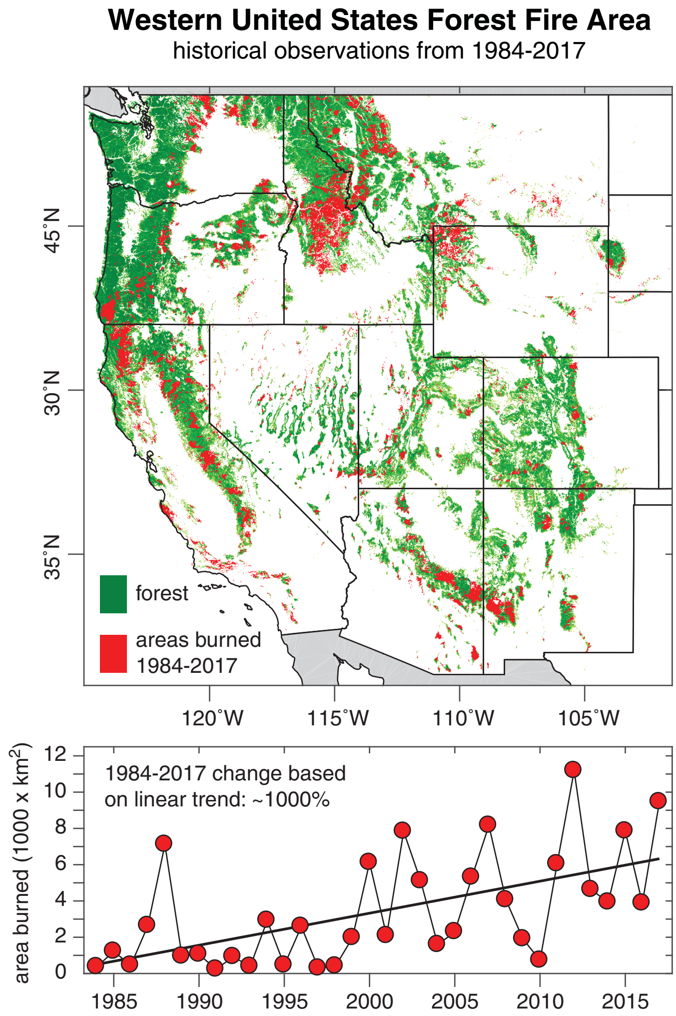

Fig. 3. Western U.S. forest-fire area for 1984 to 2017. (**Top**) Map of forest-fire areas. (**Bottom**) Annual forest-fire area according to the U.S. Forest Service Monitoring Trends in Burn Severity (MTBS) project for 1984 to 2016 (90) and the MODIS version 6 burned-area product for 2017 (91). The MODIS burned-area record was linearly calibrated to the MTBS record during overlapping years of 2001 to 2016. The linear trend is derived from least-squares regression.

Water resources

Climate change impacts on snow hydrology and water scarcity are especially pronounced in the western United States. Observed trends toward warming-induced reductions in snowpack were first widely reported by Mote *et al.* (122). Likewise, up to 60% of climate-related trends in earlier river flow, warmer winter air temperature, and lower snowpack from 1950 to 1999 are attributed to human activities (82).

Since the EF, there has been substantial progress in quantifying trends in snowpack and associated impacts on water availability (Fig. 1, left column). Springtime warming over the past half century has resulted in a higher proportion of precipitation falling as rain versus snow in the western United States (123), earlier snowmelt onset by 1 to 2 weeks in the western United States (124), reductions in stream flow during the driest part of the year in the Pacific Northwest (125), earlier-in-the-year stream flow in snow-fed rivers in North America (126), and reductions in snow cover and snowpack over the Northern Hemisphere (127).

Climate models project accelerated changes in snow hydrology, both in the western United States and globally. Decreases in midlatitude snowfall (128, 129) are projected to reduce snow cover and depth (127, 128), accelerating hydroclimatic change in snow-dominated regions of the western United States (130), including losses in annual maximum water stored in snowpack of up to 60% in the next 30 years (131, 132). Losses of snow cover and water equivalent depth would fundamentally change the sources and timing of runoff in many midlatitude and mountainous regions (133), including the western (134), midwestern, and northeastern parts of the United States (135) (Fig. 1, middle column).

New research highlights risks from snowpack droughts (133, 136). These periods of very low snowpack negatively affect the water supply and other aspects of the Earth system, including rare and endangered species (e.g., salmon, trout, and wolverine) (137, 138) (Fig. 1, right column).

Research since the EF has highlighted the southwestern United States as a region of particular concern. On the Colorado River, elevated temperatures were an important contributor to the drought of 2000 to 2014, and continued warming is projected to drive greater reductions in river flows (139, 140) (Fig. 1, middle column). On the Rio Grande, warming temperatures are contributing to reductions in the fraction of precipitation that becomes river flow (141, 142).

Global urban freshwater availability is threatened by climate forcing and water management practices (143, 144), leading to a projected increase in the number of people living under absolute water scarcity (144, 145) (Fig. 1, right column). In addition, new evidence suggests that further global warming is likely to erode water quality in the United States by increasing nutrient loading and eutrophication, particularly in the Midwest and Northeast (146) (Fig. 1, right column).

Sea level rise and coastal areas

Understanding of the present rates of global and regional SLR, the role of contributing processes, the range of future rates, and the observed and projected impacts has improved since the EF (147). Evidence of the role of SLR in exacerbating impacts of recent hurricanes (15, 17, 19) further highlights the risks (Fig. 1, left column).

Recent studies project SLR at greater than 7 mm year^{-1} after ~2050 (148). This is a global average SLR rate unprecedented in the last 7000 years (149). Recent acceleration of SLR in the U.S. Northeast and Gulf Coast adds to the longer-term trend (150). Annual exceedances of flood thresholds are increasing or accelerating at locations along the U.S. coastline (151), with the majority of tide gauge locations projected to pass a tipping point for flooding (more than 30 days year^{-1} with water higher than 0.5 m above mean high tide) in the next several decades (152). With these rates of SLR, the stratigraphic record and modern analogs that serve as our traditional sources of insight are lacking, limiting our ability to predict the form, magnitude, and spatial extent of future changes to the coastal landscape (153, 154).

Research since the EF documents increased risks of SLR, especially for the higher levels of SLR now within the range of projections (155) (Fig. 1, middle column). SLR has and will increasingly expose coastal populations, economies, and infrastructure to hazards such as flooding, erosion, and extreme events. An SLR defined by the National Oceanic and Atmospheric Administration (NOAA) as an "Intermediate Low Scenario" of 0.5 m by 2100 results in tidally forced flooding approximately every other day for much of the East Coast and the Gulf of Mexico, whereas the "Intermediate Scenario" (1.0 m by 2100) leads to daily flooding in all U.S. coastal regions (156). In the United States, projected population growth approximately doubles the number of people at risk of inundation by 2100, to 4.2 million for an SLR of 0.9 m and 13.1 million for an SLR of 1.8 m (157). By 2110, a high SLR scenario results in the projected loss of more than 80% of West Coast tidal wetlands (158).

Coastal erosion and flooding risk are already affecting real estate values. For example, in Miami-Dade County, property subject to high-tide flooding is appreciating at a lower rate than properties at higher elevations, causing displacement through "climate gentrification" (159) (Fig. 1, left column). Furthermore, as older and less resilient residential structures are damaged or destroyed by coastal storms and chronic shoreline retreat, they are typically replaced by more resilient but also more expensive structures (159, 160).

New evidence since the EF highlights interactions between the SLR and other sectors (Fig. 1, middle column). The SLR and extreme events threaten the movement of goods among major port cities (161), which can lead to economic disruption (162), with cascading impacts far from the coastal zone, as well as opportunity costs associated with ensuring the viability of ports and other coastal infrastructure. Likewise, the domestic and international missions of the U.S. military, including disaster relief and humanitarian assistance, are increasingly affected by SLR, as discussed below.

Energy, infrastructure, and settlements

The EF found that "the evidence strongly supports the view that climate change presents risks of serious adverse impacts on public welfare from the risk to energy production and distribution as well as risks to infrastructure and settlements." This evidence has become stronger and broader since the EF, especially on the basis of increased understanding of the relationship between human-caused climate change and extreme events (10, 11) (Fig. 1, left column).

On the basis of analysis by Wilbanks *et al.* (163), Dell *et al.* reported that "changes in water availability, both episodic and long-lasting, will constrain different forms of energy production [including those] from fossil fuels (coal, oil, and natural gas), nuclear power, biofuels, hydropower, and some solar power systems …" (164). Recent studies indicate that warming water bodies and the reduced availability of water for cooling power plant operations and for hydropower will continue to constrain power production at existing facilities and permitting of new power plants (163, 165). In some parts of the country, electric utilities and energy companies compete with farmers and ranchers, other industries, and municipalities for water rights and availability (166).

Recent work documents an increase in energy demand for cooling buildings, with a shift from predominantly heating to predominantly cooling in some regions and a greater reliance on electricity relative to other energy sources (163, 167).

Given that a substantial fraction of America's energy and transportation infrastructure is located in low-lying coastal and riverine areas, much of that infrastructure is vulnerable to flooding from extreme weather events (168). Likewise, adverse effects on U.S. military infrastructure and surrounding communities have resulted most notably from drought and flooding, as discussed below.

The Third U.S. National Climate Assessment concluded that "in parts of Alaska, Louisiana, the Pacific Islands, and other coastal locations, climate change impacts … are so severe that some communities are already relocating from historical homelands to which their traditions and cultural identities are tied" (169, 170, 171). In particular, "physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increase the vulnerability of rural communities" (172).

The effects of rising temperatures are perhaps most severe in the Arctic, which is warming more than twice as fast as the global average (173) (Fig. 1, left column). Communities across the Arctic are experiencing impacts, including effects from the loss of sea ice, SLR, erosion, and permafrost thaw. These changes have been under way for decades, but much of the documentation has occurred since the EF. Arctic warming is endangering human health, destroying public infrastructure, and threatening water resources, cultural resources, and access to subsistence resources and traditional food storage (174, 175).

The risk and severity of climate impacts are particularly high for coastal communities in Alaska, where loss of land-fast sea ice is increasing storm impacts and permafrost thaw is exacerbating coastal erosion rates (176) (Fig. 1, left column). Thirty-one Alaskan villages face imminent threats from flooding, erosion, and permafrost thaw (177). None of these villages have yet relocated, largely because of the lack of a governance framework to facilitate relocation efforts (178).

Permafrost thaw has a substantial economic cost, quantified mainly since the EF. Ground subsidence and collapse, particularly in ice-rich areas, negatively impact the structural integrity of buildings, roads, and industrial infrastructure, including gas and oil development (175). Cumulative projected costs of climate change damages to public infrastructure in the state of Alaska are estimated at \$5.5 billion for a high-emissions scenario [Representative Concentration Pathway 8.5 (RCP8.5)] and \$4.2 billion for a medium-emissions scenario (RCP4.5) for 2015 to 2099 (179). The greatest economic impact is expected to result from road flooding, followed by building damage as a result of near-surface permafrost thaw.

Ecosystems and wildlife

The first global meta-analyses of climate change impacts on wild species, mostly from terrestrial ecosystems, estimated that about half had responded by shifting their ranges poleward and upward and about two-thirds had responded by advancing their timing of spring events such as tree budburst and bird nesting (180). New studies since the EF have clarified and extended these findings, expanded documentation for marine systems, and illuminated responses at all levels of biological organization (181) (Fig. 1, left column). This new evidence makes clear that prior global estimates underestimated the impacts of anthropogenic climate change on ecosystems and wildlife.

Research since 2009 illuminates new range boundary dynamics that are more complex than simple northward or poleward shifts (182). For example, terrestrial range limits are shifting faster where local warming is stronger (183). Likewise, lower elevation limits set by precipitation can expand downward in response to increased rainfall, despite regional warming (184). Changes in behavior, the timing of activities, or the use of habitat can complement range shifts as a means of matching activity to the range of preferred temperatures (185).

By contrast, marine limits are typically set by physiological thermal tolerances and thus respond more strongly and predictably than equivalent terrestrial limits (186). The mean rate of movement in marine systems (187) reflects the faster poleward movement of isotherms in the oceans than on land (188, 189). The rapid range shift of marine organisms covers many taxa, including phytoplankton (470 km per decade), bony fish (278 km per decade), and invertebrate zooplankton (142 km per decade) (189). Taxa on the move also include important disease organisms, such as *Vibrio* bacteria, which have recently caused unprecedented outbreaks of food poisoning and infection of wounds [reviewed in (190)].

Research since 2009 on the timing of spring events illuminates changes that defy simple expectations (Fig. 1, left column). In plants that require chilling ("vernalization") to determine that winter is over, winter warming slows development whereas spring warming speeds development. Actual changes in timing reflect the combination of these opposing effects, potentially resulting in development that is accelerated, delayed, or unchanged (191).

Before the EF, it was predicted that biological responses would lag behind changes in climate (192). Studies since 2009 have documented that this lag is already occurring. Across Europe, species are responding more slowly than climate is warming, causing bird and butterfly communities to suffer a "climate debt" (193). Likewise, populations of yellow warbler with detectable climate debts had the lowest population growth rates across the United States (194). By contrast, plants that have advanced their timing most strongly have had more positive population growth rates (195).

Similarly, at the time of the EF, there was an assumption that a sensitivity to warming would be most important at the limits of species' ranges. However, several newer studies demonstrate that life history trade-offs can cause species to be constrained by the limits of their climatic tolerances even in central areas of their ranges (196, 197) (Fig. 1, left column).

Biological diversity and the services that ecosystems provide to humans face risks from climate change. The magnitude and timing of these risks are influenced not only by direct effects of climate on organisms but also by compounding effects of other stresses (198, 199), especially land use by humans, changes in disturbance regimes, defaunation (200), and ocean acidification (see below). Biotic interactions related to pollination, food resources, competition, pests, diseases, and predators can also amplify the risks (201). Since the EF, new research has provided additional detail on many of these risks and on the groups of species and ecosystem services that are most vulnerable (202) (Fig. 1, left column).

Extinction risk from climate change is broadly distributed across taxonomic groups, with 21st-century warming threatening about 15% of all species in a world of continued high emissions (202). Risks are especially great for species with small ranges or in habitat types that are spatially limited or rapidly shrinking, including Arctic sea-ice ecosystems (203) and mountaintops (198). Recent large-scale bleaching in warm-water coral reefs (204) and forest mortality events (205) provide clear evidence of risk under current conditions. In the United States, national parks have warmed at twice the national average rate, with precipitation declines at four times the average, highlighting risks to areas of high conservation value (206). Research since the EF underscores risks of climate change for diverse ecosystem services, such as those associated with the role of coral reefs in supporting fisheries (207) (Fig. 1, middle column) and the contribution of forests and soils in GHG balance (208).

Ocean acidification

The removal of anthropogenic CO_2 emissions by air-sea gas exchange and chemical dissolution into the ocean alters the acid-base chemistry of the ocean. Since the EF, scientific understanding of this process and of its possible negative effects on marine life has improved (Fig. 1, right column).

Excess CO_2 gas in the ocean reacts with water, resulting in a series of chemical changes that include reductions in pH, carbonate ion (CO_3^{2-}) concentrations, and the saturation state for carbonate minerals used by many organisms to construct shells and skeletons (209). Such chemical changes are now well documented in the upper ocean. Acidification in coastal waters can be exacerbated by local pollution sources (210). Over the next several decades, trends in near-surface acidification are likely to closely track atmospheric CO_2 trends (211), with acidification hot spots in coastal upwelling systems, the Arctic, and the Southern Ocean (212, 213).

Evidence since the EF reveals a wide range of biological responses to elevated CO_2 and ocean acidification (Fig. 1, right column). For all marine species, the effects of current and future ocean acidification must be framed in the context of a rapidly changing ocean environment with multiple human-driven stressors, particularly ocean warming (214). Warming is reducing open-ocean oxygen levels and exacerbating coastal hypoxia driven by excess nutrients (215), the same nutrient pollution that also causes estuarine and coastal acidification.

Model and data syntheses indicate that acidification may shift reef systems to net dissolution during the 21st century (216). Coral bleaching from ocean warming is already having negative consequences for biologically rich coral reef ecosystems that provide food, income, and other valuable ecosystem services to >500 million people around the world (217), and the combined effects of warming and acidification are expected to worsen in the future (207).

Different kinds of organisms vary substantially in their responses to acidification, with generally negative effects for many mollusks and some plankton to neutral and even positive effects for other species (218). Lower seawater carbonate saturation states reduce calcification and may restrict the geographic habitat for planktonic pteropods (219) that are prey for many fish, marine mammals, and seabirds.

Many shellfish, and perhaps some kinds of crustaceans, are vulnerable to acidification, especially in larval and juvenile stages, with possible repercussions for valuable U.S. and international fisheries (220, 221) (Fig. 1, right column). During the mid-2000s, low-pH waters associated with coastal upwelling led to reduced larval survival of Pacific oysters in some U.S. Pacific Northwest shellfish hatcheries, a problem that has been largely addressable so far through adaptive strategies (222). Wild-harvest fisheries may be more at risk, particularly in regions with combined social and ecological vulnerability (223). Less is known about acidification responses in fish, with most studies indicating weak or no effects

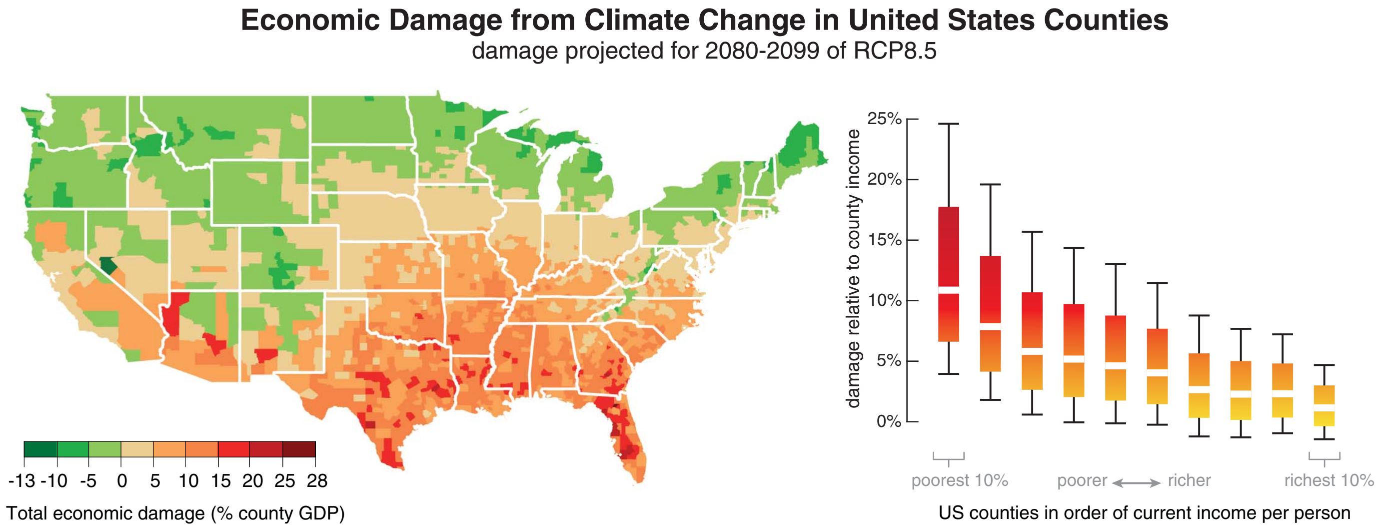

Fig. 4. Total direct economic damage integrated over agriculture, crime, coastal storms, energy, human mortality, and labor in 2080 to 2099 under a scenario of continued high emissions (RCP8.5). (**Left**) Damages in the median scenario for each county. Negative damages indicate benefits. (**Right**) Range of economic damages per year for groupings of U.S. counties, on the basis of income (with 29,000 simulations for each of 3143 counties) as a fraction of county income (white lines, median; boxes, inner 66% of possible outcomes; outer whiskers, inner 90% of possible outcomes). [Adapted from (*238*)]

on growth and reproduction. However, a number of studies report negative effects on fish olfaction and behavior (*224*).

Taken as a whole, acidification will likely exacerbate many of the climate warming effects on marine ecosystems, including shifting species ranges, degrading coral reefs, and expanding low-oxygen zones.

Violence and social instability

Since the EF, a number of studies have used historical data to explore whether changes in environmental conditions influence the risk of violence or instability (*225*). In general, high temperatures and rainfall extremes amplify underlying risks (*26*) (Fig. 1, right column). These effects are not uniform (*226*). Many factors, including political institutions (*227*), income levels (*228*), and local economic structures (*229*), play a role in determining the structure of these effects.

A robust and generalizable finding is an increased risk of threatening and violent interactions between individuals under hot conditions (Fig. 1, right column). In the United States, exposure to high temperatures is associated with higher rates of domestic violence (*230*), rape, assault, and murder (*231*, *232*), as well as greater use of threatening behaviors, such as aggressive language in social media posts (*233*) and horn honking in traffic (*234*), and higher rates of violent retaliation in sports (*235*). Emerging evidence also indicates that hot periods elevate the risk that individuals harm themselves, including by suicide (*27*, *236*). U.S. data indicate no evidence of adaptation (*27*, *232*).

Effects of temperature [+2.4% per SD (σ)] and rainfall (0.6% per σ) on interpersonal violence are both highly statistically significant, according to a meta-analysis (*237*). If these responses to historical fluctuations translate to future climate change, warming of 1°C could lead to an increase in national violent crime (rape, assault, and murder) by 0.88% (±0.04%) (*238*). Under RCP8.5, this trend projects to a warming-caused increase in violent crime of 1.7 to 5.4% by 2080 to 2099. Warming is projected to increase the national suicide rate by 0.6 to 2.6% by 2050 (*27*).

Many studies document a heightened risk of violence between groups of individuals when temperatures are hot and/or rainfall is extreme (*26*) (Fig. 1, right column). The patterns are similar for organized violence, such as civil conflicts (*228*, *239*), and disorganized violence, such as ethnic riots (*240*), with highly statistically significant effects of temperature (+11.3% per σ) and rainfall (3.5% per σ, over 2 years) (*237*).

Political instability is heightened in hot periods, even in contexts where political institutions are sufficiently robust to avoid outright violence (Fig. 1, right column). The probability of political leadership changes, through both democratic process (*241*, *242*) and "irregular" conditions (*243*, *244*), rises in warm periods. Coups are more likely in hot years with extreme rainfall in agriculturally dependent countries (*245*).

By degrading economic conditions, climate events may contribute to out-migrations of populations seeking better opportunities. Drought and soil loss in the Dust Bowl induced mass out-migration from the rural Midwest (*246*), and young working-age individuals left the corn belt during periods of extreme heat in recent decades (*247*). Likewise, periods of high temperatures have been linked to migration from rural regions of Mexico to the United States (*247*, *248*). Population movements after periods of extreme heat or dryness have been documented in multiple regions (*249*–*251*), and high temperatures in agrarian regions elevate international applications for political asylum (*252*).

National security

Since the EF, the American military and intelligence communities have substantially increased their integration of climate change into national security strategies, policies, and plans. These considerations have been reflected in analyses of the national security implications of climate change by the U.S. Department of Defense, with almost 50 reports considering climate security impacts published between 2010 and 2018 (*253*) (Fig. 1, right column).

The National Intelligence Council (NIC) has warned Congress about the security risks of climate change every year since 2008, after the release of the landmark report by the CNA Military Advisory Board, "National Security and the Threat of Climate Change" (*254*). The NIC's "Worldwide Threat Assessment," which reflects the intelligence community's consensus on the most substantial risks to national security, in 2018 for the first time included a robust section titled "Environment and climate change," noting a range of security risks related to environmental concerns (*255*). The 2018 Defense Authorization Act, signed by President Donald J. Trump, stated that "climate change is a direct threat to the national security of the United States …" (*256*). During the Trump presidency, 16 military leaders, including Secretary of Defense James Mattis (*257*), have voiced concerns about climate change and its security implications. Chairman of the Joint Chiefs of Staff General Joe Dunford stated, "Climate change … is very much something that we take into account in our planning as we anticipate when, where and how we may be engaged in the future and what capabilities we should have" (*258*).

New studies strengthen the evidence that climate change causes weather patterns and extreme events that directly harm military installations and readiness through infrastructure damage, loss of utilities, and loss of operational capability (Fig. 1, right column). An SLR of 3.7 feet would threaten 128 military bases (*259*). Thawing permafrost exposes foundations to damage, whereas the loss of Arctic sea ice causes coastal erosion near critical facilities. Intensifying wildfires threaten facilities, transportation infrastructure, and utility lines. Fire-hazard days and inclement weather suspend outdoor training, and droughts limit the use of live-fire training. Greater storm frequency and strength put a strain on the resources of the defense support of civil authorities at home, as well as on assistance to humanitarian efforts and disaster relief around the world (*260*). As of 2018, 50% of military installations both at home and abroad had already reported damage due to climate change (*260*). Droughts or unpredictable rainfall could leave armed forces stationed abroad vulnerable to being disconnected from potable water supplies, a cause for concern given that protecting convoys for the "resupply of fuel and drinking water for troops in-theater costs lives" (*261*).

Climate change increasingly disrupts existing international security dynamics in geostrategic environments (Fig. 1, right column). Reduced Arctic sea-ice extent will open the way for more trade, as well as oil and gas extraction, turning a historically neutral territory into a potential political flashpoint. Moreover, the U.S. military now has to operate in an increasingly open water Arctic region as sea ice retreats. As Secretary of Defense Mattis recently stated, "America's got to up its game in the Arctic" (*262*). Both China and Russia have been deepening their Arctic presence through investment and the development of ports. As much as 15 percent of China's trade value could travel through the Arctic by 2030, and between 20 and 30 percent of Russia's oil production will come from deposits in the Arctic shelf by 2050 (*263*). These interests will require further American military and coast guard activity in the region, as well as broader diplomatic and scientific engagement.

Indirectly, climate change has a major effect on national security by acting as a "threat multiplier" (*254*) or "accelerant of instability" (*264*) (Fig. 1, right column). This means that climate change heightens the risk posed by threats the United States is already facing and, in aggregate, fundamentally alters the security landscape (*265*). In both the 2010 and 2014 quadrennial defense reviews (*264*, *266*), the Department of Defense emphasized how seriously the military takes this dangerous dynamic, a commitment that receives meaningful redress every year in its annual strategic sustainability performance plans (*267*).

As discussed in other parts of this Review, an expanding body of evidence reinforces how climate change fuels economic and social discontent, and even upheaval. This includes extreme weather events, which raise the risk of humanitarian disasters, conflict, water and food shortages, population migration, labor shortfalls, price shocks, and power outages (*255*).

Economic well-being

Research on the economic consequences of climate change has advanced substantially since the EF, with important progress on understanding nonagricultural sectors and broad measures of well-being (*225*, *268*) (Fig. 1, right column). In the United States, economic impacts of hot temperatures and changing tropical cyclone environments are clearly documented (*238*), and growing evidence indicates long-term adverse effects on the labor force (*269*–*271*). Other impacts, such as those from water availability or wildfire risks, are thought to be important but remain less well understood (*272*).

Since the EF, new "top-down" analyses of overall macroeconomic performance estimate that warming by an additional 1°C over 75 years can be expected to permanently reduce the U.S. gross domestic product (GDP) by ~3% through direct thermal effects (*273*) and that the U.S. GDP can be expected to be ~4% greater at 1.5°C than at 2°C above preindustrial temperatures (*274*) (Fig. 1, right column). The average projected alteration of cyclone activity under "business as usual" may cost the United States the equivalent of 29% of one year of current GDP (in net present value discounted at 3% annually) (*275*). In one study, the net cumulative market-based cost of thermal effects in RCP8.5 by 2100 should be valued at $4.7 trillion to $10.4 trillion (in net present value discounted at 3% annually) (*276*). Notably, in some cases these top-down analyses are able to account for both the opportunity costs and benefits of adaptations undertaken by populations as they adjust to new climatic conditions (*276*).

"Bottom-up" analyses examining impacts on individual sectors or industries have key advantages, including capturing the value of nonmarket impacts such as the loss of human life or biodiversity (*238*). Evidence from combining sector-specific analyses of impacts such as agricultural output (*277*), the quantity of labor supplied by workers (*278*), energy demand (*167*, *279*), mortality rates (*279*), crime rates (*232*), SLR (*280*) and tropical cyclone damage (*281*) suggests U.S. costs equivalent to 1.2% of GDP for each 1°C of warming, with poorer counties experiencing an economic burden roughly five times that of wealthier counties (*238*) (Fig. 1, right column, and Fig. 4).

Conclusions

The EPA Administrator found in 2009 that the EF for six long-lived GHGs was "compellingly" supported by "strong and clear" scientific evidence (*5*). Since 2009, the amount, diversity, and sophistication of the evidence have increased markedly, clearly strengthening the case for endangerment. New evidence about the extent, severity, and interconnectedness of impacts detected to date and projected for the future reinforces the case that climate change may reasonably be anticipated to endanger the health and welfare of current and future generations. For the sectors analyzed in the 2009 EF, new evidence expands the range of case studies, deepens the understanding of mechanisms, and analyzes the contribution of climate-related extremes. In many cases, new evidence points to the risk of impacts that are more severe or widespread than those anticipated in 2009. Several categories of climate-change impacts, including effects on ocean acidification, violence, national security, and economic well-being, are now supported by such broad evidence that they warrant inclusion in the framing of endangerment. In sum, the EF, fully justified in 2009, is much more strongly justified in 2018.

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Science

Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases

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The case for endangerment

In 2009, the U.S. Environmental Protection Agency (EPA) established the so-called ''Endangerment Finding.'' This defined a suite of six long-lived greenhouse gases as ''air pollution.'' Such air pollution was anticipated to represent a danger to the health and welfare of current and future generations. Thus, the EPA has the authority to regulate these gases under the rules of the U.S. Clean Air Act. Duffy *et al.* provide a comprehensive review of the scientific evidence gathered in the years since then. These findings further support and strengthen the basis of the Endangerment Finding. Thus, a compelling case has been made even more compelling with an enormous body of additional data.

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